September 26, 2022

Brian Oh, Comprehensive Planning Manager
Permit Sonoma County of Sonoma
2550 Ventura Avenue
Santa Rosa, CA 95403

Dear Mr. Oh:

Sonoma Land Trust (SLT) provides these comments on the Draft Environmental Impact Report ("EIR") for the Sonoma Development Center Specific Plan ("Specific Plan," "Proposed Plan," or "Project"). The Sonoma Developmental Center ("SDC") property can play a pivotal role in providing much-needed affordable housing while protecting Sonoma County's ecological and recreational resources for future generations. The Specific Plan also presents a unique opportunity for California to demonstrate how redevelopment of a state-owned property can deliver community benefits such as climate resilience, affordable housing and expanded park access, while achieving priorities such as the 30x30 biodiversity conservation initiative.

Because SDC is owned by the state, there is also a public trust obligation to conserve and protect the property—and especially the Sonoma Valley Wildlife Corridor—as an "ecological unit" above and beyond the specific direction provided by the 2019 legislation[1]. Under the public trust doctrine, navigable waters, tidelands and wildlife resources are held in trust for all of the people, and the state acts as the trustee to protect these resources for present and future generations. This is acknowledged in Guiding Principles #3 and #4 of the Specific Plan.

The Proposed Plan for the redevelopment of the SDC core campus will have significant and unidentified impacts to the local and regional environment—most notably to wildlife connectivity, wildfire safety, hydrology and management of water resources. As discussed in detail in Attachment A and in the analysis provided by biology, transportation, wildfire, and hydrology experts (Attachments B, C, D, E, and F),[2] the

[1] Government Code Section 14670.10.5

[2] The comments in Attachments A through F are incorporated herein by reference. Please refer to these comments for further detail and discussion of the EIR's inadequacies. We request that the County respond both to the comments in this letter and to each of the comments in each of the Attachments.

EIR fails to adequately inform decisionmakers and the public about the numerous environmental impacts of the SDC Specific Plan. Instead the EIR defers both the required analysis and development of mitigation measures to the future, which violates the basic requirements of the California Environmental Quality Act (CEQA).

The detailed comments of SLT focus on the additional analysis and evidence needed to fulfill CEQA's primary responsibility of fully disclosing the environmental consequences of this large-scale development project that will significantly alter the landscape of the Sonoma Valley. The attempt to use the concept of a "self-mitigating" Specific Plan avoids the responsibility of analyzing the impacts first to understand what needs to be mitigated, before jumping to the next step of determining what measures are necessary and effective to reduce impacts to less than significant. Put simply the EIR fails to "show its work" and connect the dots between the Project's significant impacts and the vague (and mostly deferred) mitigation measures contained in the Specific Plan.

The incredible environmental values and assets of SDC—and the site's history and legacy of care—require an equally exceptional EIR and Specific Plan. These will be the guiding documents for decades to come, and the rush to meet an unrealistic deadline for approval of the EIR and Project that does not enjoy strong public support is unnecessary. SLT suggests an approach that will allow the County to still move forward in a timely manner to meet Project objectives, satisfy the 2019 legislation related to the disposition and future use of SDC, and improve and correct flaws in the environmental documents. This approach meets CEQA requirements, improves consistency with the County's General Plan and fulfills Guiding Principle #5 to promote sustainable development practices in building and landscape design.

SLT recommends that the Planning Commission and Board of Supervisors decline to certify this EIR and instead direct staff to use the historic preservation alternative as the starting place for a new and revised preferred project, and a revised Specific Plan and EIR that addresses the flaws identified in the Attachments to this letter.

We recommend that the historic preservation alternative be revised to start with an affordable housing project of 200+/- homes (Phase 1), and to allow for future development phases consistent with whichever proposal the California Department of General Services (DGS) selects as the winning bid pursuant to their surplus property sale process for the SDC core campus. The EIR acknowledges that the County and public have no accurate estimate of how much development will actually occur at SDC, because we don't know which proposal DGS will select to enter into an Exclusive Negotiating Agreement for the sale of the campus. As the EIR states on page 77:

> "...development of most of the properties in the Planning Area would be implemented through the market-driven decisions that the selected buyer(s) would make for their properties, and no development rights or entitlements are specifically conferred with the Proposed Plan. Furthermore, given that the

> majority of future development under the Proposed Plan is residential, varying levels of density bonuses are available under the State depending on the level of affordable housing provided. Thus, it is difficult to project the exact amount and location of future development that may result."

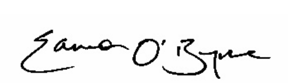
According to the schedule released by DGS, a buyer will be selected in late October, which gives Permit Sonoma, the public and the decision makers an opportunity to focus on a real-world proposal that will drive "*the exact amount and location of future development*." This will also resolve the problem of speculating about financial feasibility and making unfounded assumptions on how much and what type of housing needs to be built on the site to subsidize the affordable housing mandates.

Importantly, the historic preservation alternative also requires significant modification to expand the wildlife corridor, riparian and open space protections and setbacks. SLT's top priority is ensuring that the Specific Plan furthers Guiding Principle #3. Therefore, the revised historic preservation alternative must include and meet the following specific performance standards:

- Provide sufficient setbacks from all creeks designed to protect water quality and quantity, instream and riparian habitat, and wildlife connectivity
- Provide a sufficient buffer that reduces the current footprint of the north side of the SDC campus adjacent to Sonoma Creek to allow wildlife to safely travel through the Sonoma Valley Wildlife Corridor
- Ensure human activities and improvements at SDC do not impair wildlife's use
- Ensure new roads and increased traffic do not create a danger to wildlife
- Ensure new development does not create new sources of light, glare, or noise that would impair wildlife's use of the Corridor
- Ensure new development does not increase the risk of wildfires that would harm the natural and built environments
- Ensure runoff from new impermeable development does not result in erosion or contamination of creeks and riparian areas.

Developing these performance standards will require additional study and resources, and SLT is prepared to assist in that effort to ensure that the Sonoma Valley Wildlife Corridor and natural environment continue to function as a regional habitat linkage for the entire North Bay. Thank you for considering the comments and recommendations in this letter and each of the Attachments. We hope that our suggested approach can secure community support before the Specific Plan and EIR go to the Board of Supervisors for consideration and approval.

Sincerely,



Eamon O'Byrne
Executive Director

Attachments

Attachment A: Sonoma Land Trust's Comments

Attachment B: Prunuske Chatham, Inc. Comments

Attachment C: Pathways for Wildlife Comments

Attachment D: Neal Liddicoat, Griffin Cove Transportation Consulting, PLLC Comments

Attachment E: Alexandra Syphard, Conservation Biology Institute Comments

Attachment F: Gregory Kamman, CBEC Eco Engineering Comments

ATTACHMENT A

Attachment A

Sonoma Land Trust's Comments on the Draft Environmental Impact Report for the Sonoma Developmental Center Specific Plan

These comments provide the Sonoma Land Trust's input on the Draft Environmental Impact Report ("EIR") for the Sonoma Development Center Specific Plan ("Specific Plan," "Proposed Plan," or the "Project"). As discussed below and in the analysis that follows provided by biology, transportation, wildfire, and hydrology experts (Attachments B, C, D, E, and F to September 26, 2022 letter from SLT to Brian Oh),[1] the EIR fails to provide a stable project or analyze the full scope of impacts that would foreseeably result from the buildout of the draft Specific Plan. Relying on the Specific Plan's goals and policies—which are replete with caveats and qualifications—the EIR treats the Specific Plan as a self-mitigating project. But the EIR does not actually do the analysis or present the substantial evidence necessary to support that conclusion. Nor does the EIR incorporate the purported self-mitigating aspects of the Specific Plan into a formal mitigation monitoring and reporting program, which program is required under CEQA to ensure that a project's mitigating elements are meaningful and enforceable and actually achieve their stated goals.

The errors in the EIR are especially consequential in this case, given the immense specificity of the draft Specific Plan. If the draft Specific Plan is adopted, the County will know substantially where specific uses will be located and what the footprint and intensity of those uses will be. The County is relying on that specificity to streamline future environmental review of development under the Specific Plan, including by avoiding altogether future environmental review wherever possible. Specific Plan at 7-3 (indicating that certain types of development under the Specific Plan might be exempt from further CEQA review and stating that the "County intends to rely on these provisions for exemptions and tiering to the maximum extent feasible"). Particularly given the County's stated objectives, it is critical that the EIR analyze fully all foreseeable impacts of all development allowed under the Specific Plan and that it mitigate those impacts found to be significant. The EIR cannot and should not defer to future environmental review the analysis of the Project's impacts and identification of mitigation.

The EIR also fails to properly include documents referenced and relied on by the EIR. For example, the DEIR references a traffic study for the Project, but fails to attach it as an appendix to the EIR. EIR at 410, Footnote 118 [references the Focused Traffic Operations Analysis for the SDC Specific Plan (W-Trans, August 2022 [actually July 6, 2022])].

Similarly, the EIR references an evacuation study for the Project site prepared by Kittelson and Associates, but fails to append this document. EIR at 506. Under well-established

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[1] These expert reports are submitted as part of the Sonoma Land Trust's letter to the County and will not be submitted separately. The County must respond separately to each of the comments in this Attachment A and to each of the comments in each of the expert reports.

case-law, the lead agency is required to present all relevant reports relied upon to prepare the EIR as part of the document.

As described below, the current EIR fails to adequately inform decisionmakers and the public about the environmental impacts of the SDC Specific Plan. The final EIR must be significantly revised to include all necessary evidence, analysis, and mitigation if it is to comply with CEQA.

PROJECT DESCRIPTION

- The EIR fails to provide an accurate, stable, and finite project description.

- The Project Description does not provide a clear description of the amount of development allowed under the Specific Plan. The EIR also does not include an accurate representation of the amount of development that is identified in the Draft Specific Plan. Table 4-2 in the Specific Plan includes a range of housing units permitted in the various districts of the SDC with a maximum of 1,210 units. The table notes that a +/- 10% deviation in each district is allowed subject to approval by the Community Development Director, which could lead to a maximum of 1,331 units (1,210+121). A footnote to Table 4-2 notes that "While the base housing unit range for each district is represented as a range, the total base number of units built across all districts *should* equal the total shown in the table" (emphasis added). However, there is no further detail describing how this unit count would be implemented and any lesser number (e.g. 733) enforced when each district has a range of unit allotments. Furthermore, the Specific Plan at 4-12 acknowledges that developers would be able to use State and County density bonuses for inclusionary housing and notes an additional 200 market rate units. However neither the Specific Plan nor the EIR explain how that number was developed. Furthermore, the Specific Plan identifies another planned 100-unit affordable housing project that is anticipated to be developed (with County involvement) on the SDC site. According to current State density bonus law, a 100% affordable project could seek a density bonus of up to 80%, which could lead to an additional 80 units beyond the 100 identified. The Specific Plan could accommodate at least 1,331 units before density bonus allowances and sets no upper limit on the number of units allowed, while the EIR analyzes a maximum of 1,000 units (EIR Table 2.5-1).

- While the Project Description residential unit count is different than the units identified in the Specific Plan, there are also sections within the EIR that cite statistics with unclear sources, leading to cloudy and unsupportable conclusions. The Project Description notes the development of 1,000 residential units and a future population of 2,400 persons (average size of 2.4 persons per household). This is in contrast with the average household size in Sonoma County of 2.6 persons per household as identified in the EIR at 369 (Population and Housing section). What is the data point to suggest that the average household size at SDC would be lower than the County-wide average? This discrepancy of 200 persons is not reflected in any of the analyses that rely on population, such as Public Service and Recreation, Utilities and Service Systems, Air Quality and Greenhouse Gas Emissions.

- Compounding the confusion over accurate unit counts and the accuracy of analyses, some of the impact sections reference different numbers than the Project Description, resulting in an unstable project description and confusion about key elements of the Project. EIR at 429 (Land Use and Transportation Network Assumptions) states that “the analysis presented in this section is based on an assumption that implementation of the Proposed Plan would result in 1,000 residential units with State and County density bonuses, including 435 single family units, 345 multifamily units, and 220 senior housing units.” But neither the EIR Project Description nor the Specific Plan indicates that the 1,000 residential units would be inclusive of State and County density bonuses. Nor does the EIR Project Description or Specific Plan identify the split between single family and multi-family units or provide for senior housing units. Where did these assumptions come from? How can they be relied upon for the Transportation analysis? Other sections that made assumptions regarding the split between units types include Population and Housing, Public Service and Recreation, Utilities and Service Systems. In the Public Services and Recreation section, Table 3.13-4 at p.402 (Student Generation Rates) analyzes 500 single family units and 280 affordable/apartment units (780 in total) to conclude a total new student population number. Not only is this assumption of the number of unit types not in the Project Description (what is the source?), but it is also a different unit split assumption than what is used in the Transportation section. Beyond transportation, what unit assumptions were used for the projected Water Demand Estimates (EIR Table 3.15-1) or the analyses for wastewater, solid waste generation, etc.? Calculations for these utilities are based on different use factors for different unit types, but the data tables do not reference the unit counts assumed and because of the lack of information in the Project Description, there is no clarity or validity to the information.

- EIR at 77 states “While the project buildout projection reflects a reasonably foreseeable maximum amount of development for the Planning Area through 2040, *it is not intended as a development prediction or cap that would restrict development in any of the five subareas*. *Rather, the Proposed Plan allows for flexibility in the quantity and profile of future development within and between subareas, as long as it conforms to the policies and standards, including permitted densities and FARs, in the Specific Plan*” (emphasis added). This statement is problematic in that neither the Specific Plan nor the EIR identify what the maximum development potential for the Specific Plan would be at the permitted densities and FARs of each land use district. Therefore it is impossible to know the actual maximum buildout envisioned by the Specific Plan. Also, what five subareas does this this statement refer to?

- Since the overall development capacity permitted by the Specific Plan is unclear, the subsequent analyses that rely on the unit count presented in the Project Description are therefore inaccurate. The unit counts identified in the Specific Plan and EIR are inconsistent and call into question analyses completed for the many of the impact areas, including the transportation section (VMT assessment), air quality and greenhouse gas emissions calculations, noise analysis, wildfire/emergency evacuation analysis, biological resources assessment, and utility needs assessment, among others. The failure to accurately describe the overall development capacity of the Project is a serious and pervasive deficiency, as it renders faulty the EIR’s environmental impact analyses as well as the discussion of potential mitigation measures and alternatives to minimize those impacts. As a result of the understatement of development potential, the EIR understates the true impacts of the Project.

- CEQA requires that the EIR analyze all elements of the project. But the EIR's Project Description omits key elements, preventing the reader from fully understanding the full scope of the Project and resulting in an EIR that fails to accurately assesses the impacts of the Project. These deficiencies include the following:

    - The Specific Plan will be adopted along with amendments to the Sonoma County General Plan and Zoning Code, however details of the amendments and proposed zoning are not identified in the Project Description.

    - A portion of the Core Campus west of Arnold Drive is part of the Sonoma State Home Historic District and includes two individually contributing historic resources—the Sonoma House and the Main Building, which is a National Historic Landmark. The Project Description identifies the total square footage of existing building square footage that will be retained for adaptive reuse (EIR at Table 2.5-3), but does not identify where the buildings are. Which buildings will remain and which buildings will be demolished?

    - What has been assumed for duration of site work, building demolition, and construction of new buildings as well as reuse of existing facilities? What is the phasing plan for the buildout of the Project? The Specific Plan provides only one concrete policy for phasing (Policy 4-3, which requires completion of at least 10,000 square feet of retail businesses and at least 200 housing units west of Arnold Drive before beginning construction of any housing east of Arnold Drive). But given that buildout will occur over a nearly 20 year period, phasing is critical and can ensure additional future construction occurs only if it will not result in additional significant environmental impacts.

    - EIR at 59 notes "The site will have a system of distributed energy resources (DERs) that will generate electricity on-site, which could include solar, wind, geothermal, and methane gas co-generation, a process that captures and burns the potent methane gases that are emitted from solid waste, such as from landfills, wastewater treatment plants, dairies, and other facilities." There is no land use district in the Specific Plan that would allow a methane gas co-generation facility at SDC, so it is unclear where such a facility could be located. The Specific Plan and EIR contain a "Utilities" land use classification, but a gas co-generation facility is not identified in this category and there are no areas on EIR Figure 2.4-1 (Proposed Land Uses) that are designated "Utilities". Where would this facility be located? Where are the impacts of a new methane co-generation facility analyzed? They do not appear to be addressed in any other sections of the EIR. Likewise, the Project Description and Utilities classifications omit geothermal, even though the SDC property has geothermal wells, which are not identified in the Specific Plan or EIR.

- There are existing uses outside of the Core Campus (in the agricultural area between the Core Campus and Hwy 12 and the current recreational uses on the west side of the SDC). Were they included in the baseline/existing conditions? What assumptions have been made regarding their continued operation and/or expansion of these uses?

- The EIR repeatedly identifies the Core Campus as the focus of future development, but future uses and any improvements outside the core campus must be identified and analyzed as well – especially as they relate to impacts on sensitive resources. Since the General Plan amendment(s) and proposed rezoning(s) for the SDC site in its entirety is unknown, the permitted uses in areas outside the Core Campus is unclear. What land use changes are contemplated for areas outside of the Core Campus? What zoning, specific plan, and general plan land use designations will apply to SDC property outside of the Core Campus?

- The EIR does not fully describe the intensity and distribution of future residential and non-residential development. EIR Figure 2.4-1 identifies the location of future land use designations, but the Project Description should provide a summary table that identifies proposed land use districts, amount of land (acreage) with that designation, and the maximum development potential in that district (non-residential square foot and residential units). Without this information, it is not clear how residential units and non-residential square footage will be distributed throughout the site and what impacts that distribution might have. How many acres are identified in each land use designation? What is the maximum development potential for each land use category based on the acreage and allowed density (for both residential units and non-residential square footage)? How do the units and square footage overlay on the land use map provide a sense of development distribution throughout the Core Campus? How much development is allowed in more sensitive areas east of Sonoma Creek? How can the public and decisionmakers understand the actual impacts and correctly identify different areas and subareas if the boundaries are to be determined?

- EIR at 51 states "Appendix A of the Specific Plan contains a Standard Conditions of Approval document that shall consist of conditions required to be implemented upon development of the Proposed Plan to mitigate potential environmental impacts. In addition, the Proposed Plan includes amendments to the County's General Plan and Zoning Code." Will all of the policies and standard conditions of approval that comprise mitigation to project impacts be adopted in a reporting program of some sort? How will the policies and standard conditions be enacted and implemented as effectively and with as much accountability as mitigation measures?

- EIR at 82 states that "the Proposed Plan would require the following approvals and discretionary and ministerial actions by the County of Sonoma: Adoption of ordinances, guidelines, programs, and other mechanisms for implementation of the Proposed Plan." This is a very vague description of a long list of future actions that will need to be taken to ensure the successful implementation of the Specific Plan (and the policies/programs that are serving as mitigation for project impacts). CEQA Guidelines Section 15124(d) requires that the Project Description contain a "list of permits and other approvals required to implement the project," so this section should be more detailed and clear. What specific ordinances, programs, and other implementation mechanisms are proposed for adoption? What amendments to the Zoning Code and/or General Plan are contemplated with the adoption of the Specific Plan? What other County policy documents might be impacted/amended as a result of the Specific Plan?

BIOLOGICAL RESOURCES

- The comments presented below refer to and build on comments prepared by Prunuske Chatham, Inc. ("PCI Comments") and Pathways for Wildlife ("Pathways Comments") on the EIR and Specific Plan, attached below as Attachments B and C to Sonoma Land Trust's September 26, 2022 letter to Brian Oh. The County must respond to these comments *and* the comments in Attachments B and C.

- The EIR fails to adequately analyze or mitigate the Project's impacts on biological resources. The EIR's analysis both understates the severity of the potential harm to biological resources within and adjacent to the proposed Project site and neglects to identify sufficient mitigation to minimize these impacts. What little analysis is present is not supported by data or substantial evidence. Given that analysis and mitigation of such impacts are at the heart of CEQA, the EIR must remedy these deficiencies to comply with CEQA.

- The "programmatic" nature of the proposed EIR is no excuse for a lack of detailed analysis. The EIR must provide an in-depth analysis of the Project, looking at effects as specifically and comprehensively as possible. Because it looks at the big picture, a program level EIR must provide *more* exhaustive consideration of effects and alternatives than an EIR for an individual action, and must consider cumulative impacts that might be slighted by a case-by-case analysis.

- Further, it is only at this early stage of the redevelopment of SDC that the County can design wide-ranging measures to mitigate County-wide environmental impacts. A "program" or "first tier" EIR is *not* a device to be used for deferring the analysis of significant environmental impacts. It is instead an opportunity to analyze impacts common to a series of smaller projects, in order to avoid repetitious analyses. Thus, it is particularly important that the EIR for the Project provide detailed and comprehensive analysis of the existing conditions and the full range of development proposed by the Specific Plan, rather than deferring such analysis to when specific development is proposed at a later time. Meaningful analysis of impacts now would help inform the design and details of the Specific Plan to best minimize environmental impacts.

- The EIR fails to address Executive Order N-82-20, which establishes the state's goal to conserve at least 30 percent of California's land and coastal waters by 2030 with a particular focus on protecting and enhancing wildlife corridors.

  - The Specific Plan proposes to permanently conserve approximately 755 acres of contiguous open space outside the Core Campus. How does this open space preservation fit within the State's goals under Executive Order N-82-20?

  - The Sonoma Valley Wildlife Corridor encompasses over 10,000 acres of land stretching from Sonoma Mountain east across Sonoma Valley to the Mayacamas Mountains. It is a key linkage in a larger corridor from coastal Marin County to eastern Napa County. SDC lies at the heart of the Corridor. Since the 1990s, the Sonoma Valley Wildlife Corridor has been recognized as an area of significant wildlife presence and movement. The critical linkages and wildlife use have been well established by the scientific community.[2] Maintaining and enhancing the permeability of the Corridor and the ability of wildlife to use and disperse through SDC is therefore critical to meeting the Project's sustainability and open space conservation guiding principles and to ensure the viability and efficacy of other conserved lands in the Corridor throughout Sonoma County. *E.g.,* EIR at 65 (Guiding Principle 3: "Integrate Development with Open Space Conservation. Promote a sustainable, climate-resilient community surrounded by preserved open space and parkland that protects natural resources, fosters environmental stewardship, and *maintains and enhances the permeability of the Sonoma Valley Wildlife Corridor* for safe wildlife movement throughout the site. Support responsible use of open space as a recreation resource for the community.") (emphasis added). Given its recognized role in wildlife migration, how does the Specific Plan ensure protection and enhancement of the Sonoma Valley Wildlife Corridor pursuant to the Specific Plan's guiding principles and Executive Order N-82-20?

  - How would the Wildlife Corridor contribute to or impact the overall effect of land conservation efforts under Executive Order N-82-20?

  - Why does the EIR not address Executive Order N-82-20 or analyze the Project's consistency with a mandate for conservation of biodiversity resources on state-owned property?

  - Is the Specific Plan consistent with Executive Order N-82-20?

  - Will the Specific Plan impact the State's ability to meaningfully conserve at least 30 percent of California's land and coastal waters by 2030 in Sonoma County?

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[2] Bay Area Open Space Council. 2011. The Conservation Lands Network: San Francisco Bay Area Upland Habitat Goals Project Report. Berkeley, CA; Penrod et al. 2013. Critical Linkages: Bay Area & Beyond. Produced by Science & Collaboration for Connected Wildlands, Fair Oaks, CA in colloboration with the Bay Area Open Space Council's Conservation Lands Network.
Merenlender et al. 2010. Mayacamas Connectivity Report.

- How will the Specific Plan impact the effectiveness of conservation efforts under Executive Order N-82-20?

- There are significant information gaps regarding wildlife use at SDC that must be resolved to understand the scope of impacts from the proposed redevelopment. Obtaining this information will be critical to informing protection areas, buffer sizes, levels and location of development, and appropriate best management practices or improvements to avoid or minimize Project impacts. *See generally* PCI Comments; Pathways Comments.

  - For example, the EIR indicates that no site survey was completed to determine the presence or location of special-status or other species. The EIR cannot determine the impacts of development under the Specific Plan—the locations and footprints of which are known—until such survey is completed. *E.g.,* PCI Comments at 13. The EIR should also make use of existing data sources, such as the species observation list previously shared by the Sonoma Ecology Center, which the EIR inexplicably ignores.

  - Similarly, the EIR does not include data regarding use of the Sonoma Valley Wildlife Corridor by special-status species or other wildlife. Pathways Comments at 10-11.The study proposal that Pathways for Wildlife prepared for Sonoma Land Trust, which was included in Sonoma Land Trust's comments on the Notice of Preparation, is representative of the vetted and scientifically proven methodology for conducting wildlife connectivity studies. This type of study is necessary to be able to determine and analyze the Project's impacts to Wildlife Corridor. The Sonoma Land Trust had offered to partner with the County and State to conduct this study so that this information would be available and could be used as part of the EIR, but their offer was not accepted prior to release of these documents.

- The County must first identify the information gaps that need to be filled in order to determine the impacts of the Project. For example, a detailed study is needed to establish a baseline of wildlife use on SDC prior to redevelopment. What other information gaps need to be filled in order to determine the impacts of the Project?

- How will the phased build-out of the Project induce or modify impacts to biological resources?

- Would the impacts to biological resources be different if the Project were phased differently?

- How would the impacts to biological resources vary if only a portion of the Project were built out?

- How will the County determine whether redevelopment of SDC increases interference with wildlife movement or use within the property or across the larger corridor? What metrics will the County use to gauge impacts to wildlife movement? Which species will be analyzed? What specific performance standards must development meet to ensure that the Wildlife Corridor remains permeable and viable as development is phased in?

- How will the County ensure that SDC redevelopment does not result in a reduction of wildlife species diversity?

- How will the County ensure that SDC redevelopment does not result in a reduction of wildlife species abundance?

- The EIR acknowledges that wildlife and their habitat may be considered sensitive to noise and other operational impacts. *E.g.*, EIR at 337-338. The Specific Plan proposes more than 1,000 units of residential development in addition to commercial and visitor-serving development. By contrast, in recent years, the human activity at SDC has been considerably reduced. Even before facility closure, the site only supported approximately 415 clients living there, 470,000 sf of client housing, 49,000 sf staff housing, and 643,400 sf offices, shops, etc. California Department of Developmental Services. (2012). Sonoma Developmental Center Building Use Survey. Department of Developmental Services. October 2012.

    - Do the impacts identified by the EIR scale in a linear fashion based on the amount of development, the number of residents, and the extent of human activity at operation?

    - How did or will the County quantify the change in magnitude of operational impacts by virtue of the significant increase in population and operational activities under the Specific Plan as compared to a recent baseline?

- The EIR fails to identify a consistent baseline against which the Project is evaluated. Selection of an appropriate baseline is particularly important in this case because the SDC property has been gradually vacated since the 1960s, as facility operations wound down and the facility ultimately closed in 2018.[3] In the meantime, development of the surrounding area has proceeded with reduced assumptions about the level of human activity at SDC—for example, evacuation capacity of roadways, levels of sewer service, water use, and recreation. Further, SDC's historic operations are not a reliable benchmark for the intensity of the proposed Project, as the former institutional use did not have the same level of impacts as proposed residential and commercial development. SDC residents did not drive cars and the employees operated in shifts, reducing traffic and

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[3] Sonoma Developmental Center Existing Conditions Assessment, Chapter 6 at 200 (noting that growth "reversed in the 1960s owing to a national trend towards deinstitutionalization"), available at https://transformsdc.files.wordpress.com/2020/01/1-chapter6.pdf; Plan for Closure of the Sonoma Developmental Center, California Health and Human Services Agency, October 1, 2015, at 16 (by May of 2015, SDC served only 405 residents); Gov. Code § 14670.10.5(a)(4) (SDC ceased all residential operations in 2018).

other impacts. Estimates of this Project's impacts should therefore be made based on comparisons to recent, rather than historic, site occupation and use.

- With respect to biological resources, the EIR fails to adequately describe the baseline condition of the Sonoma Valley Wildlife Corridor.
    - The EIR provides no data regarding actual use of the Wildlife Corridor by individual species.
    - The EIR does not analyze whether or how the gradual reduction in human activity at SDC since the 1960s has changed the operational characteristics of the Wildlife Corridor.
    - The EIR does not provide data or analysis to show whether or how increasing human activity in the Core Campus in excess of historic levels will impact wildlife movements within and through the Wildlife Corridor.

- The EIR acknowledges that wildlife and their habitats may be sensitive to noise impacts. EIR at 337-338. However, the EIR fails to analyze or mitigate for noise impacts to these specific sensitive receptors.
    - The EIR relies on quantitative thresholds from the CEQA guidelines, but it fails to analyze or explain whether these thresholds are applicable to wildlife or habitat receptors. EIR at 345-346.
    - The EIR's vibration threshold only contains standards for human receivers and structures. EIR at 346. It is silent as to what constitutes a significant impact to wildlife or habitat.
    - The Specific Plan policies that "address noise" ignore wildlife and habitat receptors.
        - Policy HAZ-1 defines "noise-sensitive receiver" as "residences, schools, day care facilities, hospitals, nursing homes, long term medical or mental care facilities, places or worship, libraries and museums, transient lodging, and office building interiors." EIR at 347.
        - Policy HAZ-1 does not impose standards for nighttime construction noise that are designed to reduce impacts to wildlife or habitat. EIR at 347-348.
        - Policy HAZ-2 establishes quantitative vibration standards only with respect to humans and structures. Policy HAZ-2 does not establish quantitative vibration standards designed to reduce impacts to wildlife or habitat. EIR at 348-349.

- Notwithstanding that the Specific Plan defines "noise-sensitive receiver" to exclude wildlife or habitat, the EIR concludes that construction noise impacts to "noise-sensitive receivers, such as Special Status species and their habitat … would be less than significant" because, inter alia, nighttime construction noise would be subject to the Sonoma County General Plan 2020 noise standards. EIR at 349-350. This conclusion is unsupported and is contradicted by the Specific Plan. Per Policy HAZ-1, nighttime construction noise is only subject to the Sonoma County General Plan 2020 Table NE-2 standards "If construction activities occur … within 0.5 miles of a noise-sensitive receiver (residences, schools, day care facilities, hospitals, nursing homes, long term medical or mental care facilities, places or worship, libraries and museums, transient lodging, and office building interiors)." EIR at 347.

- Project-generated noise is a particular concern because noise has been shown to modify the behavior of species that are present at or are similar to those present at the SDC site. Noise can affect the spatial distribution of wildlife and can cause changes in predation and other critical behaviors. If project-generated noise were to alter the dispersal of wildlife through the Sonoma Valley Wildlife Corridor or otherwise substantially affect the behavior of special-status species or species of concern, those impacts would constitute significant impacts under the EIR's chosen significance thresholds. *See* Biological Resources Criterion 1 (a significant impact is one that causes a "substantial adverse effect … on any species identified as a candidate, sensitive, or special-status species in local or regional plans, policies, or regulations, or by the California Department of Fish and Game or U.S. Fish and Wildlife Service"); *see also* Biological Resources Criterion 4 (a significant impact is one that affects movement of wildlife through a wildlife corridor). The EIR must therefore analyze a range of noise-related impacts and other operational impacts in detail to ensure that those impacts will not constitute unmitigated significant impacts.

    - Mountain lions in particular are known to be sensitive to noise. Mountain lions have been documented using the Sonoma Valley Wildlife Corridor through the SDC property. Mountain lions are also a species of concern, facing significant threats in the Bay Area and around the state. The EIR does not even acknowledge the presence of mountain lions at the SDC site, let alone analyze and mitigate impacts to mountain lions. Because mountain lions are designated as a "Specially Protected Mammal" by the California Department of Fish and Wildlife, impacts to mountain lions could constitute significant project impacts under Biological Resources Criterion 1. The EIR must study and mitigate potentially significant impacts to mountain lions.

    - Similar considerations apply to the project's light impacts. The EIR must document wildlife dispersal through the SDC site and compare those data to the Project's various development plans in order to analyze the Project's construction and operational light impacts to biological resources.

- The EIR also fails to disclose or analyze the projected impacts of the proposed Highway 12 connector road. Two options for connector roads are shown in Specific Plan Figure

3.1-1, and three types of facilities (a direct connection to Highway 12, an emergency access connection, and a pedestrian/bike connection) are all alluded to in accompanying text. These connections would have foreseeable direct, indirect, and cumulative impacts on the Project's biological resources, including wetlands, drainages, and the Sonoma Valley Wildlife Corridor. How does the EIR propose to address and mitigate the impacts of these connectors?

- Given intensity of proposed development and SDC's proximity to major regional parks, including Sonoma Valley Regional Park to the northeast and Jack London State Historic Park to the west, it is foreseeable that the Project's biological and other impacts will extend to and impact resources in those parks. The EIR must consider the impacts of the Project on biological resources within existing parks, including but not limited to impacts to biological resources from the increased water demand that would result from the construction, occupation, and operation of more than 1,000 residential units, a hotel, and other facilities.

- The EIR fails as an informational document because it does not analyze the Project's significant *unmitigated* environmental effects *before* identifying mitigation measures and analyzing their effectiveness. The County cannot condense these two steps into one or disguise mitigation actions as project features. Even if mitigation measures can be implemented as features of the Project, the EIR must evaluate the Project's true impacts without those measures in place before it can propose, analyze, and adopt needed mitigation. The EIR here skips this crucial step and fails to connect the dots between the Project's impacts and selected "mitigation." As a result, decisionmakers and the public do not know what the Project's unmitigated impacts would be or how the cited policies and conditions would purport to mitigate those impacts.

    - The EIR fails to describe fully the environmental setting of the Project. An EIR's description of a project's environmental setting crucially provides the baseline physical conditions by which a Lead Agency determines whether an impact is significant. Here, the EIR fails to accurately portray the site's underlying environmental conditions and therefore undercuts the legitimacy of the environmental impact analysis.

        - For example, the EIR judges impacts to biological resources primarily by estimating impacts to special-status plants and wildlife. EIR 221-251. But the EIR does not include any observational data regarding the presence or absence of these species. *Id.*

            - The EIR relies exclusively on the California Natural Diversity Database to "identify special-status species *with the potential* to occur in the SDC area." EIR at 221 (emphasis added). By definition, the species identified in the EIR *may not occur* in the SDC area. Likewise, as the EIR admits, the EIR's identification of special-status species may be under-inclusive. *Id.* ("Lack of information in the CNDDB and other reports … does not imply that the species does not occur… This lack of information may reflect a lack of Project or reporting more than absence of special-status species. Thus, there may be additional occurrences of special-status species within this area that have not yet been surveyed and/or mapped.”).

- Surveys for sensitive plant and animal species are entirely absent.

- Instead, the EIR improperly defers critical studies and surveys until after project approval.

- The EIR cannot identify what the impacts to specific special-status species will be or how significant those impacts will be, because the EIR cannot state with any degree of certainty whether or to what degree those species are present in the areas planned for development.

- The EIR cannot remedy its lack of analysis by punting to “[f]uture project specific biological surveys [that] will be necessary to confirm presence or absence of sensitive resources on future development sites.” EIR at 237. The Specific Plan is incredibly detailed. It shows specifically where different types of development will be located within the Core Campus and describes in detail what each type of development will look like. *E.g.*, EIR at 69-80. The Specific Plan breaks the Core Campus into development districts (EIR at 74) and identifies building square footage for commercial, hotel, office, public, institutional, and utility use (EIR at 80). In short, the County already knows what types of development could occur under the Specific Plan and substantially where those different types of development would occur. The EIR cannot avoid analyzing the foreseeable impacts of that development simply because more granular analysis may later be required.

▪ The EIR similarly indicates that the Project may impact wetlands and other waters. EIR at 235. However, the EIR admits that “formal wetland delineations have not been performed for the SDC and it is anticipated that additional wetlands will be mapped during future site assessments.” *Id.* The EIR cannot analyze or explain what the impacts to wetlands will be, how significant those impacts will be, or even if development will be possible in the areas planned for development if the EIR does not know where wetlands are located on the SDC site.

o The EIR improperly defers analysis of Project impacts until later stages of development and fails to explain how it reaches its conclusion that impacts will be less than significant.

- The EIR's impact methodology violates CEQA because it does not actually disclose or analyze any particular impacts. It simply states without analysis, explanation, or substantial evidence that certain unspecified impacts may occur. Decisionmakers and the public thus lack sufficient information about the nature and scope of potential impacts to evaluate those impacts for themselves.

    - For example, the EIR states that "[t]wo specific projects could have the potential to impact special status species and sensitive natural communities. The proposed Highway 12 connector project would follow Sonoma Creek in a southerly direction, and then proceed east adjacent to the open space area outside the SDC core area." EIR at 241. The EIR concludes that "[w]ith implementation of Station Conditions of Approval BIO-1 through BIO-13, potential impacts would be less than significant." *Id.* But at no point does the EIR disclose what potential impacts the Highway 12 connector project could have on special status species or sensitive natural communities. Decisionmakers and the public have no way of knowing whether the connector threatens habitat loss, increased mortality from vehicle strikes, or something altogether different. And without knowing what the impact is, decisionmakers cannot know what it is that Conditions of Approval BIO-1 through BIO-13 are supposed to be mitigating. Equally significant, the EIR does not disclose what the second of the "[t]wo specific projects" that threaten impacts is. Decisionmakers and the public are left to guess.

        - What specifically are the anticipated impacts of the Highway 12 connector?

        - How will Conditions of Approval BIO-1 through BIO-13 mitigate those impacts?

        - What is the second specific project that could impact special status species and sensitive natural communities?

        - What specifically are the anticipated impacts of that second project?

        - How will Conditions of Approval BIO-1 through BIO-13 mitigate those impacts?

    - The EIR also states that "stream restoration and bridge maintenance projects are expected within aquatic features, [so] direct impacts would occur." EIR at 252. But the EIR fails to elaborate about what those "direct impacts" might include.

- What specific impacts are anticipated from stream restoration and bridge maintenance projects?

- How frequently are such projects anticipated to occur and at what locations?

- The EIR states that the Project would not have a substantial adverse effect on state or federally protected wetlands in part because no new ground-disturbing activities would occur during Project operation. But the EIR does not discuss or analyze potential operational impacts to wetlands from recreation or other non-construction activities during Project operation. EIR at 254.

  - The Specific Plan proposes using known wetlands for recreational purposes. *E.g.*, Specific Plan at 2-2 ("Designating an area at Suttonfield Lake for off-leash dogs and water recreation…"). What are the specific anticipated impacts from recreational uses and off-leash dog use at Suttonfield Lake?

- The EIR states that "[i]mplementation of the Proposed Plan would have a significant impact on migratory species, corridors, or nursery sites if the siting, construction, or operation of development allowed under the Proposed Plan would impede on or remove migratory corridors or nursery sites." EIR at 255. The EIR then concludes that the Project would not impede migratory corridors or nursery sites. *Id.* But the EIR never defines what level of imposition rises to the level of a significant impact. *Id.* The EIR states that "recreational trails, in or near habitats that include wildlife corridors … are considered to be uses consistent with open space management and are not considered substantial impacts to the wildlife corridor functionality of the site." *Id.* But the EIR's conclusory statements provide no data or analysis about the impact of recreational trails or other uses on wildlife behavior, especially if over 2000 new residents and 900 employees significantly expand public use and recreation. The EIR's conclusions are not supported by substantial evidence.

- The EIR next concludes that the "Proposed plan does not conflict with local ordinances, therefore, impacts related to conflict with local policies or ordinances would be less than significant." EIR at 257. However, the EIR does not identify specific local policies or ordinances against which the Project was analyzed. It simply states that the "[f]uture projects under the Proposed Plan would conform with local policies and ordinances including the Sonoma County Tree Protection Ordinance and the Sonoma County General Plan." *Id.* The EIR's so-called "analysis" fails to mention other local rules and policies that the EIR identified as applicable to the Project, including the County Heritage or Landmark Tree Ordinance or the Valley Oak Habitat Combining District (EIR at 210). Nor does the Biological Resources section discuss or analyze the Project's consistency with Measure K, through which Sonoma County residents renewed protections for community separators and protected tens of thousands of acres of open space and agricultural land from subdivision and sprawl. EIR at 207-212. Without substantial evidence of consistency—or at least a more complete accounting of applicable policies and regulations—the EIR's consistency determination is just a conclusory statement. *See* EIR at 257. Decisionmakers and the public cannot independently verify the Project's consistency with local rules and regulations, and the EIR fails as an informational document.

- ▪ The EIR does not explain why its selected significance criteria are relevant or appropriate.

    - The EIR identifies six significance criteria for impacts to biological resources, but fails to explain why these criteria were selected. EIR at 236. The EIR neither discloses the origin of these criteria nor provides data or analysis to support their use as significance thresholds under CEQA. Due to this lack of evidence, decisionmakers and the public cannot meaningfully gauge whether the EIR's significance criteria are adequate markers of the Project's environmental impacts.

    - How did the County select its chosen significance criteria?

    - Why were other significance criteria not considered?

- o The EIR's approach to mitigation presents two issues. First, the EIR evades responsibility for developing, enforcing, and monitoring mitigation measures by incorporating its chosen mitigation directly into the Specific Plan. The EIR cannot disclose the Project's "unmitigated" impacts because, under the EIR's approach, no impacts have gone unmitigated. Second, the purported mitigation that County incorporates in the Specific Plan punts to uncertain future actions and thus defers the analysis and development of any meaningful mitigation to a later date. By incorporating deferred mitigation into the Specific Plan, the EIR cannot meaningfully analyze what mitigation may be appropriate or how effective that mitigation may be. In so doing, the EIR denies decisionmakers and the public the opportunity to fully understand the Project's impacts and improperly delegates the County's legal responsibility to mitigate those impacts.

- The EIR relies on Specific Plan policies and Conditions of Approval to avoid, reduce, or mitigate the Project's potentially significant impacts. The EIR must therefore treat these policies and conditions as formal mitigation measures. It must analyze fully the effectiveness of the mitigation against specific identified impacts and must include the mitigation measures in a Mitigation Monitoring and Reporting Program.

    - The EIR's conclusions as to the effectiveness of mitigating policies and conditions are not supported by analysis or substantial evidence. They are simply a means by which the EIR avoids identifying or analyzing the Project's unmitigated impacts, as required by CEQA. This approach fails to disclose unmitigated impacts and fails to support the County's chosen mitigation.

        - For example, the EIR concludes that with the implementation of Specific Plan Policies 2-6 through 2-26 and Conditions of Approval BIO-1 through BIO-13, "the impact of future development under the Proposed Plan on species identified as candidate, sensitive, or special-status species would be less than significant." EIR at 242. But the EIR neither identifies specific impacts that the Project will have on specific candidate, sensitive, or special-status species, nor explains how or to what degree the cited policies and conditions would reduce those impacts. EIR at 241-251.

            - What analysis supports the County's conclusion that Specific Plan Policies 2-6 through 2-26 and Conditions of Approval BIO-1 through BIO-13 would reduce impacts to special-status species to less-than-significant levels?

            - How can the County conclude that the cited policies and conditions will reduce impacts if it has not yet identified and analyzed those specific impacts or the impacted species?

            - How does the County anticipate the cited policies and conditions would reduce impacts to special-status species?

        - Similarly, the EIR asserts that "implementation of policies 2-25, 2-27, 2-29, and 2-30 would ensure impacts to riparian resources [from the proposed highway connector project] would be less than significant.” EIR at 252. But again, the EIR fails to identify what specific impacts the connector road would have or indicate how and to what degree the cited policies would mitigate those impacts.

    - The EIR further asserts that the “implementation of applicable policies” would render “the operational impact on riparian habitat and other sensitive activities … less than significant.” EIR at 252. The EIR asserts that applicable policies would restrict access by humans and domestic animals to specific areas and would reduce the trampling or degradation of riparian habitat. But the EIR is silent about other potential and foreseeable impacts, such as litter, fire risk, noise, lighting, and vibration.

- To the extent the Specific Plan policies and Conditions of Approval cited in the EIR could mitigate for the Project’s impacts, that mitigation is impermissibly deferred.

    - For example, Condition of Approval BIO-14 improperly relies on existing regulatory programs and the permitting processes of other agencies to “[a]void, minimize, or mitigate for impacts to aquatic communities.” EIR at 252. In so doing, the County delegates its legal responsibility to assess and mitigate Project impacts to “the Army Corps, RWQCB, [or] CDFW.” Condition of Approval BIO-14 defers to the issuer of any required permit(s) to design appropriate mitigation and provides no clear benchmark or performance standard(s) that that mitigation must meet. Unless the County is the permitting agency, Condition of Approval BIO-14 does not clearly provide for County oversight of this process. Such delegation of authority to analyze and mitigate environmental impacts is improper.

    - Similarly, Condition of Approval BIO-16 requires the Project Sponsor to develop a habitat mitigation plan subject to approval by the agency or agencies with oversight over any impacted aquatic resource. EIR at 254. That Condition defers to the habitat mitigation plan—and therefore the Project Sponsor(s) and other agencies—to analyze the scope and effect of the impact to aquatic resources and to design appropriate mitigation. Here, too, the County improperly delegates its legal responsibility to future developers and regulators and fails to provide concrete performance standards for resulting mitigation.

            - Analysis of impacts and mitigation cannot be deferred to a later date but must be performed prior to project approval. Nor may a lead agency satisfy CEQA by approving a project subject to conditions requiring the applicant to prepare future studies and mitigation measures, because in so doing the agency would be improperly delegating its legal responsibility to assess a project's environmental impact. Instead, the lead agency itself must prepare or contract for the preparation of impact assessments that reflect the agency's independent judgement. Where the finalization of mitigation is deferred, the EIR must explain why it cannot be finalized now and must establish performance standards for such mitigation that will ensure the impact will be reduced to a less-than-significant level. How does the EIR here meet these requirements?

        - The EIR's conclusions that impacts to biological resources are insignificant is unsupported by either meaningful analysis or substantial evidence.

- Even if the EIR could mitigate impacts through Specific Plan policies and conditions of approval, the policies and conditions identified in the EIR are not sufficient to avoid potentially significant impacts.

    - The EIR failed to conduct field studies or survey plants and wildlife at the SDC site. EIR at 221, 236. The EIR therefore admits that there may be special-status plants and wildlife present on site that are not accounted for in the EIR's list of special-status species. EIR at 221. However, the EIR concludes that "[i]mplementation of the Proposed Plan would not have a substantial adverse effect, either directly or through habitat modifications, on species identified as a candidate, sensitive, or special-status species" because future development will comply with standard conditions of approval that target special-status species. EIR at 241-251 (BIO-2 [special-status bats], BIO-3 [American badger], BIO-4 [nesting raptors], BIO-5 [burrowing owl], BIO-6 [northern spotted owl], BIO-7 [tricolored blackbird], BIO-8 [special status nesting birds], BIO-9 [western pond turtle], BIO-10 [foothill yellow-legged frog, red-bellied newt, and California giant salamander], BIO-11 [California red-legged frog], BIO-12 [California freshwater shrimp and listed salmonids], BIO-13 [special-status plants]. Even if these conditions of approval were sufficient to address the named special-status species, they would not address impacts to candidate, sensitive, or special-status mammals, reptiles, or amphibians that may be present in the SDC area but which may not be captured in the EIR's list of special-status species. *See* EIR at 221. The County simply cannot know, and EIR cannot analyze, whether and to what degree the Project may impact as-yet unidentified special-status species until the County conducts appropriate surveys.

- The EIR's analysis and mitigating policies and conditions focus only on construction impacts. *See, e.g.,* Conditions of Approval BIO-1 through BIO-14. But operational impacts could be equally if not more significant.

  - For example, significantly increased recreational uses from thousands of new residents and workers near the Wildlife Corridor or Suttonfield Lake could have potentially significant impacts to wildlife movement, wetlands, or special-status species by locating hikers and pets near critical habitat. The EIR generally assumes these impacts are less than significant because recreational uses are broadly consistent with open space management principles. But consistency with open space management principles does not necessarily mean that these uses would not negatively and significantly impact habitat or wildlife behavior. Increased visitor use along trails across SDC may alter behaviors and cause some species to avoid those areas.

  - Increased vehicular traffic that results from the development would also likely increase human-wildlife interactions. Wildlife are already documented to traverse Highway 12. How will development under the Specific Plan contribute to and mitigate the risk of vehicular collusions? How will increased traffic change wildlife behavior in the Sonoma Valley Wildlife Corridor and throughout the SDC site? The EIR cannot presently answer these questions because it has not analyzed the operational impacts of the Project on wildlife.

  - The surveys and related work discussed in Conditions of Approval BIO-1 through BIO-14 only apply when development is occurring. They do not continue to apply during Project operation and thus cannot mitigate operational impacts that are driven simply by the presence of humans and human activity. The EIR must analyze and mitigate operational impacts in addition to construction impacts.

- The EIR relies on policies and conditions that are vague and unenforceable. The EIR fails to show how these vague and unenforceable policies and conditions could definitively avoid or mitigate potential significant impacts to biological resources.

  - Specific Plan Policy 2-7: Prohibit lights within the wildlife corridor and along the creek corridor.

    - This policy prohibits lights from being physically located within the wildlife corridor and along the creek corridor, but it does not clearly prohibit light intrusion into the wildlife corridor or the creek corridor from lights located outside the corridors. Without prohibiting light intrusion, the EIR cannot show that project lighting will not impact biological resources in the wildlife and creek corridors.

- Specific Plan Policy 2-8: Maintain wildlife crossing structures by periodically checking for and clearing debris, vegetation overgrowth, and other blockages from culvert and bridge crossing structures; within the Core Campus, the Project Sponsor should develop and execute a maintenance program in collaboration with the owner and operator of the preserved parkland and open space.

  - This policy is vague and unenforceable. It provides only that the Project Sponsor "*should* develop and execute a maintenance program." There is no guarantee that a maintenance program will be developed or executed.

- Specific Plan Policy 2-10: Within the wildlife corridor, limit mowing and the removal of dead plant material to the absolute minimum required for fire safety. If possible, mowing should be conducted outside the nesting bird season, or nesting bird surveys should be constructed within 14 days of mowing.

  - This policy is vague and unenforceable. It states that mowing *should be* conducted outside the nesting bird season and that nesting bird surveys *should* be "*constructed*" within 14 days of mowing only *if possible*. As an initial matter, it is not clear what it means for a nesting bird survey to be "constructed." Surveys must be *completed* within an appropriate time of any mowing activity in order to adequately inform whether and how that mowing activity is conducted. Further, this policy provides no indication what entity will be responsible for determining whether nesting bird surveys are possible or whether it is possible to mow outside of the nesting season.

    - Who does the County envision will be responsible for those decisions?

    - What sort of oversight will the County, the Project proponent, the owner, etc. have to ensure this policy is actually complied with?

    - What are the impacts to nesting birds if is it not possible to avoid mowing during the nesting bird season or if it is not possible to conduct timely surveys?

        - How often does the County anticipate it would not be possible to avoid mowing during the nesting bird season or that it would not be possible to conduct timely surveys?

        - What factors would contribute to compliance with this policy not being possible?

        - How effective would this mitigation be if it is regularly not possible to avoid mowing during the nesting bird season?

        - How will the County enforce compliance?

- Specific Plan Policy 2-15: Collaborate with local wildlife protection groups to create and distribute educational information and regulations for residents and employees to guide safe interactions with wildlife onsite. Materials should be accessible to all ages and abilities and could include posted signs, disclosures, fliers, or informational sessions, among other things.

    - This policy is vague and unenforceable. Materials *must* be accessible to all ages and abilities (not should).

    - How will the County gauge compliance with this policy?

    - How will the County enforce compliance with this policy and regulations?

    - Until the County identifies what regulations will be implemented, how can the County know that the regulations implemented will be sufficient to mitigate impacts to wildlife?

- Specific Plan Policy 2-17: Adhere to residential nighttime noise standards to the extent feasible.

    - This policy is vague and unenforceable.

    - It is not clear to which standards this Policy refers. What are the standards with which the County envisions compliance?

    - Who determines whether and when it is feasible to adhere to residential nighttime noise standards?

    - How often does the County anticipate that it will not be feasible to adhere to residential nighttime noise standards?

- Under what circumstances does the County anticipate that it would not be feasible to adhere to residential nighttime noise standards?

- What are the activities for which the County anticipates that it may not be feasible to adhere to residential nighttime noise standards?

- What additional mitigation would be required if it is not feasible to adhere to residential nighttime noise standards? Or if no further mitigation would be required, the impact would be significant and must be identified and analyzed in the EIR. What would be the impacts if the mitigation is infeasible?

▪ Specific Plan Policy 2-20: Require that new development preserve existing trees to the fullest extent feasible. Locate new construction and public realm improvements around existing landscaping features.

  - This policy is vague and unenforceable.

  - Who determines whether and when it is feasible to preserve existing trees?

  - How often does the County anticipate that it will not be feasible to preserve existing trees?

  - Under what circumstances does the County anticipate that it would not be feasible to preserve existing trees?

  - What are the types of development for which the County anticipates that it may not be feasible to preserve existing trees?

  - What additional mitigation would be required if it is not feasible to preserve existing trees? Or if no further mitigation would be required, the impact would be significant and must be identified and analyzed in the EIR. What would be the impacts if the mitigation is infeasible?

▪ Specific Plan Policy 2-21: Preserve and enhance the wetlands east of the core campus as a fire break, groundwater recharge, and habitat area.

  - This policy is vague and unenforceable.

  - This policy is not valid mitigation because it lacks clearly defined standards and is not specific enough to effectively implement or enforce. Who will determine whether wetlands are sufficiently "preserved" or "enhanced"? On what basis will those determinations be made?

- Specific Plan Policy 2-22: Leave standing or downed dead trees in place for wildlife habitat whenever they do not present a hazard for fire safety or recreational users, except within the managed landscape buffer.

  - This policy is vague and unenforceable.

  - This policy is not valid mitigation because it lacks clearly defined standards and is not specific enough to effectively implement or enforce.

  - Who determines whether dead trees present a hazard for fire safety or recreational users?

  - What constitutes a sufficient hazard that would authorize removal?

  - How frequently does the County anticipate that dead trees would constitute a hazard and would be removed pursuant to this policy?

  - What additional mitigation would be required if trees are removed?

- Specific Plan Policy 2-25: Include protective buffers of at least 50 feet along Sonoma and Mill creeks, as measured from the top-of-bank and as shown on Figure 2.2-1: Open Space Framework, to protect wildlife habitat and species diversity, facilitate movement of stream flows and ground water recharge, improve water quality, and maintain the integrity and permeability of the Sonoma Valley Wildlife Corridor, and the ability of wildlife to use and disperse through the SDC site. Manage protective buffers so that they support continuous stands of healthy native plant communities.

  - The EIR does not analyze or explain why a 50-foot buffer is appropriate or sufficient to reduce impacts to creeks at SDC. Merely stating that an impact will occur is insufficient; an EIR must also provide information about how adverse the adverse impact will be. Likewise, merely stating that an impact will be mitigated is insufficient; an EIR must explain how the mitigation will avoid or reduce impacts.

  - A 50-foot buffer is not sufficient to reduce impacts to riparian resources. The EIR states that the riparian forest along Sonoma Creek has an average width of 150 to 300 feet—three to six times the width of the proposed buffer. Why is the required buffer so significantly smaller than the riparian resources it is meant to protect?

- What and where is Mill Creek?

- The 2019 Land and Water Protection Proposal (which was signed off on by Regional Parks, California Department of Fish and Wildlife, and Sonoma County Ag + Open Space calls for significantly larger buffers, including a 300-foot buffer along Sonoma Creek, a 300-foot buffer along Asbury, Mill/Hill, and Butler Canyon Creeks (exception for a 100-foot buffer along Mill/Hill Creek within the core campus), and a 100-foot wetland buffer.

    - Why did the EIR depart from this approved proposal?

    - On what basis does the EIR conclude that smaller buffers will protect wildlife?

▪ Specific Plan Policy 2-26: Prohibit the use of all pesticides, rodenticides, and poisons in materials and procedures used in landscaping, construction, and site maintenance within the Planning Area. This restriction *should* be included in all Declarations of Covenants, Conditions and Restrictions (CC&Rs) to ensure that future homeowners are aware of the requirements (emphasis added).

- This policy is vague and unenforceable. It does not guarantee that the prohibition on pesticides, rodenticides, and poisons will be included in all CC&Rs.

▪ Specific Plan Policy 2-28: Prior to the commencement of the approval of any specific project in the Proposed Plan area, Project Sponsors shall contract a qualified biologist to conduct studies identifying the presence of special-status species and sensitive habitats at proposed development sites and ensure implementation of appropriate mitigation measures to reduce impacts to sensitive habitat or habitat function to a less than significant level.

- This policy improperly defers analysis of impacts and mitigation that must be conducted now in this EIR. Analysis of impacts cannot be deferred to a later date but must be performed prior to project approval. Conducting thorough analysis at this stage is the only way decision-makers and the public can have sufficient information about impacts and mitigation to be able to evaluate the impacts of a proposed project for themselves. The needed analysis could then inform the location of various uses and development within the Sonoma Development Center and allow consideration of alternatives that minimize biological impacts. By deferring analysis of Project impacts and mitigation through implementation of the Specific Plan, the EIR fails to provide sufficient information to the public and decisionmakers and therefore fails as an informational document.

TRANSPORTATION

- The comments presented below reference comments prepared by Neal Liddicoat, Griffin Cove Transportation Consulting, PLLC ("GCTC") on the EIR and Specific Plan, attached below as Attachment D to Sonoma Land Trust's September 26, 2022 letter to Brian Oh.

- The Specific Plan and its EIR include goals and objectives for this Project that include a focus on non-motorized modes of transportation within and between the Project area and local communities (e.g., Specific Plan at 3-2 and DEIR at 6. However, the proposed site maps do not demonstrate any such connections. Creating walkable and bikeable connections to Glen Ellen (including Eldridge) will be critical to encouraging non-motorized forms of transportation. How will Project design ensure connections would be implemented to meet the Project's stated goals with respect to sustainability and community character?

- The Project requires some new road development—even if only for emergency access—and will result in substantial increases in traffic volumes. Increased traffic through the property on Arnold Drive will put tremendous pressure on wildlife. Additionally, development of new roadways (e.g., on the east side of SDC) will impair existing ecological connections across the Sonoma Valley Wildlife Corridor. The EIR fails to address the impact of increased traffic on wildlife.

- Wildlife movement within SDC and across the Corridor is already constrained. Currently, there are only two options for wildlife to move east-west across the core campus without having to cross the Arnold Drive roadway: along Sonoma Creek or along Hill Creek. Along the eastern edge of SDC, safe wildlife crossing of Highway 12 is limited to three culverts on Butler Creek and its tributaries. These small crossings under Highway 12 are the most critical locations for wildlife moving east-west across Highway 12 both within SDC and on nearby lands. High levels of wildlife movement have been documented at all three of the culverted crossings. The increased traffic and development of the Project will further constrain wildlifes' east-west movement opportunities, resulting in will have significant impacts on
wildlife. How will Project design ensure safe wildlife crossings are retained?

- The Project, including the Specific Plan policies, fail to ensure that new road construction, increased traffic volumes, and traffic speeds on SDC do not increase interference with wildlife movement and use within the property or across the larger corridor or result in increased road mortality. Development and human activities should be limited near the crossing structures. To help mitigate these impact, the Project design should:

- limit new road, driveway, and trail construction, especially outside the core campus area
- If new roads are constructed or old roads upgraded, incorporate crossing structures to accommodate wildlife
- Install speed bumps and wildlife crossing signage at critical junctures

- The EIR's transportation analysis presents a description of the Project, including a specific breakdown of housing unit types, that is inconsistent with both the EIR Project Description and with the description of the project in the Specific Plan document. GCTC at p. 2. The transportation analysis assumes a maximum of 1000 residential units, but assigns a specific breakdown of uses (i.e., 435 single family units, 345 multi-family units, and 220 senior residential units). GCTC Report at 1. Different types of housing typically result in different amounts of trip generation and VMT. Neither the Specific Plan nor the DEIR specify this particular breakdown of uses. On what basis does the EIR base the assumption of different types of residential units?

- The EIR bases its analysis of VMT on a model completed by MTC. EIR at 433. However, the EIR uses the average VMT per capita for the entire nine county Bay Area for comparison of the Project's VMT. This comparison is inappropriate because in rural areas without established mass transit and limited alternative transportation options, the VMT is likely to be higher. The EIR analysis should have used average VMT figures for the County, or preferably, for a sub-area that includes all of the towns in the vicinity of the Project.

- The EIR assumes the existing VMT is 59,654 and the proposed Project would result in a VMT of 60,285 in 2040. DEIR at 183. The EIR provides no explanation regarding how these figures were derived. Given that the SDC campus is largely unoccupied, it appears that the existing VMT figure is artificially inflated, which skews the VMT analysis. The EIR's assumed VMT calculation suggests that the total VMT will only increase by 631. Without accounting for non-residential uses (e.g., office, commercial, etc.) the VMT for the 1,000 residential units would amount to an increase in VMT of 0.631 per dwelling unit, which is not realistic. If we consider the non-residential uses, the incremental increase in project-related VMT is even lower. In addition, the air quality section of the EIR indicates that the Project-related population will increase by 2,500 people for the residential portion of the Project. The Transportation section states that ". . . residential uses in the Plan area with implementation of the Proposed Plan would on average generate 15.2 VMT per capita . . ." EIR at 445. The population increase of 2,500 multiplied by 15.2 VMT per capita would result in 38,000 VMT, which is far greater than the total increase of 631 claimed in the EIR. This calculation only considers residential uses so the actual VMT would be far greater. Therefore, the EIR's VMT calculation as presented is simply not credible. Moreover, the EIR admits that the Specific Plan policies cannot be guaranteed to reduce significant VMT impacts so the correct conclusion regarding this impact after mitigation is that it would remain significant. EIR at 35.

- The EIR does not provide a transportation analysis of the proposed Project without assuming the construction of the new Hwy 12 connector. Since the feasibility of this road has not been determined, what are the LOS and VMT impacts without the new connector?

- The EIR presents a flawed analysis of the Project's consistency with applicable plans.

    - The EIR acknowledges that the Sonoma County General Plan objectives require traffic operation standards of level-of-service ("LOS") C on roadway segments and LOS D at intersections. EIR at 443. The EIR concedes that the Project may exceed the established LOS standards. *Id.* Even though LOS is no longer used for evaluating a project's traffic impacts, when the general plan includes LOS standards, LOS does need to be considered when evaluating a project's consistency with the general plan.

    - Instead of estimating Project-related traffic and evaluating the Project's consistency with County LOS standards, the EIR concludes, absent any evidence, that the Project would be consistent with LOS targets established in the General Plan. EIR at 444. As discussed below, this conclusion appears to be erroneous. GCTC at p. 2.

    - The EIR references a traffic impact analysis prepared for the Project, but fails to include it in the EIR. GCTC at p. 2. Specifically, the EIR references the Focused Traffic Operations Analysis for the SDC Specific Plan (W-Trans, August 2022). EIR at 410, Footnote 118. The focused traffic study revealed that under future conditions with implementation of the SDC Specific Plan, two intersections are projected to operate unacceptably if no modifications to the current roadway configurations are made. GCTC at 2 and 3. The intersection at Arnold Drive/Harney Street would operate unacceptably at LOS F during the p.m. peak hour and the future new intersection on SR 12 at the new SDC Connector Road would have unacceptable LOS E operation on the stop-controlled connector road approach. *Id.* The study also revealed that at buildout of Project, the segment of SR 12 between Arnold Drive and Trinity Road and the segment of Arnold Drive between SDC and Madrone Roadwould would continue to operate below the County's standard at LOS D. GCTC at 3. Although these road segments are also identified as falling short of the County LOS standard without the Project, no mitigation measures were proposed to allow operation at an acceptable LOS. In any event, it is clear that these two roadway segments will fail to meet the County LOS standard upon completion of the Project, thereby violating the General Plan objectives. *Id.* The information necessary to address conformance with General Plan Objective CT-4.1 and CT-4.2 exists, but was not included within the DEIR, which would have allowed public review.

- Although the focused traffic study identifies improvements to would remedy LOS deficiencies, no assurance is provided that those measures would be implemented. GCTC at 3. Why does the EIR not disclose this study or its contents? The County must make this traffic report available to the public.

- The EIR underestimates Project trip generation.

    - The EIR employs the SCTM19 travel demand forecasting model used by the Sonoma County Transportation Authority ("SCTA") to estimate the Project's trip generation. However, the EIR fails to disclose the specific trip generation factors employed in the trip generation model. As a result, it is impossible for document reviewers to understand or evaluate the accuracy of those factors or the resulting trip generation estimates. GCTC at p. 3. What specific trip generation factors were used? What is the substantial evidence to support those factors?

    - Traffic impact analyses frequently evaluate trip generation using the Institute of Transportation Engineers ("ITE") document Trip Generation Manual. An estimate of trip generation based on the ITE Manual information (hereto referred to as the "ITE estimate") versus the estimate documented in the EIR provides perspective on the credibility of the EIR Project's transportation analysis. GCTC at p. 3. For purposes of comparison, the ITE estimate considers two scenarios: one uses the Project plan described in the EIR transportation section and one considers the maximum residential development scenario described in the Specific Plan document. *Id.* Using industry-accepted procedures and conservative assumptions, both ITE estimate results indicate a substantially higher trip generation than disclosed in the EIR. GCTC Letter, Table 1 at p. 5.

    - For the first ITE estimate using the EIR Project plan, the trip generation estimate shows 6,556 residential trips and 5,697 non-residential daily trips for a total of estimated trip generation of 12, 253. GCTC at p. 5 and 6. This denotes a difference of approximately 114 percent more trips than the EIR estimate of 5,736. GCTC letter at p. 5 and EIR at 440. Although a small difference between model-based trip generation and ITE trip rates is expected, a difference of this magnitude brings into question the validity of the EIR's analysis. *Id.*

    - For the second ITE estimate using the maximum residential development scenario described in the Specific Plan document, the trip generation breakdown shows 8,593 residential trips and 5,697 non-residential trips for a total of estimated trip generation of 14,290, which is an even larger difference than the EIR estimate. GCTC at p.6.

    - The ITE analysis presented in the GCTC letter reveals that the EIR substantially underestimates the Project's trip generation. This faulty analysis implicates the EIR's vehicle miles travelled ("VMT"). GCTC at p. 7. Trip increases described in the GCTC letter will similarly translate to roughly equivalent increases in VMT. *Id.* and EIR at 447. Although the EIR already concludes that VMT impacts would be significant and unavoidable, the EIR's failure to accurately estimate trips results in a failure to disclose the extent and severity of those impacts, which is impermissible under CEQA.

- The EIR substantially overestimates internal trips.

  - The EIR's transportation analysis assumes that 24.4 percent (approximately 1,398 of the Project's total 5,736 daily trips) of Project-generated trips would never leave the project site ("internal trips"). EIR at 440 and GCTC at p. 7. However, here too, the EIR is overly optimistic and over estimates the internal trips. Even where job opportunities and other amenities exist within the Specific Plan area, residents will still commute to existing jobs and drive off site to nearby communities. There is no guarantee that people who live on site will work there. GCTC employed three different methods to estimate internal trips at the SDC site. GCTC at pps. 7 and 8. Under each of the methods, GCTC found internal trip values ranging from 6.5 to 8.8 percent, all substantially lower that the 24.4 percent value used in the EIR analysis. GCTC at p. 8. Consequently, the DEIR analysis has substantially overstated the number of internal trips and grossly underestimated the number of external trips. *Id.* In this way, the EIR failed to accurately assess the off-site transportation-related impacts of the Project. *Id.*

  - The EIR's underestimate of the number of external trips, leads to similarly understated Project-related VMT, which serves as basis for determining the significance of the Project's transportation impact. In short, the Project's transportation impact has been greatly understated due to a failure to provide an accurate estimate of the volume of traffic resulting from the Project. See, GCTC Table 3 at p. 9. This failure to accurately estimate traffic impacts in turn implicates the air quality and greenhouse gas analyses, noise analysis, wildfire/emergency evacuation analysis, and biological resources assessment, among others.

- The EIR presents a flawed Project traffic assignment.

  - The EIR presents a flawed analysis of projected traffic volumes for the three road segments that provide access to the Project site: Arnold Drive north of the site, Arnold Drive south of the site, and the proposed Highway 12 connector. GCTC letter at p. 9. Despite the fact that the EIR omitted some of the data related to Project existing traffic volumes, GCTC was able to derive the Project traffic assignment on each roadway segment. *Id.* In each scenario analyzed in the EIR, the volume of project trips assigned to regional access roads falls substantially short of the 4,338 external trips claimed in the EIR. GCTC at p. 9 and Table 4 at p. 10. In the analyses implementing the Highway 12 connector, the volume of traffic on Arnold Drive north of the site is shown to be reduced upon completion of the Project, which seems highly unlikely. *Id.* Although some variability in these types of analyses can sometimes occur, none of the factors that would contribute to such variability (such as the presence of alternative routes that allows for redirecting traffic to less congested routes) apply at the Project site. GCTC at p. 10.Therefore, substantial evidence fails to support the EIR's analysis and conclusions, and the EIR fails to accurately account for the full volume of Project-related traffic.

- The EIR's vehicle- miles travelled analysis is inaccurate and misleading.

  - The EIR's VMT analysis is equally concerning and is flawed for several reasons. GCTC at 11. First, the VMT analysis assumes a 15 percent reduction in VMT based on transportation demand management ("TDM") trip reductions. *Id.* However, the EIR provides no support for its assumption regarding a 15 percent trip reduction. *Id.* Even the EIR admits that "the ability for individual development projects to achieve a 15 percent reduction in VMT is uncertain." EIR at 447. The GCTC analysis suggests that the VMT would be substantially greater than disclosed. GCTC at 11. Second, the employment VMT figures (also called "Home-Work VMT per Worker") presented by the EIR are highly questionable. *Id.* Specifically, the planning area baseline average (7.1), the countywide baseline average (12.4), and the regional baseline average (16.9) for home-based commute VMT per worker are all higher than the EIR value assigned for home-based commute VMT. *Id.* The EIR's finding that the Project's home-based commute VMT would be 4.8 is approximately 67 percent of the corresponding value for the Planning Area, 39 percent of the Countywide value, and only 28 percent of the Bay Area Region value. *Id.* This unexplained discrepancy, along with the aforementioned flaws in the analysis raises serious concerns about the EIR's credibility. GCTC at p.12.

  - The EIR relies on Specific Plan Policy 3-41 to reduce the Project's VMT impact. GCTC at p.12. This policy requires all development to reduce vehicle trips by 15 percent below rates listed in the ITE Trip Generation Manual using TDM strategies. *Id.* and Specific Plan at p. 3-12. However, as the GCTC letter explains, this policy does not make sense given that the Project's proposed trip generation is already so low. *Id.* In other words, if the Project's trip generation estimate is to be believed, the Project trip rate is already substantially less than 15 percent below ITE trip rates. Therefore, unless the Project's trip generation estimate is corrected, Specific Plan Policy 3-41 is meaningless. GCTC at p.13.

- CEQA requires EIRs to include all feasible mitigation to reduce a significant impact to an insignificant level even where an impact is significant and unavoidable. Here, the EIR fails to identify mitigation measures that would reduce the Project's traffic impacts. These include measures found in the California Air Pollution Control Officers Association ("CAPCOA") report "Handbook for Analyzing Greenhouse Gas Emission Reductions, Assessing Climate Vulnerabilities, and Advancing Health and Equity, Public Draft, August 2021, found at https://www.airquality.org/ClimateChange/Documents/Handbook%20Public%20Draft_2021-Aug.pdf. Some of these measures could include, for example:

MM T-7: Bus Shelter for Existing/Planned Transit Service - Bus or streetcar service provides headways of one hour or less for stops within one-quarter mile; project provides safe and convenient bicycle/pedestrian access to transit stop(s) and provides essential transit stop improvements (i.e., shelters, route information, benches, and lighting).

MMT-31: Orient Project Toward Transit, Bicycle, or Pedestrian Facility

MM T-38: Implement Preferential Parking Permit Program. (For electric vehicle and other alternative fuel vehicles.)

MM T-39: Implement School Bus Program

MM T-40: Implement a School Pool Program

MM T-42: Provide Electric Shuttles

MMT-47: Required Project Contributions to Transportation Infrastructure Improvement

MM E-23: Use Microgrids and Energy Storage

- In sum, the EIR's transportation analysis is flawed. Particular deficiencies were identified with respect to the volume of traffic associated with the Project, how much of that traffic will be captured internally, the assignment of that traffic to the stud y area roads, and the validity of the estimate of Project-related vehicle-miles traveled. GCTC at 13. These failures implicate the validity of the conclusions presented in the EIR. *Id.*

- The errors and omissions in the Transportation analysis implicate the EIR's analyses of other topics, including air quality and greenhouse gas emission impacts.

WILDFIRE RISKS AND EVACUATION PLANS

- The comments presented below reference comments on the EIR and Specific Plan prepared by Alexandra Syphard, Senior research ecologist specializing in wildfire science and fire ecology, Conservation Biology Institute ("Syphard Letter"), attached as Attachment E to Sonoma Land Trust's September 26, 2022 letter to Brian Oh.

- The EIR fails to adequately analyze Project-related impacts related to evacuation during a wildfire. The EIR references an evacuation analysis prepared by Kittelson & Associates that is not included in the EIR or its Appendices and is not available anywhere on the SDC Specific Plan website. The County must make this report available to the public.

    - The EIR fails to adequately describe the baseline conditions relevant to evacuation. In past fires, Highway 12 became so congested that it took hours to drive even short distances.

- The evaluation of project-related wildfire evacuation impacts lacks adequate information. For example, the EIR fails to provide details related to implementation of the proposed vegetated fuel buffers, their size, how they would be managed, and how they would be maintained.

- In addition, it defies logic that the evacuation of more than 2,000 cars (and potentially 3,000 or more depending on the number of housing units and number of jobs) during a wildfire would increase travel time during an evacuation by fewer than 15 seconds. The EIR fails to provide the basis for this conclusion or provide or even summarize the evacuation analysis prepared by Kittelson & Associates.

- In addition, the unstable project description and the flawed transportation analysis add to the uncertainty regarding the number of proposed housing units and the corresponding amount of increased traffic, which will exacerbate fire risk and the ability to safely evacuate.

- The EIR fails to adequately evaluate project-related wildfire risk.

    - It is common knowledge that fire is an ever-present danger in Sonoma County. Decades of fire suppression, a changing climate, the epidemic of dead and dying trees, combined with a record drought equate to a recipe for disaster in the region. As County staff acknowledge, the combination of dense forests, heavy fuel loads, low humidity, potential for high winds, and the steep terrain can rapidly turn even small fires into lethal, major disasters. EIR at 500 and 501.

- The environmental destruction wrought by wildfires is exacerbated by development in the Wildland-Urban Interface, which unwisely places people and structures directly in the line of fire.

    - Here, not only is the proposed Project located within the Wildland-Urban Interface, it is surrounded by lands designated as moderate, high, or very-high fire hazard severity zones ("FHSZ"). EIR Figure 3.16-2 Fire Constraints.

    - As the EIR recognizes, the site's natural vegetation and slopes are conducive to the rapid spread of wildland fires as was the case during the Sonoma Complex fires in 2017. EIR at 502.

- As the EIR acknowledges regarding wildfire ignition risk, " the majority—95 percent—are caused by human activity." EIR at 500.

    - Increased housing density, the location, and the pattern of development drives wildfire risk. Syphard et al. 2013. Isolated or remote clusters of development, such as the one proposed here, are particularly vulnerable (Syphard et al. 2016).

    - This is especially true when the housing is surrounded by high FHSZs.

- It is well established that most human-caused wildfires start near roads and housing development (Syphard and Keeley 2015 and others). Therefore, not only is the likelihood that more fires will start near the project site (that in turn increases the number of fires that could become destructive), but the increase in transportation into and out of the new development increases the likelihood of fires starting in the area. The EIR fails to address this fact.

- The EIR states that impacts related to wildfire risk will only be considered significant if "the Proposed Plan risks exacerbating those existing environmental conditions." EIR at 506. The EIR lists several criteria for evaluating fire risk, but fails to evaluate the risk of having a substantial increase in population on-site and increased use of the open space.

- The proposed increase in population on-site, particularly at the maximum level allowed, would exacerbate fire risks for three reasons:

    - increased housing density

    - a substantial increase in vehicles on the site and

    - a substantial increase in use of the undeveloped open space areas.

- Increased housing density and population on site, especially at the proposed low- to medium densities, would increase opportunities for fires to ignite; and there is still ample continuous vegetation in the surrounding landscape for wildfires to spread. (Syphard et al. 2007, Syphard et al. 2019, Radeloff et al. 2018).

- Research shows that the location of human ignitions tends to occur closest to roads and human infrastructure (Molina et al. 2019, Chen and Jin 2022). Increased vehicles on site would increase opportunities for fires to ignite. Therefore, the addition of people coming into and out of the area because of the new development increases the likelihood of more fires starting on-site and in adjacent areas.

- In addition, it is reasonable to assume that with an increased population of 2,400 people, or more, there will be a significant increase in use of open space areas, which will in turn, increase wildfire ignition risk. Therefore, the Project would exacerbate wildfire risk, especially if the site can eventually house even more people.

- The EIR fails to analyze any of these factors, fails to provide evidence that the Project will not exacerbate wildfire risk, and incorrectly concludes that impacts related to wildfire risk are less-than-significant.

- The EIR fails to adequately analyze project-related wildfire risk exposure of people and structures due to flooding, landslides, runoff, post-fire slope instability, or drainage changes.

- The Specific Plan and its EIR indicate that all proposed development would be located on the flat part of site. However, some structures located near the boundaries of the Core Campus are adjacent to steep slopes (within areas preserved as open space), which are known landslide-susceptible areas, and contain vegetative wildfire fuels. EIR at 521.

- The EIR relies on Policy 2-31 to reduce risks of flooding and landslides. However, as indicated above, this policy lacks details about how fuel management would be implemented and maintained in areas susceptible to flooding and landslides.

    - This information is important because some types of vegetation are more prone to ignition than others.

    - In addition, vegetation removal could result in unintended consequences, such as exacerbating slope instability especially after a wildfire.

- The EIR entirely ignores potential exposure and risk to people from flooding, runoff, or drainage changes.

    - As explained further in the section on hydrology and water quality below, the EIR defers all analysis related to exposing people or structures to a significant risk of loss, injury or death involving flooding, including flooding as a result of the failure of a levee or dam, or inundation by seiche, tsunami, or mudflow. EIR at 299 to 301.

    - The EIR presents contradictory information related to the potential for flood risk. Specifically, the EIR discloses high risk of flood hazards (EIR at 286 and 287) but defers analysis and identification of feasible mitigations until after Project approval. EIR at 300.

    - The EIR's approach of deferring analysis and mitigation violates CEQA.

- The EIR does not adequately analyze increased fire risk to neighboring residents and wildlife

    - Given the increased sources of ignition associated with new development and increased traffic, how will the Project exacerbate risk of wildfire ignitions to neighboring communities, e.g., Glen Ellen, Sonoma?

    - How will the Project exacerbate risks to biological resources due to increased risks of wildfires?

- The EIR fails to provide evidence that proposed policies and measures will reduce impacts to less than significant levels.

- The Project proposes vegetated fuel management buffers but fails to provide details related to buffer size, management, and maintenance.
  - Why is there no fuel management buffer on the north side of the development site?
  - How will annual grass areas be managed to reduce ignitability of the landscape?
  - What criteria will be applied to determine what types of trees or shrubs will be removed and what types will be retained?
  - What is the plan regarding maintenance of native vegetation, such as chaparral, trees, and shrubs that provide shade and humidity and may be less likely to ignite than grass?
- Proposed Policy 2-31states that "shrubs and chaparral *should* be limited within the managed landscape buffer" (emphasis added).
  - How will this "limit" be established? Given that this is not a mandatory requirement, what impacts will occur if it is not?
- Proposed Policy 2-34 indicates that "minimum clearance of fuels surrounding each structure will range from 4 feet to 40 feet in all directions, both horizontally and vertically" and that areas with "greater fire hazards will require greater separation between hazards." EIR at 508.
- What areas of the campus have greater fire hazards that may require more intensive vegetation removal? What sort of shrubs and trees, and therefore wildlife habitat, would be removed under this policy? What would be the biological impacts of such removal?
- What entity is responsible for ensuring that the fuel management buffers are properly implemented and maintained?
- The County must provide answers to these critical questions and identify other measures for avoiding risk other than vegetation removal, such as avoiding development altogether in areas of greater fire risk.

- Many of the policies relied upon to mitigate the significant increased risk of wildfires are inadequate because the measures are vague and unenforceable.
  - For example: SP Policy 2-42 provides for an educational campaign regarding wildfire risk to future residents. However, the EIR fails to specify the details of implementation.

- Who is ultimately responsible for ensuring that the policies are followed?

- Who will ensure that the educational campaign referred to in Policy 2-42 is updated and continued?

- How long will these policies serve to help offset the increased risk that comes with the development?

- The EIR fails to identify measures that would reduce personal vehicle use through implementation of mass transit. Having thousands of people driving vehicles on roadways on the site will increase opportunities for fire ignitions.

  - The EIR should consider additional mitigation. For example, the Project should include on-site shuttles for the life of the Project, providing transportation for residents to and from the Project site and Eldridge area to the towns of Sonoma, Napa, Petaluma, Rohnert Park, and Santa Rosa throughout the day and evening.

- All policies and best management practices should be included as measures in a Mitigation Monitoring and Reporting Plan to ensure implementation and enforceability.

HYDROLOGY AND WATER QUALITY

- The comments presented below reference comments prepared by Gregory Kamman, CBEC Eco Engineering ("CBEC") on the EIR and Specific Plan, attached below as Attachment F to Sonoma Land Trust's September 26, 2022 letter to Brian Oh.

- The EIR Project Description and Project Plan fail to provide sufficient detail about land use changes to complete the necessary hydrologic and water quality assessments to evaluate the Project's hydrological impacts. Due to the lack of an adequate Project Description, the EIR determinations that potential hydrologic and water quality impacts are less than significant requiring no mitigation measures is unsupported.

- Redevelopment of the SDC site has the potential to impact the hydrology of interconnected groundwater, spring, and stream systems through changes in land cover, storm water management, and water use. Impacts may include changes to the quantity, quality, and timing of storm water runoff, infiltrated water available for vegetation and groundwater recharge, and the magnitude, frequency, and extent of critical low flows in steams and low water conditions in wetlands. The EIR does not adequately analyze these impacts.

- The EIR leaves many questions related to hydrology and water quality unanswered. For instance:

  - What is the extent of change in impervious surface footprint under this Project? The EIR states only that the Proposed Plan may increase the amount of impervious surfaces. EIR at 298. Even if final numbers will not be known until developers submit future development proposal, the Specific Plan provides the location and types of uses such that the EIR can estimate the changes to impervious surfaces at SDC.

  - How would the change in impervious surfaces impact the quantity and quality of discharge into Sonoma Creek or its tributaries?

  - How would proposed stormwater facilities change those processes?

  - What are the quantitative impacts on the recharge of groundwater aquifers that will result from the Project?

  - How will the change in extraction of raw water from streams, springs, and aquifers impact environmental quality, including species of concern at the SDC site and beyond compared to recent demand at SDC?

  - How will projected changes to patterns of temperature and precipitation, such prolonged periods of drought combined with more intense precipitation events affect water needs and impacts of proposed development at SDC?

- The EIR cannot defer the analysis and development of mitigation measures for the Project's impacts on hydrology and water quality. The Specific Plan identifies the location, intensity, and square footage of the different land uses proposed in the Specific Plan: residential, commercial, hotel, office, public, institutional, and utility use (EIR at 80). In short, the County already knows what types of development could occur under the Specific Plan and substantially where those different types of development would occur. Yet, the EIR fails to address the following questions:

  - How would Project design ensure there would be no substantial increase in the magnitude, frequency, duration, or extent of low-flow events or flood events on springs, streams, and wetlands located at or downstream of the SDC property that may result from changes in land cover, storm water management, and/or the volume, rate, or duration of surface run-off from the site?

  - How would Project design ensure there would be no substantial degradation of water quality (as per state and local water quality standards), including pollutant load transported by storm water runoff from the site (e.g., sediment load, nutrients, metals, and hydrocarbons) that may impact the extent and quality of aquatic habitats?

  - How would Project design ensure there would be no substantial reduction of infiltration and ground-water recharge such that there would be a net deficit in aquifer volume or a lowering of the local groundwater table?

    - How would Project design ensure there would be no substantial increase in water temperatures in receiving streams resulting from runoff of warm storm water from the site?

    - How would Project design ensure there would be no substantial net increase in withdrawals or diversions from area springs and streams, including Roulette Springs, Hill Creek, Asbury Creek, and Sonoma Creek, within critical low-flow periods (summer, fall, drought conditions) or as annual averages?

    - How would Project design ensure there would be maximum possible on-site reuse of treated wastewater as water supply for landscape irrigation, groundwater recharge, or other water supply needs, to minimize environmental impacts of raw water sourcing?

- The EIR fails to adequately analyze Project-related impacts tied to compliance with applicable regulations protecting water quality. EIR at 294.

    - Impact 3.9-1 - The EIR concludes that impacts related to implementation of the Proposed Plan would not violate any federal, state, or local water quality standards or waste discharge requirements. EIR at 29 and 294. However, the EIR fails to actually analyze how changes in site runoff and associated erosion potential will change.

        - Performing the required analysis would require detailed hydrologic and hydraulic modeling that incorporates all changes in land use (i.e., impervious surfaces) and runoff estimates to determine where and by how much flow rates and erosion potential may impact receiving waterways. Best Management Practices and other measures could then be designed correctly to mitigate these impacts. Without this information, the EIR cannot adequately evaluate the impacts before and after mitigation.

        - The EIR bases its conclusion, in part, on implementation of proposed Policy WQ-1. However, this policy only requires consistency with existing laws and regulations. Under CEQA, merely requiring compliance with existing laws and agency regulations does not conclusively indicate that a proposed project would not have a significant and adverse impact.

        - The EIR also relies on implementation of as yet unspecified Best Management Practices ("BMPs"). EIR at 294. The EIR provides only a laundry list of potential BMPs with no indication or commitment regarding which ones may be implemented or what performance standards they must meet. The EIR fails to address the following questions: What BMPs would be appropriate given specific site conditions? What is the expected efficacy of each measure? What residual impacts might remain after implementation of specific BMPs?

        - An EIR may not defer preparation of mitigation measures except in limited circumstances. Without performance standards and an explanation of why mitigation cannot be developed now, the EIR cannot insist the anticipated impacts will be insignificant and defer the development of specific mitigation measures to some future time. Guidelines § 15126.4 (a)(1)(B). The EIR failed to comply with this bedrock CEQA requirement.

- The EIR fails to adequately analyze Project-related impacts related groundwater recharge.

    - Impact 3.9-2 - The EIR concludes that the project will not interfere with groundwater recharge such that it may impede sustainable groundwater management of the basin and associated potential impacts are less than significant. *Id.* Similar to its analysis of other hydrological impacts, the EIR fails to provide any analysis of how the proposed Project development will alter groundwater recharge. Having failed to analyze the impact, the DEIR again relies on compliance with existing regulations and unspecified BMPs.

    - The EIR has an obligation to describe any potential changes in recharge. Simply stating that unspecified BMPs that support groundwater recharge will be integrated into the Project is insufficient information to demonstrate that the measures will be effective to mitigate potential impacts.

- The EIR fails to adequately analyze Project-related impacts related to flooding and erosion.

    - The Specific Plan indicates that the site is potentially vulnerable to flooding and dam inundation from a failure of the Fern and Suttonfield dams and spillways. Specific Plan at p.2-6. The EIR explains that future flood events would pose risks to structures such as bridges and culverts and that failure of the dams would exacerbate flood risks. EIR at 286 and 287. Inundation from a dam failure at Fern Lake, could flood a large portion of the Core Campus area, as well as a large area of the Eldridge community just south of the Planning Area. Suttonfield Lake is the largest dam on the site and inundation from a failure at this lake would flood areas east of Sonoma Creek. Both failures would impact proposed residential areas.

    - The EIR concludes that Project development would not substantially alter the existing drainage patterns or result in substantial erosion and flooding on- or off-site or contribute runoff that would exceed the capacity of existing or planned storm drain systems. EIR at 297 and 298. Here too, these conclusions are not substantiated.

        - The EIR fails to perform and/or present results from any hydrologic or hydraulic analyses to demonstrate to what degree the project may increase runoff rates and erosion potential from new or redeveloped plan areas.

        - The EIR assumes that adhering to existing County regulations will reduce flooding and erosion impact; yet the DEIR fails to demonstrate that would be the case.

        - The EIR relies on proposed policies WQ-1 and WQ-4 regarding compliance with applicable plans which, as discussed above, is not adequate to fulfill CEQA requirements. How would these plans insure impacts were reduced to an insignificant level?

- The EIR fails to adequately analyze Project impacts related to exposing people or structures to a significant risk of loss, injury or death involving flooding, including flooding as a result of the failure of a levee or dam, or inundation by seiche, tsunami, or mudflow. EIR at 299 to 301.

    - This conclusion is contrary to the California Division of Safety of Dams ("DSOD") conclusions about Project dam safety presented in section 3.9.2.5 (Flooding – Flooding from Dam Failure) of the EIR. EIR at 286-287.

    - The EIR states, "The DSOD has classified the downstream hazard of a failure at Fern Lake as high". EIR at 286. The DEIR further states, "[T]he DSOD has classified the downstream hazard of a failure at Suttonfield Lake as extremely high." EIR at 287. These statements alone provide evidence in the record that potential flooding impacts are potentially significant and require thorough analysis.

    - Despite these disclosures, the EIR impermissibly defers necessary subsurface exploration, laboratory testing, and geotechnical studies of the dam sites to determine potential for failure and need for mitigations. EIR at 300.

    - The EIR relies on implementation of Policies WQ-2 and WQ-3 as mitigation for the significant risks associated with locating housing and businesses in the inundation zone, stating that these policies provide for future geotechnical evaluations. *Id.*

        - WQ-2 states "Any potential hazard to life or property in the Planning Area shall be properly investigated by the appropriate licensed professional."

        - WQ-3 states "All development that requires a geotechnical, hydrological, or environmental report shall utilize the recommendations of said report and be in compliance with regulatory agencies." EIR at 294 [listed as standard conditions of approval].

        - These proposed policies fail to mitigate potential impacts. Instead, they defer analysis and mitigation until after project approval and leave important questions unanswered. For example:

        - On what basis is the County concluding that dam failure would not pose a significant risk to people on- and off- site?
        - When would the required studies be performed?
        - Where would the anticipated embankments and installation of subsurface drainage control measures be implemented?
        - What is the risk of potentially locating thousands of people on the site given the condition of the dam and the known high risk that it may fail?
        - How will the required Emergency Action Plan impact the proposed Project? EIR at 300.
        - How would potential short term mitigation measures (i.e., lowering of the water levels in the Lakes through spillways at lower elevations) impact the environment on- and off-site? *Id.*
        - How would implementation of potential long term stabilization measures (i.e., reconstruction of the dam) impact the environment on- and off-site? *Id.* When will appropriate evaluations be performed?
    - Under CEQA, studies related to hazards that have the potential to increase safety risks to life and property must be performed prior to project approval. It is critical to perform such evaluations now to determine the level of risk and to include necessary mitigations, which could include changes to the Specific Plan, major repairs or fortifications of the dams, or other mitigation measures as appropriate to avoid or minimize those risks.

- The EIR concludes that Project impacts related to obstructing implementation of a water quality control plan or sustainable groundwater management plan would result in less-than-significant impacts, absent any analysis or evidence. EIR at 301.
    - As with all of the other hydrology impacts listed above, the EIR relies on compliance with existing policies and regulations to minimize impacts and fails to present any analysis to support its conclusion.

WATER SUPPLY

- The comments presented below reference comments prepared by Gregory Kamman, CBEC Eco Engineering ("CBEC") on the EIR and Specific Plan, attached below as Attachment F to Sonoma Land Trust's September 26, 2022 letter to County Planner, Brian Oh.

- The EIR presents a flawed analysis of Project-related water demands and available supply.

    - The EIR asserts that the analysis of water supply and projected water demand is conservative. EIR Appendix D at pdf page 593. But this is not the case.

    - As an initial matter, the proposed Project water demand estimate is based on the assumption that the Project consists of *516* residential units along with non-residential uses. EIR Appendix D Table 2 at 605. But EIR Appendix D Table 1 (at p. 602) indicates that at build-out in 2045, the Project will have constructed 1000 units plus commercial, hotel, office, public, institutional, and utility uses. And as explained above with respect to the Project Description, the number of residential units could exceed 1300. Even if allowed to build out to only 1000 residential units, the EIR underestimates water demand by 484 units or roughly half.

    - The EIR analysis of the availability of water supplies to meet proposed project water demands is flawed. EIR Appendix D presents the results of this analysis. Based on review of Appendix D by CBEC at 4 and 5, the analysis is faulty and fails to demonstrate there is sufficient water supply to meet the Project's future (full buildout) water demands.

        - The EIR indicates that estimated Project water demands by the year 2045 will be 342 acre-feet per year (AFY). EIR Appendix D, Table 2 at p.14. The EIR indicates that the available reliable supply of water for the period 2030-2045 is 356 AFY. EIR Appendix D, Table 9 at p. 31. Given how close the reliable water supply (356 AFY) is to full buildout demands (342 AFY), there is little room for error in terms of future water supply management.

        - The EIR water supply estimate shows that the historic (1969-2007) water use (demands) for the SDC averaged 622 AFY and peaked at 1,143 AFY in 1986 (pg. 12, Appendix D).

        - According to the EIR, the water use estimated for full buildout (2045) of the Project is a little more than half historic SDC water demands. How can this be given that the Project proposes 1000 residential units, a hotel, commercial, and industrial uses? See, EIR Appendix D, Table 1 at p. 13. Even with conservation measures, it appears that Project water demands would be similar to, if not greater, than the historic use.

    - Upon review and cross-checking data and information presented in the EIR, CBEC identified several questionable results that suggest the EIR water demands are significantly underestimated. EIR Appendix D, Tables 1 and 2. These findings are as follows:

        - The EIR only provides water use estimates for the proposed hotel but considers only water used by employees. EIR Appendix D Table 2 at p.16. Water use by guests staying at the proposed 100,000 square-foot hotel is not accounted for in the annual water demand estimate. Incorporating guest water use into the demand estimate could easily result in total annual Project demands that exceed available reliable supply.

        - CBEC identified a significant math error in the DEIR demand estimates for General Commercial, Office, Public/Industrial, and Research & Development land uses presented in EIR Appendix D, Table 2 at p.16. This is shown in Table A of CBEC's report, which merges data from Tables 1 and 2 in EIR Appendix D. When independently calculating water demands using the 2045 land use areas and Water Use Factors provided in Appendix D, the respective 2045 water demands for the General Commercial, Office, Public/Industrial, and Research & Development land uses result in values that are two orders of magnitude higher than those reported in the EIR, which results in an increased annual Project water demand of 9,846 AFY (see CBEC Letter at Table A).

- The EIR's water supply evaluation is inconsistent with Sonoma County guidelines.

    - The Permit Sonoma website provides guidelines (8-2-1 Water Supply, Use and Conservation Assessment Guidelines) for the preparation of Water Supply Assessments. The purpose of this policy is to provide guidance to applicants and their representatives on how to prepare a Water Supply, Use, and Conservation Assessment (henceforth, the "Assessment"). The Assessment may be a stand-alone document, or supplemental to a hydrogeologic study, Zero Net Use report, or other water supply related report. These guidelines are intended for discretionary and ministerial projects. Discretionary projects that are dependent on groundwater or surface water will typically require an Assessment with the use permit application. The Assessment will inform the environmental review process and conditions of approval.

    - The authority of the Assessment falls under Sonoma County General Plan, Water Resource Element Goals WR-2 and WR-4, Objective WR-4.1, WR-4.2, and WR-4.3, and Policies WR-2c, WR-2d, WR-2e, WR-4b, and WR-4f. Therefore, the EIR Water Supply Assessment (EIR at Appendix D) should adhere to County Guidelines. Appendix A to the County's Guidelines includes water use estimates for residential, landscape, agricultural, and Commercial and Industrial uses that are greater than those factors presented in EIR Appendix D, Table 2 (see CBEC Letter Table B). Applying the Sonoma County water use estimates to Project water demand estimates results in higher residential and irrigated area water demands than presented in the EIR. *Id.*

    - CBEC's analysis, which corrects the EIR's math errors and applies the Sonoma County guidelines' water use estimates to the EIR demand estimate tables, results in a total annual Project water demand of 10,231 AFY, a values three times higher than reported reliable supply (356 AFY). This annual total demand will be even higher when hotel guest water use is considered.

- o Based on the aforementioned skewed water supply evaluation, how will Project water demand affect water supply for wildlife and habitat? How will it affect other resources?

OTHER ENVIRONMENTAL IMPACTS

- In 2016, Sonoma County voters passed Measure K, which renewed critical protections for community separators throughout the County. The EIR must analyze how locating new development—particularly the high-density development proposed as the upper end of the Project description—is consistent with the County's general plan, especially if the Project requires a new road through the Glen Ellen/Agua Caliente Community Separator. This analysis must include a complete accounting of whether and how the Project would comply with Community Separator objectives and policies, which require, inter alia, that development minimize the removal of trees and mature vegetation and minimize impervious surfaces. While the EIR acknowledges that most of the SDC property is located within a local voter-approved Community Separator overlay, it fails to adequately analyze the impact of road development therein.

- The EIR must clearly analyze the impact of the proposed Highway 12 connector not only on VMT, but also on each of the impact areas for which increased vehicle traffic threatens other impacts. For example, the construction of a new roadway has foreseeable impacts to biological resources through habitat degradation and interference with wildlife movement and connectivity. Similarly, use of a new roadway would increase wildfire risk by siting new human activity and ignition sources, such as vehicles, where none previously existed. A new road also induces growth by providing access to new areas and decreasing travel times. The EIR does not adequately analyze the full scope of foreseeable impacts from the proposed Highway 12 connector and therefore cannot adequately mitigate those impacts.

- The EIR does not adequately analyze the Project's consistent with the County's general plan, especially the policies and goals designed to protect biological resources.

- The EIR fails to analyze the Project's construction impacts, claiming the analysis would be speculative without more details about the development projects. However, the County has information about the proposed land use types, and square footage, and can therefore include an analysis of anticipated construction period impacts based on that information. In addition, the EIR should have included a quantitative assessment of health risk impacts.

- The EIR relies on the 2017 Scoping Plan rather than the current Draft 2022 Scoping Plan. The newer plan includes incorporates the State's carbon neutrality goals and consistency with Executive Order EO B-55-18) and an updated Efficiency Threshold. The updated Scoping Plan requirements should have been considered in the EIR.

- The EIR calls for future geotechnical study/investigation to establish appropriate mitigations. However, the EIR fails to include performance standards for the mitigation measures. Therefore, the EIR defers both analysis and mitigation for geotechnical impacts.

- The EIR discloses that noise along the Highway 12 Connector would increase from zero to 59 decibels. EIR at Table 3.11-9 at p. 352 and 353. However, the EIR concludes that this increase would not result in a significant impact because the increase noise level does not increase by more than 3 decibels. This is clearly an error. EIR at 353.

- The EIR insists that, given the extensive park and recreational opportunities that will be offered within the Planning Area, development under the Proposed Plan would not increase the use of existing neighborhood and regional. EIR at 406. However, the EIR provides no evidence that the planning area parks will meet all park needs of residences.

- The EIR identifies a number of Specific Plan policies purportedly designed to reduce impacts to cultural and historic resources. But the EIR fails to explain how these policies would actually achieve that goal.

    - Policy 2-47: Consider adaptively reusing Sonoma House as a museum dedicated to the history of the SDC facility, collaborating with Sonoma County, the State of California, the Glen Ellen Historical Society, and other community groups for design and programming of the space, if feasible.

        - This policy is vague and unenforceable. It does not require adaptive reuse of Sonoma House or set forth standards to guide whether adaptive reuse would be feasible.

        - Who determines whether adaptive reuse is feasible?

        - What benchmarks must be met for adaptive reuse to be feasible in this context?

    - Policy 2-48: Provide resources and learning opportunities for residents and visitors about all phases of the history of the site. Materials should be accessible to all ages and abilities and could include posted signs, fliers, or informational sessions, among other things.

        - This policy is vague and unenforceable. Resources and learning opportunities *must* be available to people of all ages and abilities.

- Policy 2-52: Require any unanticipated discovery of archeological or paleontological resources to be evaluated by a qualified archeologist or paleontologist.
  - This policy is vague and unenforceable.
  - What standards must guide the evaluation by an archeologist or paleontologist?
  - What additional mitigation would be required if the archeologist or paleontologist were to identify resources of cultural or historic significance?

- The cultural resources analysis suffers from the same self-mitigating errors as the majority of the EIR. For example, the EIR concludes that "the impact of implementation of the Proposed Plan on individually significant historical resources would be less than significant with implementation of the proposed policies and actions referenced [in the EIR] and existing State regulations." EIR at 295. The EIR must first analyze the Project's unmitigated impacts before it can propose mitigation. Otherwise, decisionmakers and the public cannot meaningfully evaluate whether, how, and to what degree the purported mitigation would actually reduce significant impacts.

- The EIR acknowledges that certain land use policies or designations in the County's General Plan are relevant to the SDC redevelopment and that the Specific Plan is inconsistent with some of those policies or designations. EIR at 305, 312, 321. Yet the EIR fails to specify which General Plan policies or designations it analyzes. Decisionmakers and the public therefore cannot rely on the EIR or independently evaluate its analysis.
  - The EIR must identify the specific General Plan goals, policies, and designations that are relevant to SDC. For example, Sonoma County General Plan Policy LU-4l directs the County to "[c]onsider construction of pedestrian access, pathways, and streetlights in some Community Opportunity Areas which may be deficient in such infrastructure, particularly … Glen Ellen." Similarly, Policy LU-20i instructs that commercial lands in Glen Ellen should support uses of a "size, scale, and intensity" that "is consistent and compatible with the character of the local community." Development in Glen Ellen must also comply with the Glen Ellen Development and Design Guidelines. General Plan Policy LU-20hh. The EIR must analyze any inconsistency with these and other applicable land use planning directives.
  - The EIR also states that the Project will require a General Plan amendment and zoning amendment, both of which will ostensibly be adopted at the same time as the Specific Plan. EIR at 321. But the EIR fails to disclose what those amendments will entail or analyze the environmental impacts of those amendments.

- The EIR states that the Project would have a significant impact to land use if development would "physically divide an established community." EIR at 317. The EIR concludes that no division would occur because the Project includes a bike path and other features to enhance connectivity around the Project site. But the EIR ignores that the development proposed under the Specific Plan would nonetheless create a physical barrier in the Sonoma Valley and the Sonoma Valley Wildlife Corridor where none currently exists. Further, in addition to creating a physical barrier, the Project would dramatically increase human activity over present levels. Even if the Project contains elements that could increase connectivity, the population increase that results from the Project would foreseeably result in less tangible barriers, such as increased traffic. The EIR must acknowledge and fully analyze how these impacts would divide Glen Ellen, including the portions of Glen Ellen on either side of the campus, and Sonoma Valley communities more broadly.

- The EIR also acknowledges that "[n]ew construction has the potential to disconnect the remaining contributing resources in the Core Campus from those in Community Separator and Regional Parks lands to the east and west, consequently disrupting the feeling and character within the historic district. This would affect the cohesiveness of SSHHD's overall integrity to the point that it would no longer be eligible for listing in the NRHP, CRHR, or as a California Historic Landmark." EIR at 296. In other words, the Project would physically divide a historic district and thereby destroy its character as such.

    - How is this not a physical division of an established community that would constitute a significant land use impact?

- As discussed in the above sections, the draft Specific Plan fails to include adequate performance standards to ensure that impacts from development will remain less than significant as the Project is built out. Particularly if the EIR is going to defer development of key mitigation—and it should not do so—the EIR and Specific Plan should adopt a phased-development model that establishes clear and robust performance standards that must be met before the next phase of proposed development can proceed. Build-out should begin with the most important phase(s) of development, namely the construction of affordable housing.

- The EIR fails to adequately analyze the Project's air quality and greenhouse gas emissions.

    - The EIR's air quality analysis is based on a description of the Project that assumes construction of 1,000 residential units, 190,000 square feet of office use, 40,000 square feet of commercial/retail use, and 90,000 square feet of hotel, 90,000 square feet of public/institutional/utility uses. EIR at 168. As discussed above, this description is inconsistent with the other descriptions in the Specific Plan and EIR. As discussed throughout these comments, the unstable project description implicates the environmental analysis, including the analysis of impacts to air quality. The result is that by underestimating residential units, traffic, and VMT, the EIR underestimates air quality and greenhouse gas emission impacts

  - For example, the EIR claims that the Project would not conflict with BAAQMD's 2017 Clean Air Plan, based in part on a screening of the Project's estimated impacts against four criterion. EIR at 183. One of those criteria addresses whether the Project will result in an increase in projected VMT or vehicle trips that is less than or equal to projected population increase. *Id.* Given the significant underestimation of Project-related traffic and related VMT, as discussed above, the EIR's analysis of air quality impacts is also unreliable and its conclusion that the Project would be consistent with the Clean Air Plan is unsupported.

- The EIR fails to adequately analyze and mitigate the Specific Plan's aesthetic impacts.

  - The EIR lacks support for its conclusion that development under the Specific Plan would not have a substantial adverse effect on a scenic vista (Criterion 1).

    - EIR at 89 states that that the SDC site is within a Historic Combining District, which is designed to "protect those structures, sites and areas that are remainders of past eras, events and persons important in local, state or national history, or which provide significant examples of architectural styles of the past, or which are unique and irreplaceable assets to the county and its communities. Alterations to existing structures and construction of new structures within historic districts shall be consistent with the historic district design guidelines adopted by the board of supervisors."

    - EIR at 102 notes that the current County General Plan requires the County to identify and preserve roadside landscapes that have a high visual quality as they contribute to the living environment of local residents and to the County's tourism economy. Furthermore, General Plan objectives additionally aim to provide guidelines so future land uses, development, and roadway construction are compatible with the preservation of scenic values along designated scenic corridors, of which Arnold Road is one.

    - The SDC's historic landscape creates a unique scenic vista along the length of Arnold Road. Some Specific Plan policies identify historic buildings and contributing buildings to be retained, however the policy language is vague and unenforceable, which results in uncertainty as to whether the resources are going to be retained or whether the scenic vista is going to be lost. For instance, Specific Plan Policy 4-23 states "Preserve and reuse the contributing resources identified in Figure 4.3-1, to the greatest extent feasible." How can it be ensured that scenic resources including the Arnold Road historic landscape will be retained and maintained? Without firm and enforceable requirements, it cannot be concluded that the impacts to roadside landscapes and scenic vistas is less than significant.

- Furthermore, the EIR does not identify a threshold of significance to determine what loss of historic/scenic resources would be acceptable and considered less than significant. Therefore, it is impossible to determine whether the policies identified in the Specific Plan are sufficient to prevent a substantial degradation to a scenic resource, which in this case is the high-quality roadside landscape of Arnold Road.

- For Impact 3.1-1, EIR at 103 concludes that since "construction will be clustered only in the previously developed Core Campus and that new development will keep with the overall scale and development height variation of the current SDC campus, adverse effects on the scenic vistas of SR 12 on the eastern edge of the Planning Area and the scenic landscape unit on the western edge of the Planning Area would be less than significant." However, the EIR fails to recognize that the existing SDC campus is considered a scenic resource due to its historic significance and roadside landscape along a scenic corridor. The substantial change to the scenic resource allowed by the lax policies to protect contributing buildings will result in a substantial adverse impact and cannot be substantiated as a less than significant impact.

o The EIR lacks support for its conclusion that the Specific Plan would not substantially degrade the existing visual character or quality of public views of the site and its surroundings (Criterion 3).

- Arnold Road is a known scenic corridor with a 200' buffer on either side that is subject to development restrictions and design criteria (Sonoma County General Plan 2020 Figure OSRC-1). Specific Plan Policy 5-O states that "Arnold Drive, development *should* maintain the feel and scale of the buildings and landscape along Arnold Drive, including with a variety of building types and scales, a continuous landscape setback, activity, and views into the SDC site" (emphasis added). While this is a laudable goal, it is also an unenforceable measure with ambiguous language ("should") and cannot be relied upon to ensure that the existing visual character will be maintained along this scenic corridor.

- EIR at 106 states that "with adherence to existing and proposed policies and standards, development under the Proposed Plan would improve rather than substantially degrade the existing visual character of the site, and this impact would be less than significant." By what metric is the visual character being measured to determine that it will improve with the proposed project?

  - The EIR does not identify thresholds against which the proposed degradation of the visual character and quality views of the site can be assessed to come to the conclusion that the impacts will be less than significant. Therefore, this conclusion is unfounded.

- The EIR lacks support for its conclusion that the Specific Plan would not create a new source of substantial light or glare which would adversely affect day or nighttime views in the area (Criterion 4)

  - The EIR qualitatively discusses the light and glare impacts that will result from the operation of the project (lighting from future building fixtures, building windows, automobile headlights, parking lot lighting). What are the expected impacts from security lighting or other sources during the construction phases of the project?

  - The EIR references Specific Plan Policy 2-7, which prohibits lights within the wildlife corridor and along the creek corridor. To what sections and at what width of the creek corridor would this prohibition apply? For the purposes of enforcement of this requirement, what area is considered a "wildlife corridor?" The whole SDC area is designated a Habitat Connectivity Corridor – is that the area this policy is referring to?

  - The EIR references Specific Plan policies 5-32, 5-39, and 5-43, which all refer to maintaining a thick buffer of vegetation in order to buffer lights to protect wildlife within the preserved open space areas. For each of these policies, which serve as mitigation to address light and glare impacts, what are the type and/or height of needed vegetation or depth/width of the buffers to provide suitable light and glare protection to the creek corridors? The EIR or Specific Plan should contain policies or mitigation measures requiring a photometric plan or other metric by which light impacts can be assessed and should also have a policy or mitigation measure addressing maximum light standard height and spacing.

  - EIR at 107 concludes that "with adherence to existing and proposed policies and standards, development under the Proposed Plan would not substantially increase the amount of nighttime lighting or glare in the already previously developed Core Campus or surrounding open space areas. Impacts associated with light and glare would be less than significant." What thresholds of significance have been used to quantify this statement? What data has been collected regarding the existing light environment and the proposed light environment to be able to draw this conclusion?

ALTERNATIVES

- The EIR fails to analyze a reasonable range of alternatives to the proposed Project. Though couched as "alternatives," each of the alternatives discussed in the EIR would inexplicably implement the draft Specific Plan policies—in other words, each alternative assumes the de facto adoption of the draft Specific Plan policies even if the draft Specific Plan is not formally adopted by the County. Additionally, with the exception of the Historic Preservation Alternative, the impacts of the proposed alternatives are substantially the same. The EIR's decision to constrain alternatives in this way is not only unsupported, but also threatens to obscure project alternatives that could actually reduce project impacts, such as alternatives with fewer residences and less commercial concentrated on a smaller development footprint. The EIR must analyze a reasonable range of alternatives, including an alternative based on the development proposal that the State ultimately chooses through its RFP process. Once the State selects a development proposal, the County will better understand the location and intensity of proposed development and will therefore be able to conduct a more thorough analysis of project impacts.

- The County should decline to certify this EIR and instead direct staff to use the Historic Preservation Alternative as the starting point for a new and revised preferred project, with a revised Specific Plan and EIR that address the flaws identified in this and the following Attachments.

    - The Historic Preservation Alternative should be revised to start with an affordable housing project of 200+/- homes (Phase 1), and to allow for future development phases consistent with whichever proposal the California Department of General Services (DGS) selects as the winning bid pursuant to their surplus property sale process for the SDC core campus. The EIR acknowledges that the County and public have no real idea of how much development will actually occur at SDC, because we do not know which proposal DGS will select to enter into an Exclusive Negotiating Agreement for the sale of the campus. EIR at 77. Since we will know by late October who DGS has selected as the buyer, developing an alternative based on the DGS-selected proposal will give Permit Sonoma, the public, and decisionmakers an opportunity to focus on a real-world proposal that will drive "*the exact amount and location of future development*." EIR at 77 (emphasis added). This approach would also resolve the problem of speculating about financial feasibility and making unfounded assumptions regarding how much and what type of housing needs to be built on the site to subsidize the affordable housing mandates.

    - Importantly, the historic preservation alternative also requires significant modification to expand wildlife corridor, riparian and open space protections and setbacks. In order to further Guiding Principle #3, the revised historic preservation alternative must include and meet the following specific performance standards:

    - Provide sufficient setbacks from all creeks designed to protect water quality and quantity, instream and riparian habitat and wildlife connectivity

    - Provide a sufficient buffer that reduces the current footprint of the north side of the SDC campus adjacent to Sonoma Creek to allow wildlife to safely travel through the Sonoma Valley Wildlife Corridor

    - Ensure human activities and improvements at SDC do not impair wildlife's use

    - Ensure roads and traffic do not create a danger to wildlife

    - Ensure new development does not create new sources of light, glare or noise that would impair wildlife's use of the Corridor

    - Ensure new development does not increase the risk of wildfires that would harm the natural and built environments

    - Ensure runoff from new impermeable development does not result in erosion or contamination of creeks and riparian areas.

- The EIR mischaracterizes and misapplies the State legislation governing the disposition and planning process for SDC.

  - Government Code section 14670.10.5 (the "Legislation") does not establish any financial objectives for the redevelopment of SDC.

    - The EIR repeatedly states that economic viability is a stated objective of the State Legislation governing disposition of the SDC property. *E.g.*, EIR at 527 (stating the guiding principles "seek to further the State's goals for the SDC site established in California Government Code Section 14670.10.5 for promoting housing, especially affordable housing and housing for those with development disabilities; preserving open space surrounding the Core Campus; and ensuring that development is economically viable."); EIR at 532 ("State law stipulates that the SDC Specific Plan … ensure the financial feasibility of development"); EIR at 533 (concluding an outcome would be "contrary to the economic objectives codified in State law") (citing the Legislation). Not so. The "Legislation only directs that the County consider the economic viability of future development during the planning process: "The planning process shall facilitate the disposition of the property by amending the general plan of the county and any appropriate zoning ordinances, completing any environmental review, and addressing the economic feasibility of future development." Gov. Code § 14670.10.5(c)(1). It does *not* require that the County ensure economic viability or even prioritize economic viability. *Compare id. with* Gov. Code 14670.10.5(c)(3) ("shall provide for the permanent protection of the open space and natural resources as a public resource to the greatest extent feasible") *and* (c)(4) ("shall require that housing be a priority in the planning process and that any housing proposal determined to be appropriate for the property shall include affordable housing"). Protection of open space and affordable housing are priorities under the Legislation; economic viability is merely a *consideration*.

- The only objective that requires financial feasibility is the County's own guiding principle.

  - The County—not the State—requires that the Specific Plan "[e]nsure that the proposed plan is financially feasible and sustainable, as financial feasibility is essential to the long-term success of the project." EIR at 528. The EIR proposes to ensure financial feasibility by ensuring "that the proposed plan supports funding for necessary infrastructure improvements and historic preservation while supporting the Sonoma Valley community's needs and galvanizing regional economic growth." *Id.*

    - The County's goal to ensure long-term fiscal sustainability is a binary goal. A project either is feasible (i.e., capable of being completed) or it is not. A project either is sustainable or is it not. A project either pencils or it does not. Nothing directs the County to *maximize* economic returns or to compare the relative returns of the various alternatives. *E.g.,* EIR at 532 (criticizing the Reduced Development Alternative as "less economically viable … than the Proposed Plan"). As discussed above, the *only* two Project features that must be maximized under the Legislation are open space preservation and affordable housing. *See generally* Gov. Code § 14670.10.5.

    - The County provides a clear path towards ensuring that the Project is financially feasible and sustainable by ensuring that the Project will generate enough revenue for the developer to be able to fund the necessary infrastructure improvements the site requires.

    - Nothing in the County's objectives or in the Legislation requires the Project to prioritize returns on investment or requires the EIR to analyze the comparative returns of the various project alternatives. Yet comparison of hypothetical and speculative returns on investment inexplicably forms a central pillar of the

EIR's alternatives analysis. *E.g.*, EIR at 530 (comparing the relative economic value of the No Project Low Development Alternative against the Proposed Plan), 531 (same with respect to the No Project High Development Alternative), 532 (same with respect to the Reduced Development Alternative), 533 (same with respect to the Historic Preservation Alternative). Because alternatives must be studied to reduce environmental impacts—not to maximize economic returns—this approach is not only unjustified but contrary to CEQA.

- The alternatives analysis cites inconsistent assumptions to guide its analysis and justify its conclusions. Because it is unclear on which assumptions the EIR actually relies, decisionmakers and the public cannot decipher the anticipated impacts of the proposed alternatives or independently judge the EIR's analysis.

  - For example, on page 530, the EIR concludes that the No Project: Low Development Alternative would result in a greater number of "small-lot and townhome units" because those units "generate much higher financial returns." On page 537, the EIR removes any reference to townhomes and concludes that that same alternative would prioritize "single-family homes to maximize financial feasibility." Then on page 541, the EIR backtracks, stating again that the No Project: Low Development Alternative "would likely have a larger proportion of small-lot single family and townhomes … to achieve financial feasibility." The EIR further muddies the water in its analysis of the Reduced Development Alternative, which the EIR concludes would exhibit "a preference for more *large lot*, single family homes to maximize financial feasibility." EIR at 553 (emphasis added). On page 557, the EIR further specifies that these large lot residential developments would focus "more on single-family *detached* residential units than other typologies." (emphasis added). Finally, in its discussion of the Historic Preservation Alternative, the EIR again states that "large lot, single-family homes" would "maximize financial feasibility." EIR at 561; *see also* EIR at 566 (noting that the Historic Preservation Alternative would also prioritize "single-family *detached* residential units") (emphasis added).

    - Even assuming that the State's chosen developer would prioritize maximizing financial returns when selecting housing typologies—and the EIR has given no justification to support that assumption—it is logically impossible for three different housing types to each provide higher returns on investment than the next. Either townhomes provide higher returns or large-lot detached single-family residences do. The EIR's conclusions about which housing typologies would be employed under each alternative are therefore contradictory and unsupported by substantial evidence.

      - Which housing typology or typologies would provide the highest financial returns?

        - Why does the County believe it fair to assume that a developer would prioritize financial returns from housing when selecting housing typologies for this complex development, which includes multiple revenue streams and a mandatory obligation to prioritize affordable housing?

    - Further, even if these housing types provided similar returns on investment, the EIR does not explain why one alternative would maximize returns with townhomes while another would maximize returns with large-lot detached single-family homes. The EIR needs to justify why those design choices are appropriate assumptions in order for the alternatives analysis to be meaningful.

- The EIR also makes inconsistent assumptions about the impacts of increased or decreased development on the amount of construction activity that the Project will generate. Because the EIR fails to apply its assumptions consistently, decisionmakers and the public cannot rely on the analysis that is based on those assumptions.

    - For example, the analysis of the No Project: Low Development Alternative concludes that impacts to air quality and biological resources would be reduced because less residential and non-residential development would occur. EIR at 537-538 (this alternative "would result in somewhat reduced impacts on biological resources . . . because a reduced level of ground disturbance and construction activities would occur"); *see also* EIR at 539 (energy and greenhouse gas impacts would be "slightly less" because "construction activity would be somewhat reduced"). But this understanding that less construction results in less grading and ground disturbance does not carry uniformly through the analysis. For example, the EIR concludes that "[s]imilar impacts on cultural resources, and tribal cultural resources would result from the No Project: Low Development Alternative compared with the Proposed Plan because excavation, grading, and demolition would likely still be required for construction." EIR at 538. For similar reasons, the EIR concludes that this alternative would have "[s]imilar impacts on geology, soils, and seismicity … compared with the Proposed Plan. EIR at 540. Why would reduced construction activity reduce grading and ground-disturbance based impacts to one class of resources but not to another?

    - Similarly, notwithstanding the EIR's concession that construction-related impacts would be reduced under the No Project: Low Development Alternative, the EIR concludes that "[i]mpacts related to hazards and hazardous materials … would be similar to those of the Proposed Plan because construction would have similar risks, associated with the accidental release of hazardous materials." EIR at 540; *see also* EIR at 570 (applying the same assumptions to the Reduced Development and

Historical Preservation alternatives). Why would less development reduce certain construction-related impacts but not others?

  - The EIR does not draw equivalent conclusions with respect to the No Project: High Development Alternative. In that case, the EIR notes that "[g]reater impacts on cultural resources, and tribal cultural resources would result from the No Project: High Development Alternative compared with the Proposed Plan because more development would increase excavation, grading, and demolition of existing buildings and construction requirements." EIR at 546. Likewise, the EIR concludes that "construction activity would be increased, resulting in slightly greater construction-related and operations GHG emissions." EIR at 547. And "[g]reater impacts on geology, soils, and seismicity would result … compared with the Proposed Plan because excavation, grading, and demolition would still be required and increased for demolition of existing buildings and construction of new residential and non-residential units." EIR at 548. It is logical that increased construction would result in increased construction-related impacts. But it is equally logical that decreased construction would result in decreased construction-related impacts. The EIR does not explain why it assumes the former to be true but not the latter. Its analysis is facially inconsistent and does not provide adequate information by which decisionmakers and the public could independently judge the relative merits of each of the alternatives.

- The alternatives analysis relies on assumptions that are not justified or supported by substantial evidence.

  - For example, the EIR assumes without justification that key policies and conditions of approval from the Draft Specific Plan would survive and be implemented even if the Specific Plan is not adopted.

    - On page 538, the EIR concludes that the No Project: Low Development Alternative would have less than significant impacts on air quality "[w]ith implementation of the [Specific Plan] policies outlined in Section 3.3." But the No Project Alternatives assume that the Specific Plan is *not* adopted. EIR at 529 ("should the County not adopt the Specific Plan … the mostly likely course would be for the State to achieve its desired land use objectives through mechanisms other than the Proposed Plan").

      - Why would policies and conditions of approval developed in the Specific Plan to address air quality impacts of the Specific Plan exist and be implemented if the Specific Plan is not adopted?

    - The EIR also assumes that the No Project: Low Development Alternative would implement "policies similar to those" in the Biological Resources Analysis. EIR at 538 ("The policies outlined in Section 3.4, as well as the biological resource protection practices identifies in the Standard Conditions of Approval are assumed to be similar in the Low Development Alternative.”).

    - Why would policies and conditions of approval developed in the Specific Plan to address biological impacts of the Specific Plan exist and be implemented if the Specific Plan is not adopted?

- The EIR assumes the same for policies related to Cultural, Historic, and Tribal Resources. EIR at 538 (“The relevant policies and Standard Conditions of Approval identifies in Section 3.5 are assumed to be similar in the No Project Low Development Alternative.”)

    - Why would policies and conditions of approval developed in the Specific Plan to address cultural, historic, and tribal cultural resource impacts of the Specific Plan exist and be implemented if the Specific Plan is not adopted?

- The EIR assumes the same for policies related to Geology, Soils, and Mineral Resources. EIR at 540 (“Policies and Standard Conditions of Approval identified in Section 3.7 are assumed to be similar in this Alternative.”)

    - Why would policies and conditions of approval developed in the Specific Plan to address geologic impacts of the Specific Plan exist and be implemented if the Specific Plan is not adopted?

- The EIR repeats these assumptions for the No Project: High Development Alternative. EIR at 546 (stating the same assumptions for policies and conditions related to air quality, biological resources, and cultural, historic, and tribal resources); EIR at 548 (stating the same for policies and conditions related to geology, soils, and mineral resources).

    - Why would policies and conditions of approval developed in the Specific Plan to address impacts of the Specific Plan exist and be implemented if the Specific Plan is not adopted?

- It might be reasonable to assume that certain Specific Plan policies or conditions of approval would persist or be implemented under the Reduced Development Alternative or the Historic Preservation Alternative, since those alternatives would still result in a modified specific plan being adopted. But under the No Project Alternatives, the Specific Plan is—by definition—*not adopted*. EIR at 529. If the Specific Plan is not adopted, logic would dictate that the Specific Plan’s policies and conditions of approval would not be implemented. The EIR needs to justify its contrary assumption why the Specific Plan’s policies and conditions would be implemented in the absence of the Proposed Plan. Without that justification, the EIR's conclusions regarding the relative impacts of the various project alternatives are unsupported by reason or substantial evidence.

- The EIR also fails to adequately justify the assumptions underlying the selection of the No Project Alternatives.

  - The No Project Alternative(s) needs to examine what would occur if the Draft Specific Plan is not approved. As the EIR acknowledges, however, determining what would happen if the Draft Specific Plan is not approved is largely speculative. See EIR at 529 ("this EIR cannot pre-judge the State's actions").

    - The Legislature and the State Department of General Services "recognized the unique natural and historic resources of the [SDC] property and acknowledged that it was not the intent of the state to follow the traditional state surplus property process." Gov. Code § 14670.10.5(a)(3). The State has expressed an intent to prioritize affordable housing on the site and to protect the site's "exceptional open-space, natural resources, and wildlife habitat characteristics." Gov. Code § 14670.10.5(a)(6), (7), and (9). And the State has provided a framework by which the County may assume planning responsibility consistent with the objectives. Gov. Code § 14670.10.5(a)(8), (c). But nothing in the State Legislation requires the planning process to include any particular elements other than affordable housing and open space preservation. *See generally* Gov. Code § 14670.10.5. And equally significant, the State Legislation does not mandate that the State sell the SDC property through the planning process. *See* Gov. Code § 14670.10.5(c)(1) ("The director *may* … enter into an agreement with the county for the county to develop a specific plan for the property and to manage the land use planning process.") (emphasis added); *see also* Gov. Code § 14670.10.5(e)(1) ("This section shall not apply to the transfer of the property to a state agency in accordance with Section 11011."). The logical conclusion is that if the Specific Plan is not adopted, the Department of General Services could take a number of different paths, including allowing the County to develop a different specific plan for the site or transferring the property to a state agency in accordance with Section 11011. Yet the EIR concludes without explanation or justification that, if the Specific Plan is not adopted, the State would proceed with development of the site in substantial conformity with the rejected draft Specific Plan.

- On what basis does the EIR conclude that this outcome is more likely than any other possible outcome, such as DGS transferring the property to another state agency or DGS waiting for the County to develop an alternative specific plan?

- The EIR appears to rely on its claim that the current Draft Specific Plan most fully achieves the objectives outlined in the State Legislation. See EIR at 529 (concluding that "the State [would] retain[] planning control over the campus unfettered by local regulations to achieve these land use objectives" and that as a result, "the No Project Alternative would result in a palette of uses similar to those outlined in the Proposed Plan." But the only two objectives codified in the State Legislation are the mandate to prioritize affordable housing and the mandate to protect open space. *See generally* Gov. Code § 14670.10.5. So the State Legislation, standing alone, cannot justify the EIR's conclusion that the No Project Alternative would result in the same palette of uses as the Proposed Plan, which palette is designed to achieve the County's objectives—not the State's. *Compare* Gov. Code § 14670.10.5 *with* EIR at 527-528. Without further justification, the EIR cannot demonstrate that its purported No Project Alternatives reflect what would actually occur if the Specific Plan is not adopted.

- Similarly, the EIR fails to explain why the development levels in the two No Project Alternatives—which appear to be entirely arbitrary 25 percent increases and decreases in development—would be reasonably predicted to occur.

  - What data support the EIR's chosen housing and job count for the No Project: Low Development Alternative?

  - What analysis supports the EIR's chosen housing and job count for the No Project: Low Development Alternative?

  - What assumptions support the EIR's chosen housing and job count for the No Project: Low Development Alternative?

  - What data support the EIR's chosen housing and job count for the No Project: High Development Alternative?

  - What analysis supports the EIR's chosen housing and job count for the No Project: High Development Alternative?

        - What assumptions support the EIR's chosen housing and job count for the No Project: High Development Alternative?

- The EIR draws conclusions about the relative merits of its proposed alternatives without actually analyzing potential impacts or supporting its conclusions with substantial evidence. These failures obscure the EIR's reasoning and make it impossible for decisionmakers or the public to comprehend how the EIR draws it conclusions, particularly where the EIR's conclusions appear to contradict the EIR's own limited analysis.

    - For example, the EIR concludes that No Project: Low Development Alternative would result in "lower financial feasibility" that the Proposed Plan. EIR at 537. But the EIR does not document or explain why the No Project: Low Development Alternative would be less financially feasible. To the contrary, the EIR states that the alternative's development mix would shift, for example by prioritizing more single-family homes, "to maximize financial feasibility." EIR at 537.

        - What are the specific financial drivers that influence the financial feasibility of the No Project: Low Development Alternative?

        - How specifically does the financial outlook of this alternative compare to that of the Proposed Project?

    - The EIR also states that "the No Project: Low Development Alternative would have an equivalent impact related to land use, population, and housing compared to the Proposed Plan" (EIR at 541-541), notwithstanding that the No Project: Low Development Alternative would develop "to a lesser extent and in a smaller area" (EIR at 541).

        - Why did the EIR conclude that impacts would be the same even though development intensity is reduced?

        - Why does the financial feasibility of various alternatives appear to vary so greatly but the impacts do not?

    - The EIR assumes without explanation or justification that the No Project: Low Development Alternative, the Reduced Development Alternative, and the Historic Preservation Alternative would "shift some of the planned growth in the Planning Area to other locations in the region." EIR at 543, 559, 568.

        - Why is the growth planned by the Draft Specific Plan assumed to be inevitable in Sonoma County?

- The EIR concludes that the Historic Preservation Alternative "is projected to result in approximately 50 percent fewer vehicle trips than the Proposed Plan, indicating that the total VMT generated may also be roughly 50 percent lower." EIR at 569. The EIR does not cite data or analysis to support this statement.

  - How did the EIR reach these numbers?

- The EIR states that the reduction in VMT under the Historic Preservation Alternative "would be substantial though would not necessarily translate to less residential VMT per capita, which is the efficiency metric for which a significant VMT impact was identified." EIR at 569. In light of its chosen significance threshold, the EIR cannot meaningfully compare the VMT impacts of the various alternatives unless it quantifies VMT per capita for each alternative.

  - What data or analysis would be needed to determine whether the substantial reduction in VMT under the Historic Preservation Alternative would translate to less residential VMT for capita?

  - Under what circumstances does a change in total VMT translate or not translate to a change in VMT per capita?

  - The EIR states that it is uncertain whether the reduction in VMT would translate to a reduction in VMT per capita, but nevertheless goes on to conclude that the alternative's "reductions in VMT and VMT per capita would be insufficient to avoid a significant and unavoidable VMT impact." EIR at 539. By definition the EIR cannot determine the significance of the alternative's VMT per capita impact if the EIR does not know that the alternative's VMT per capita impact is. The EIR's conclusion is therefore unsupported by analysis or substantial evidence.

- The EIR does not provide a meaningful analysis of the impacts of each of the alternatives, using terms such as "largely comparable," "slightly greater," and "slightly reduced." These terms are especially inappropriate for the Historic Preservation Alternative, which is the environmentally superior alternative. The EIR incorrectly concludes that the proposed Project's impacts are "largely comparable" to reduced development alternatives. But the Historic Preservation Alternative would significantly reduce the magnitude of impacts on traffic, climate change, historic resources, noise, biological resources, public services and land use.

- The EIR states that the Proposed Project would have "superior financial feasibility" than the alternatives. EIR at 571. But the EIR does not provide data or other substantial evidence to support that conclusion. All of the statements about financial feasibility in the alternatives analysis are conclusory and lack substantiating evidence or discussion. *See* EIR at 536-571.

- The EIR defines the No Project Low Development alternative by a reduction in overall housing and job numbers. It then concludes that "[t]he proportion of both income-restricted affordable housing and affordable by design housing in the Low Development Alternative is projected to be less than the Proposed Plan." EIR at 542. But the EIR fails to provide supporting evidence for this projection. *Id.*

    - Why is the proportion of both income restricted affordable housing and affordable by design housing in the Low Development Alternative projected to be less than the Proposed Plan?

- The EIR makes the same unsupported projections with respect to the Reduced Development Alternative and the Historic Preservation Alternative. EIR at 559, 568.

    - Why is the proportion of both income restricted affordable housing and affordable by design housing in the Reduced Development Alternative and the Historic Preservation Alternative projected to be less than the Proposed Plan?

- Conversely, the EIR defines the No Project: High Development alternative by an increase in overall housing and job numbers. It then concludes that "[t]he proportion of both income-restricted affordable housing and affordable by design housing in the High Development Alternative is projected to be more than the Proposed Plan." EIR at 550. again, the EIR fails to provide supporting evidence for this projection. *Id.*

    - Why is the proportion of both income restricted affordable housing and affordable by design housing in the High Development Alternative projected to be more than the Proposed Plan?

- The EIR states that "[b]ased on prior alternatives modeling exercises completed for SDC in 2021, it is likely that the No Project: High Development Alternative would generate slightly more per capita VMT than the Proposed Project, though the difference would likely be negligible." But the EIR fails to identify, cite to, or provide copies of the analysis and results from those "prior alternatives modeling exercises." Without additional information, decisionmakers and the public cannot independently judge the strength of the EIR's analysis or the veracity of its conclusions.

- The alternatives analysis fails to discuss or analyze the impacts of any of the proposed alternatives to the Sonoma Valley Wildlife Corridor.

    - The EIR's analyses of the No Project: Low Development Alternative and the Reduced Development Alternative do not mention the wildlife corridor at all. EIR at 538 (discussing the No Project: Low Development Alternative's impact to biological resources but failing to mention or discuss the Wildlife Corridor); EIR at 554 (same with respect to the Reduced Development Alternative). Because impacts to wildlife movement—and particularly to wildlife movement within the established Sonoma Valley Wildlife Corridor—are a major issue and threshold of significance for the Project's impacts to biological resources, this omission prevents readers from understanding fully the relative consequences of each alternative.

    - How would the No Project: Low Development Alternative impact wildlife movement and connectivity through the Sonoma Valley Wildlife Corridor?
    - How would those impacts differ from the impacts the Project would have on wildlife movement and connectivity through the Sonoma Valley Wildlife Corridor?
    - How would the Reduced Development Alternative impact wildlife movement and connectivity through the Sonoma Valley Wildlife Corridor?
    - How would those impacts differ from the impacts the Project would have on wildlife movement and connectivity through the Sonoma Valley Wildlife Corridor?

- Similarly, the EIR's analyses of the No Project: High Development Alternative and the Historic Preservation Alternative refer only to those wildlife corridors that lie (or would lie) within the Core Campus. EIR at 546 (noting that under the No Project High Development Alternative, "the area devoted to the expanded wildlife corridor may be reduced or eliminated," but not discussing impacts to the remainder of the Sonoma Valley Wildlife Corridor); EIR at 563 (same with respect to the Historic Preservation Alternative, noting "the creek corridors and the wildlife corridor will also not be expanded"). By failing to analyze the alternatives' impacts to the established Sonoma Valley Wildlife Corridor and their reliance on a new road connecting to Hwy. 12 that bisects the Corridor outside the Core Campus, the EIR obscures the true impacts of those alternatives and prevents readers from accurately comparing the alternatives. The EIR cannot reliably identify an environmentally superior alternative without first comparing the full environmental effects of each proposed alternative.

    - How would the No Project: High Development Alternative impact wildlife movement and connectivity through the Sonoma Valley Wildlife Corridor?
    - How would those impacts differ from the impacts the Project would have on wildlife movement and connectivity through the Sonoma Valley Wildlife Corridor?

- How would the Historic Preservation Alternative impact wildlife movement and connectivity through the Sonoma Valley Wildlife Corridor?

- How would those impacts differ from the impacts the Project would have on wildlife movement and connectivity through the Sonoma Valley Wildlife Corridor?

CUMULATIVE IMPACTS

- The EIR states that a cumulative impact analysis "must analyze either a list of past, present, and probably future projects or a summary of projections contained in an adopted general plan or related planning document." EIR at 585. While the EIR claims that the "Proposed Project represents the cumulative development scenario for the reasonably foreseeable future in the Planning Area under the County's General Plan" and "incorporates the likely effects of surrounding regional growth," for many impacts, the EIR limits its analysis to the Plan Area rather than considering the combined effects of the Project together with the environmental impacts that are likely to occur outside the Project's Planning Area.

    - For example, the Planning Area is constrained to the SDC site. EIR at 54 (Figure 2.1-2: Planning Area Boundaries). But the Sonoma Valley Wildlife Corridor that runs through the Planning Area extends for a significant distance to the east and west, stretching from the top of Sonoma Mountain across Sonoma Creek and the valley floor to the Mayacamas Mountains to the east. Permeability of the Sonoma Valley Wildlife Corridor is important "for the movement of wildlife at a regional scale." EIR at 242. The cumulative impact boundary for impacts to the Wildlife Corridor must include the entire corridor and all projects capable of impacting the corridor if the true scope and magnitude of cumulative impacts are to be understood. Specifically, analysis of cumulative impacts on the Wildlife Corridor should encompass an area extending from the Russian River in the north to the San Pablo Bay to the south, and from the Petaluma River to the west to Napa Valley to the east. This impact boundary is necessary to capture the movements of local populations of the widest-ranging species present (i.e., mountain lions), as well as movement and dispersal among regional populations, allowing for genetic exchange, and range shifts in response to climate change over time. This boundary would include a portion of the Marin Coast-Blue Ridge Critical Wildlife Linkage identified by Penrod et al. (2013),[4] but analysis should include all land development in the region, not only within the mapped critical corridors.

[4] Penrod et al. 2013. Critical Linkages: Bay Area & Beyond. Produced by Science & Collaboration for Connected Wildlands, Fair Oaks, CA in collaboration with the Bay Area Open Space Council's Conservation Lands Network.

- The EIR's myopic focus on cumulative impacts caused by and felt within the Planning Area obscures impacts that may occur outside the Planning Area and that the Project may add to, or impacts that may occur within the Planning Area that could be cumulatively significant when impacts from projects outside the Planning Area are accounted for. The EIR must expand its cumulative impacts boundary.

- The EIR does not apply a consistent cumulative impact boundary. While the introduction to the cumulatively impacts analysis indicates that the impact boundary is the Planning Area (EIR at 585), the EIR elsewhere extends the impact boundary (e.g., EIR at 589 ("The cumulative geographic context for cultural, historic, and tribal cultural resources is the County of Sonoma.").

    - Where the EIR does use a wider impact boundary, it is not clear whether the EIR analyzes cumulative impacts based on a specific list of projects or on projected development under the General Plan. For example, at pages 589-590 the EIR states that "[i]f the Proposed Plan, in combination with other past, present, and reasonably foreseeable projects in Sonoma County, would result in the loss of or adverse changes to multiple historic or cultural resources a significant cumulative impact could result." Further muddying the waters, the EIR does not specify what other projects inform its analysis. EIR at 589-590. Instead, the EIR punts to project-level environmental review and discusses only projects to be completed within the Planning Area under the Specific Plan. *Id.* The EIR must choose an appropriate cumulative impacts boundary for each impact, justify its choice, and analyze cumulative impacts of the Project together with other past, present and future development. *See, e.g.,* Draft Environmental Impact Report for the Springs Specific Plan at 4.0-3 ("The cumulative setting for aesthetics is the Sonoma Valley Planning Area"), 4.0-7 ("The cumulative setting for biological resources includes the Plan area and the greater Sonoma County region."), 4.0-9 (The cumulative setting for … (climate change) comprises anthropogenic (i.e., human-made) GHG emissions sources across the globe.")

    - Use of the County's existing general plan for the cumulative impact analysis does not provide a meaningful analysis of cumulative impacts for the SDC Project. The County adopted its general plan more than 14 years ago in 2008, and is currently updating the general plan. The general plan's outdated cumulative impact analysis omits recent planned and approved projects and therefore does not provide a meaningful framework with which to gauge the Project's cumulative impacts.

- Specific Plan Policy 2-28 provides that prior to the commencement of the approval of any specific project in the Proposed Plan area, Project Sponsors shall contract a qualified biologist to conduct studies identifying the presence of special-status species and sensitive habitats at proposed development sites and ensure implementation of appropriate mitigation measures to reduce impacts to sensitive habitat or habitat function to a less than significant level. This policy epitomizes improper piecemealing of environmental analysis. If development under the Specific Plan is only analyzed on a project-by-project basis, the cumulative impacts of those projects will be obscured and may not be adequately mitigated. The EIR must complete all required analysis now, at the plan-level stage, in order that decisionmakers and the public can understand the full picture of what a buildout of the draft Specific Plan would entail.

EXEMPTION AND TIERING

- Much of the EIR relies on future, project-level environmental review to identify and mitigate potentially significant environmental impacts. *See, e.g.*, EIR Chapter 3.4; *see also* EIR at 589-590 (finding that cumulative impacts to cultural, historic, and tribal cultural resources would not be cumulatively considerable due in significant part to future project-level environmental review). But the Specific Plan states that the County intends to avoid future project-level environmental review to the greatest possible extent. Draft Specific Plan at 7-3 ("When a public agency has prepared an EIR for a specific plan, State law provides that residential, commercial, or mixed-use projects undertaken inconformity to the specific plan are exempt from CEQA, subject to certain requirements. Pursuant to Section 15152 of the CEQA Guidelines, projects will also be eligible to "tier" from the EIR … The County intend to rely on these provisions for exemptions and tiering to the maximum extent feasible."). Furthermore, as a matter of law, residential projects consistent with a specific plan are statutorily exempt from CEQA and do not require additional environmental review. Gov't Code § 65457.

    - If the County's goal is to evade future project-level review, how can it justify relying on future project-level review to identify and mitigate the Project's impacts?

    - In light of the Draft Specific Plan's stated goal, how will the County ensure that all necessary environmental review is completed?

ATTACHMENT B

PRUNUSKE CHATHAM, INC.

September 16, 2022

Brian Oh, Comprehensive Planning Manager
Permit Sonoma, County of Sonoma
2550 Ventura Avenue
Santa Rosa, CA 95403

Re: Comments on the Sonoma Developmental Draft Specific Plan and Draft Environmental Impact Report, Biological Resource Elements

Dear Mr. Oh:

Prunuske Chatham, Inc. (PCI)'s services were retained by the Sonoma Land Trust to provide our professional assessment of the Sonoma Developmental Center (SDC) Draft Specific Plan and Draft Environmental Impact Report. Our review and comments focus on biological resources aspects of the documents and identify inadequacies in the Draft EIR's evaluation of potential impacts on biological resources.

PCI Qualifications

PCI is an ecological consulting firm based in Sonoma County, founded in 1986. PCI provides a full spectrum of services including ecological assessment, planning, design, and restoration implementation. Our staff includes wildlife biologists, ecologists, botanists, geomorphologists, planners, civil engineers, landscape architects, and constructors. Our biological resources expertise includes natural resource management planning, park and preserve planning, botanical and wildlife assessments, wetland delineation, forestry and fuel load planning, and restoration planning and implementation. Our regulatory compliance staff provide environmental document preparation and have guided projects ranging from dam removals to park master plans to landscape-level efforts through the CEQA and permitting processes. Our design work has focused on park and trail planning, salmonid habitat enhancement, natural channel restoration, and native revegetation. Our clients range from individual landowners to non-profits, utilities, and government agencies.

PCI's qualifications to comment on these documents include our directly related prior work on the SDC site and a wide range of biological resources and CEQA planning across the North Bay for the past 30 years. In 2015, PCI prepared a Draft Resources Assessment for the Sonoma Developmental Center under contract to Sonoma County Agricultural Preservation and Open Space District. In 2018, PCI prepared the Natural and Recreational Resources element of the Sonoma Developmental Center Existing Conditions Assessment, as part of a consultant team led by Wallace Roberts Todd under contract to the State Department of General Services. PCI provides these comments based on the professional expertise and opinion of PCI's staff. These professional opinions and expertise are informed by decades of experience analyzing biological resources and impacts, application of established scientific principles, and a robust knowledge of the resources and environment at the SDC site.

103 Morris Street, Suite A-5 Sebastopol, CA 95472 707-824-4600 fax 707-824-6854

Lead PCI staff on this document review include Joan Schwan, Principal Ecologist; Carrie Lukacic, Principal Environmental Planner; Erynn Rebol, Biologist; and Celia Chatham, Biologist. Resumes for each are provided as an attachment.

Comments on the Specific Plan and the Adequacy of the EIR for Biological Resources

The Sonoma Developmental Center property's regionally important natural resources are widely acknowledged. Its extensive undeveloped lands and native habitats; creeks, lakes and springs; and location at a narrow point in a regional wildlife corridor, are all central to the considerations in planning redevelopment. The Draft EIR notes that the majority of responses received on the Notice of Preparation related to protection of these resources, reflecting strong community and agency support. PCI appreciates the attention the County and the Specific Plan team have directed toward incorporating natural resource protection into planning, and the responsiveness of the Plan to some of the specific issues raised in comments on the NOP. In particular, PCI noted that the plan incorporates:

- A clearly stated goal to "maintain and enhance the size and permeability of the Sonoma Valley Wildlife Corridor…by ensuring a compact development footprint at the SDC site and by minimizing impacts to wildlife movement and safety from human activity and development at the campus" (Goal 2-D, Specific Plan).
- Removal of several buildings on the north side of the central campus, allowing for an expanded riparian buffer along Sonoma Creek and improving habitat for wildlife in an otherwise constrained portion of the corridor.
- Policies that help limit impacts to wildlife permeability from site development, including restricting development and recreation within the wildlife and creek corridors, meeting but not exceeding defensible space requirements, maintenance of road undercrossing structures, and measures to manage lighting, noise, fencing, and pesticide use.
- A commitment to avoid increases in withdrawals from the site's springs and streams, helping maintain critical water resources for fish, wildlife, and riparian vegetation.

However, some aspects of the project conflict substantially with natural resource protection, and the Draft EIR also fails to clearly or thoroughly address a number of important biological considerations. For example:

- The Draft EIR's analysis and discussion of potential biological impacts is limited and is insufficient to determine whether the Specific Plan's potential impacts will be significant.
- The Draft EIR fails to discuss how proposed new roads, and significant increases in traffic and human activity and development density on the site, may affect wildlife movement or cause other significant impacts.
- The Draft Specific Plan and Draft EIR would permit numerous uses in "Preserved Open Space" that conflict with open space preservation goals and could cause significant impacts.

These and other issues are addressed more fully in the table below. As detailed in the table, the Draft EIR's lack of analysis of key biological impacts prevents the EIR from identifying which impacts are likely to occur or how significant they will be. Because the EIR does not adequately analyze impacts, it cannot fully develop or analyze effective mitigation measures. Further, what little de facto mitigation the EIR does propose (via Specific Plan policies and Conditions of Approval) is insufficient to reduce impacts to biological resources to less-than-significant levels. In addition to identifying analytical issues in the EIR, our comments below pose specific questions that must be answered to fill informational gaps in the EIR and facilitate complete, scientifically sound impact analysis.

PCI also observed that the Specific Plan focuses on avoiding negative impacts on natural resources and, aside from the elimination of two buildings mentioned above, does not take advantage of this key site planning opportunity to call for positive habitat improvements or restoration of impaired ecological values. In addition, the Biological Resources sections contain a number of errors and omissions in describing the basic ecological setting of the site.

PCI's full comments and questions on biological resource aspects of the Draft Specific Plan and adequacy of the Draft EIR are provided below.

<table>
<tr><th colspan="2"><h2>Specific Plan</h2></th></tr>
<tr><td colspan="2">Chapter 1 – Vision, Guiding Principles, and Context</td></tr>
<tr><td>Page</td><td>Comment</td></tr>
<tr><td>1-19
Figure 1.6-2</td><td>Is this map meant to show only known occurrences or all likely habitats? Please clarify. Multiple special-status species previously documented as occurring or likely to occur on the site are not shown. Are these excluded intentionally, and if so, why? For other species, only a portion of their known or likely distribution is shown. See PCI (2018) [1] for detailed review of potential habitat on site for these species. Species not shown, or not showing full distribution, in Figure 1.6-2, but previously documented as occurring or likely to occur are:
- Freshwater shrimp – documented on Sonoma Creek and has potential to occur on Asbury and Hill Creeks.
- Steelhead – documented in Hill Creek and potentially present in Asbury Creek, in addition to presence in Sonoma Creek.
- Species of Special Concern documented on or adjacent to the site but not shown (see PCI 2018 for location information):
  ○ California giant salamander
  ○ Foothill yellow-legged frog
  ○ Pallid and Townsends big-eared bats
  ○ Northern western pond turtle
Species of Special Concern American badger has been reported on Sonoma Mountain and also has potential to occur. Mountain lions are a "specially protected mammal in California" and of high local conservation concern; radio tracking by local researchers shows extensive use of the SDC site.</td></tr>
</table>

[1] Prunuske Chatham, Inc. (PCI). 2018. Sonoma Developmental Center - Existing Conditions Report: Natural and Recreational Resources. Appendix to: Sonoma Developmental Center Existing Conditions Assessment, prepared by WRT. https://transformsdc.files.wordpress.com/2020/01/2-cnaturallandrecreationalresourcesv3.pdf. August 2018.

	Note also that northern spotted owl is federally listed as threatened but not shown as such on map.
1-20 Figure 1.6-3	This map conflicts with known data. What is the data source? It doesn't match PCI (2018) or Sonoma Veg Map data. The large wetland on east side is labeled a "vernal pool" but this wetland is not considered a vernal pool by prior work (e.g., PCI 2018). Please adjust text or explain why the feature is considered a vernal pool, given the high conservation concern for vernal pools. This figure also omits non-native forest on core campus though it is "existing vegetation" (i.e., relevant to the map), is mapped by the Sonoma Veg Map data, and is included in Figure 2.2-1, Open Space Framework. The non-native forest should be included on this map because these trees provide habitat values, including nesting, cover, and foraging resources for birds and potential roosting habitat for bats. The potential for impacts on birds, wildlife movement, and special-status bats should be addressed in the EIR if removal of this vegetation is proposed.
1-21 First Sentence	First sentence states that "the natural landscape and the site's location in the Sonoma Valley also brings fire hazards." Similar wording is used on 2-1. That statement should be omitted or clarified to explain that human infrastructure and human activity pose the most significant risks for wildfire ignition in this area (as stated on page 500), and that weather patterns of the region in combination with local topography lead to high potential for the spread of wildfire throughout both natural lands and developed environments.
Chapter 2 – Open Space and Resources and Hazards	
Page	*Comment*
2-4 Figure 2.2-1	This figure shows "Managed Landscape/Fire Buffers" and an "Expanded Wildlife Fire Buffer." The Managed Landscape/Fire Buffers extend into what is currently open space. How will fuel reduction practices in this zone be tailored to prevent any significant impact on wildlife movement or other habitat values? What is the proposed maximum width of this buffer? All fire buffers should be no wider than necessary to meet public safety needs in order to reduce impacts on natural resources. Potential impacts include reduced permeability for wildlife movement (due to loss of cover and foraging resources, and increased exposure to human activity), damage to sensitive plant communities (i.e., within Oregon oak woodland on the west side of campus, with potential direct removal of oaks as well as potential loss of native understory diversity, reduced oak regeneration and increased potential for weedy species establishment) and within riparian forest along Hill Creek (with potential direct removal of riparian trees as well as loss of native understory diversity, potential reduced native tree regeneration, and increases in weedy species). [See, for example, Kerns et al. (2020), Perchemlides et al. (2008), and Seavy et al. (2008).] Biological Resources significance Criteria 1 through 4 indicate that these types of impact could constitute significant impacts to biological resources. These impacts must therefore be addressed in the EIR.
2-5 Figure 2.2-2	This figure showing "Preserved Open Space" does not show the two new potential Highway 12 connector roads that could be developed within or across open space, resulting in an incomplete illustration of the nature of the proposed open space.

	Project impacts to open space cannot be fully analyzed unless this figure shows these proposed new roads and calls out locations for any of the anticipated uses, such as intensive agriculture or utility development, noted in Table 4-3, that are not compatible with common understanding of the term "Preserved Open Space," which is land that is primarily undeveloped and left in a natural state, such as grasslands and open rangeland, forests, and woodlands. Locations planned for utility development or intensive agriculture (e.g. indoor crop cultivation, confined farm animal operations, row crops, vineyards, etc.) should be designated as such; otherwise, project impacts to natural resources cannot be analyzed. The Plan does include a Utilities land use type; all proposed utility developments should be shown with that label. The potential impacts of the allowable uses within the "Preserved Open Space" are not analyzed in the EIR. Until the potential impacts are analyzed, it is impossible to determine whether those impacts would be significant or whether certain Specific Plan policies could avoid or mitigate those impacts.
2-6 second paragraph	Second paragraph emphasizes vegetation management as a means to reduce wildfire hazard. The prime importance of designing buildings to be fire-resistant, and of use policies that limit the likelihood of ignition, should be emphasized here along with vegetation management. Vegetation removal from the natural landscape should not be the primary approach to fire risk reduction on the site, especially given its importance to wildlife habitat and wildlife movement through the site. See comment above on page 2-4 for further discussion of potential impacts of vegetation removal on biological resources.
2-9	To reduce impacts of trails and recreational use on biological resources, Policy 2-4 should include the decommissioning of trails that are duplicative or causing erosion or other resource damage. The current trail system includes trails that occur close together and lead to essentially the same destinations. Since each trail and its use has a cumulative impact on natural vegetation (i.e. by direct removal and often, the facilitation of invasive plant species) and on wildlife use (by the increase in human and dog presence), decommissioning duplicative or highly erosive trails will reduce the project's recreational impacts. Some of the trails on the site are also contributing to substantial erosion, resulting in soil and vegetation loss and potential impacts to water quality downstream. The site's trail system should be reviewed for such locations to decommission or realign as well. Policy 2-5 calls for setting aside a location for water recreation for people and dogs at Suttonfield Lake. Facilitating intensive dog use of the site could have significant impacts on wildlife use of the area. Dogs can affect wildlife through direct predation, harassment, scent marking resulting in wildlife avoidance, and spread of disease. Dog presence has been found to be associated with reduced habitat use by species including mountain lion, mule deer, bobcats, and small mammals such as squirrels and rabbits (Reilly et al 2017, George and Crooks 2006, Length et al. 2008); with disease transmission to gray foxes (Riley et al. 2004); and with reduced bird presence and species richness (Banks et al 2007). The potential impacts of dog use must therefore be evaluated in the EIR. Until the potential impacts analyzed, it is impossible to determine whether those impacts would be significant or whether certain Specific Plan policies could avoid or mitigate those impacts.

2-10	Goal 2-D seems to be mixing the goal of conservation of habitat on site with resource conservation more globally. Please clarify. For instance, how is "sustainable food production" a means to conserving habitat on the site? Policy 2-6 – This policy should also include and address the northwest corner. Figure 2.2-1 indicates a building will be removed in this location and the wildlife buffer expanded.
2-11	Policy 2-11 – This policy should incorporate the most recent guidance from the Dark Sky Association, which is that all outdoor lights have a color temperature of no more than 2200 Kelvins. [See A Values-Centered Approach to Nighttime Conservation - International Dark-Sky Association; darksky.org)] Dark Sky Standards also provide that: • All lights will use the lowest light level required minimum levels recommended by widely recognized professional standards bodies. • All residential and business outdoor lighting should be actively controlled through means such as timers and motion-sensing switches to ensure that light is available when it is needed, dimmed when possible, and turned off when not needed. Lighting can disrupt wildlife by altering night-time cover and hunting conditions, reducing an area's value and permeability to wildlife. For instance, lighting has been found to reduce use of movement corridors for mountain lions (Beier 1995), deer and mice (Bliss-Ketchum et al. 2016), and bats (Bhardwaj et al. 2020), reducing habitat connectivity for these species. This policy should incorporate the most recent Dark Sky Association guidance and standards in order to reduce impacts to wildlife corridor use and movement. Policy 2-16 – These are valuable requirements to help address impacts of fencing on wildlife movement, but to allow for passage of wildlife above and below fencing, the Specific Plan should also require that the maximum height of the upper strand be no more than 48" (42" preferred). Since Table 4-3 permits agricultural uses within the "Preserved Open Space," this policy must make clear that these fencing standards apply throughout areas shown as Preserved Open Space in Figure 2.2-2, regardless of whether it may be also used for agricultural uses. See also comment on p. 4-14. Policy 2-17 – The wording of this residential nighttime noise reduction policy suggests that it is optional or will not necessarily be enforced. It is therefore insufficient to reduce noise impacts on wildlife to less-than-significant levels. Noise has been shown to impact wildlife usage of habitat, resulting, for example, in reduced foraging time and efficacy, and reduced nesting use, in birds (Burger and Gochfeld 2002, Stone 2000, Aubrey and Hunsaker 1997, Shannon et al. 2016). Potential noise impacts on wildlife must therefore be analyzed in the EIR.
2-12	Policy 2-19 – The planting palette for habitat restoration or general plantings within the open space areas should be entirely composed of locally native species; the County should delete "and/or low-water plant species." The planting palette for general planting within the campus should also be composed of locally native species

	where feasible, but in ornamental landscape settings, other low-water-use plants would also be acceptable. Policy 2-21 - To ensure the proposed enhancements do not have a significant impact on wildlife movement and sensitive wetland habitat, this policy should require that development "Ensure that enhancements protect or improve wildlife habitat values." Policy 2-24 – Additional bird-friendly design measures should be incorporated in order to avoid impacts to birds. Relevant additional measures include: - Minimize the overall amount of glass on building exteriors facing water features. - Avoid transparent glass skyways, walkways, or entryways, free-standing glass walls, and transparent building corners - Utilize glass/window treatments that create a visual signal or barrier to help alert birds to presence of glass. - Avoid funneling open space to a building façade. - Strategically place landscaping to reduce reflection and views of foliage inside or through glass. - Avoid or minimize up-lighting and spotlights; and turn non-emergency lighting off (such as by automatic shutoff) at night to minimize light from buildings that is visible to birds. (See also comments on Policy 2-11 regarding lighting.) See: Resource-Guide-for-Bird-safe-Building-Design.pdf (audubonportland.org) 2-25 – Asbury Creek should be included as one of the streams requiring a setback of at least 50'. Because 50' is a minimum setback that will only protect some of the processes listed, larger buffers should be retained where they currently exist, and opportunities to expand buffers to 100' – 300' should be considered. These larger buffers will provide greater mitigation of impacts from development and human uses on wildlife movement and water quality. For example, setbacks of 100'-300' will be more effective as wildlife corridors, allow for greater natural regeneration of native trees, and provide greater water quality protection through sediment and nutrient filtration (see, for example, Hilty and Merenlender 2004, Castelle et al. 1994, and Lee et al. 2004).
2-13	2-F – In order to reduce potential wildfire impacts to wildlife and habitat, the Specific Plan needs to include managing human activities and limiting ignition potential as one of its key strategies. Measures to limit human-caused ignition should be central to residential and recreational site regulations and agricultural use policies. Policy 2-31 Fire buffers appear to encompass areas of sensitive habitat including Oregon oak woodland, valley oak woodland, and riparian forest. How will fire buffer development affect the health and quality of these sensitive vegetation types (e.g., understory diversity, natural regeneration potential, potential incursion of weeds, increased solar exposure, etc.)? How will those impacts be mitigated? These

	potential impacts need to be evaluated fully in the EIR to ensure they will be less than significant. Policy 2-32 – There seem to be some missing words in the second sentence between "Loose surface litter…shall be permitted…in order to ensure" and "the removal of trees, bushes, shrubs…". Please clarify. Retaining some surface litter is necessary to protect soil health, prevent erosion, allow for natural regeneration of native plants, and support reptiles, amphibians, and other wildlife.
2-14	Policy 2-34 – The Fuel Separation standard provides only *minimum* clearance distances. Based on this guideline, all native vegetation in this zone could potentially be removed, having a significant impact on biological resources. In order to ensure that the impact of fuel management is less than significant, the Specific Plan must identify an upper limit to the amount of clearing of native vegetation, so that as much native vegetation may be retained as possible while meeting specific fuel reduction objectives. The EIR must also evaluate the impacts from the implementation of these standards to ensure they will actually be less than significant or will be mitigated to less-than-significant levels. How will the likelihood of ignition from human causes be managed? No policies currently address this essential topic.
Chapter 4 – Land Use	
Page	*Comment*
4-8	The Parks and Recreation land use type description includes dog parks as one use type. Limiting dog presence on the site will be necessary to avoid impacts to wildlife permeability of the site. Policy 6-4 indicates that a dog park will be provided within Core Campus, at least 200' from any creeks or wildlife corridors. This 200' limitation will be valuable in reducing impacts to wildlife. Based on the Land Use diagram (Figure 4.1-2), the Ballfields, Central Green, and one area east of the creek are the only "Park" areas more than 200' from creeks. The Park area east of the creek appears to be within existing riparian habitat along Sonoma Creek, which would not be suitable for a dog park (or any other highly developed park type). Areas within the Ballfields zone, or elsewhere within the Residential or Flex Zones on the west side of Arnold Drive, would be most suitable for a small dog park.
4-14 – 4-16 Table 4-3: Permitted Uses	The table indicates that agricultural crop production and agricultural processing, as well as keeping farm animals, is permitted in both "Buffer Open Space" and "Preserved Open Space." Keeping confined farm animals, mushroom farming, and timberland conversion are also permitted in "Preserved Open Space." In PCI's experience, these types of activities are often incompatible with open space preservation because they often eliminate most or all natural vegetation, often involve construction of built facilities, and frequently exclude or reduce wildlife with fencing, trapping and other measures. How does the County envision these activities occurring in a manner compatible with open space preservation? How will needs to restrict cattle or other farm animal movement, within open space areas, be aligned with maintaining wildlife permeability?

	The table further indicates that an array of other intensive agricultural uses, including farm retail sales, indoor crop cultivation, wholesale nursery, and tasting rooms are all permitted in "Preserved Open Space." These uses are not compatible with open space preservation because they entail built facilities and removal of natural vegetation. These uses should not be permitted in Preserved Open Space. How will the potential impacts of these permitted uses be evaluated in the future? Similarly, outdoor recreation facilities and "rural sports and recreation" facilities are potentially permittable in Preserved Open Space. What types of facilities will these include? A clear explanation of this use type is needed to allow determination of potentially significant impacts to wildlife. Uses such as Frisbee golf, zip lines, and off-road vehicle use all have potential to reduce wildlife usage via habitat damage and increased human activity levels, and must be analyzed by the EIR. The table indicates that geothermal resource development, parking facilities, and public utility facilities may all also be located within Preserved Open Space. These are potentially extensive facilities that may also be incompatible with meaningful open space preservation because they entail removal of natural vegetation, construction of new buildings and other infrastructure, and a potentially heightened level of human presence and activity. They should not be permitted within Preserved Open Space unless greater detail can be provided in this Specific Plan, showing where they could be located, how extensive they are, allowing for analysis of impacts to wildlife and other biological resources in the EIR.
Chapter 5 – Community Design	
Page	*Comment*
5-4	The last paragraph indicates that sycamores will line principal axes, and other primarily deciduous canopy trees will be used on other streets. The Specific Plan should prioritize the use of native trees and other native plants for landscaping where they align with the ornamental setting, because they are well-adapted to local climate, require less water and chemical inputs to thrive, and provide habitat benefits (food resources, cover, and nesting opportunities) for the greatest variety of native animal species . Valley oaks, which form an important part of the core campus landscape already in the southwestern section, as well as coast live oak, should be incorporated where space allows to sustain oaks as a long-term element of the campus, help ameliorate historic losses of sensitive valley oak habitat, and support the many species of native birds, mammals, amphibians and invertebrates that rely on native oaks. This will also help meet Policy 5-1, establishing tree-lined avenues "..that complement the surrounding hills and open space landscape."
5-15	This section should include a statement specific to lighting meeting Dark Sky standards; this is mentioned only in passing in Policy 5-13 and should be made its own policy, to ensure cross-referencing with Policy 2-7. See comments on page 2-11, above, for further discussion.
6-9	Policy 6-4 regarding a dog park: see comment on page 4-8, above.

Adequacy of Environmental Impact Report Biological Resources Evaluation

Introduction

Page	*Comment*
p. 45 NOP and Baseline	The baseline appears to vary between sections in the EIR. For example, it appears the Transportation section may use 2019 as baseline and the Biology Section uses a different baseline. Without a proper baseline, impact analyses cannot be evaluated. Identifying an appropriate baseline is particularly important for impacts relating to intensity of human uses and presence on the site, since the population of SDC has declined so dramatically in recent years as SDC ceased operations and closed. What is the specific baseline condition used for each section of the EIR?

Section 3.4 – Biological Resources

Page	*Comment*
p. 203, paragraph 1, last sentence	"The section describes biological resources in the Planning Area (which includes the project area for the SDC), including habitats, wetlands, critical habitat, and special-status species, as well as relevant federal, State, and local regulations and programs." This section does *not* actually address potential impacts and proposed mitigation measures needed to reduce potential impacts to less–than-significant levels. In order to fully address and mitigate potential impacts on biological resources, the EIR needs to evaluate potential construction-related and operational impacts from implementation of the Specific Plan on individual species, habitats for those species across the SDC area, natural vegetation communities, movement corridors, wetland disturbance and loss, and compliance with applicable policies use.
p. 209 Sonoma County Code, Riparian and Creek Standards	This section does not mention the 50' minimum setback from streams designated by the Riparian Corridor zoning for this site. Instead, smaller setbacks are described in the first paragraph. Is the 50' minimum setback not being applied in the Plan? Reducing the width of riparian and creek setbacks could disrupt animal movement by reducing the width of animal dispersal corridors and disrupting movement through the loss of habitat, increased noise and light disturbance within the corridor, and from human or domestic animal intrusion. The EIR must evaluate the potential impacts on biological resources from a reduction in the riparian and creek setback widths and mitigate the impacts of whatever setbacks it employs to ensure that those impacts are less than significant.
p. 210 Valley Oak Habitat Combining District.	This states that measures shall be taken to "protect and enhance valley oaks on the project site" and such measures shall include, but not be limited to, a requirement that valley oaks shall comprise a minimum of fifty percent of the required landscape trees for the development project. But the Proposed Plan contains no such requirement. The EIR states that the Proposed Plan would have a significant impact on biological resources if, among other things, "Implementation of the Proposed Plan would … conflict with any local policies or ordinances protecting biological resources, such as a tree preservation policy or ordinance" (EIR, page 257, Impact 3.4-5). In order to ensure that impacts on valley oak habitat are less than significant, the Specific Plan must include a policy implementing the requirements of the Valley Oak Habitat Combining District. The policy must be added to ensure development does

	not conflict with the zoning requirements for the protection of valley oak habitat. The EIR must then analyze fully the impacts of that policy.
p. 211 Habitat Types, second paragraph.	Here and on p. 221, PCI's work on the Existing Conditions Report is cited as PCI (2015). PCI's work and the report as a whole (prepared by WRT) was completed in 2018. The document is available here: https://transformsdc.files.wordpress.com/2020/01/2-cnaturallandrecreationalresourcesv3.pdf Second paragraph also indicates that habitat types described are from the California Wildlife Habitat Relationships System. That is incorrect. PCI (2018) and all mapping associated with it use the Manual of California Vegetation-based classification refined by the Sonoma Veg Map project, which provides the more detailed and more precise classification needed to identify potential impacts on sensitive habitat types as required by CEQA. Please correct here and on relevant maps.
p. 212 Figure 3.4-1, Habitat Types map.	The large wetland on the east side of the habitat map is incorrectly labeled as vernal pool. This should be labeled seasonal wetland or wet meadow.
p. 214, Coast Redwood Forest	The first line notes that redwood forest is not considered sensitive in Holland (1986); Holland (1986) is not considered a current reference for sensitive habitat designations and therefore does not constitute substantial evidence of sensitive habitat designations. In order to accurately determine sensitive habitat designations and analyze impacts to those habitats, the EIR must use current rankings by CDFW for sensitive alliances and provide that information for each of the plant communities listed. Note that rankings of G3 or S3 or lower are considered sensitive. Because the EIR failed to rely on up-to-date evidence, the EIR failed to acknowledge that redwood forest is considered a sensitive habitat. In fact, based on PCI (2018), CDFW-ranked sensitive alliances on the site include redwood forest, madrone forest, Oregon oak woodland, valley oak woodland, bigleaf maple forest, cottonwood forest, riparian deciduous forest, native grasslands, and wetlands. The EIR needs to include a map showing all sensitive vegetation types for use in analyzing impacts in the EIR so that decision-makers and the public can fully understand the scope and location of sensitive habitat types and the Project's impacts on sensitive habitat types. Valley oak woodland is of particular concern since it occurs within and adjacent to the core campus, and protections will be needed to reduce impacts to less-than-significant levels.
p. 219 Wetlands and Vernal Pools section, paragraph 2.	Vernal pools are mentioned in the title and third sentence, and on map 3.4-1. Vernal pools are highly sensitive, specialized wetland types that, if present, would need to be included in the discussion of impacts in the EIR. Mitigation measures specific to vernal pools would also be required. It should be noted that no vernal pools have been identified in prior work (PCI 2018, Sonoma Veg Map). What substantial evidence does the County have with respect to the presence of vernal pools? Please clarify. The EIR also fails to analyze the potential impacts on the wetlands in the area from the proposed Highway 12 connector or any other proposed Plan elements. The

	impacts analysis needs to address the direct and indirect impacts of the development on wetlands within the Specific Plan area before the EIR can conclude that any impacts would be less than significant.
p. 220 Line 1	The EIR identifies *Lindera benzoin* as present on the site but this species is not known to occur in California. If the EIR intended to reference *Calycanthus occidentalis*, please correct.
p. 221-225, Special-status Animal Species.	The list includes 28 species with moderate to high potential to occur. However, the EIR fails to provide a map showing the location of the habitat necessary for the species; therefore, decision-makers and the public cannot determine what specific elements of the project may impact habitat that could support the various species listed. The EIR needs to address the potential impacts to each species on a species-by-species basis. Without a species-by-species analysis, it is impossible to determine whether and to what degree development associated with the Proposed Plan would result in potential impacts within the habitat areas presented in Table 3.4-2: Potential Special-status Wildlife. And without full analysis, it is impossible to determine what mitigation is required to reduce those impacts to less-than-significant levels. How will impacts to habitat impact the listed species and what mitigation measures are proposed to reduce the potential impact? The EIR also omits data about known occurrences of special status species on the Project site. For example, the entry for northern western pond turtle does not indicate that the species has been documented to occur on the site (see PCI 2018 for detail). The EIR's failure to survey the site for special status species or to include data regarding known occurrences prevents the EIR from fully identifying or mitigating possible impacts to special status species. The EIR fails to address the mountain lion, which is designated as a "Specially Protected Mammal" by CDFW, is a species of high local conservation concern, and is known to use the SDC site extensively. Central Coast and Southern California populations are currently under review for listing under the California Endangered Species Act. Some of the same pressures threatening mountain lions in those areas – including habitat fragmentation – are highly relevant to the population in the SDC region as well, especially in long-range planning for increased land development. Development of the types proposed in the Draft Specific Plan may have the potential to significantly impact mountain lion habitat and movement. It is, therefore, foreseeable that the Specific Plan could have a significant impact on mountain lions under significance Criterion 1 ("Have a substantial adverse effect, either directly or through habitat modifications, on any species identified as a candidate, sensitive, or special-status species in local or regional plans, policies, or regulations, or by the California Department of Fish and Game or U.S. Fish and Wildlife Service") or significance Criterion 4 ("Interfere substantially with the movement of any native resident or migratory fish or wildlife species or with established native resident or migratory wildlife corridors, or impede the use of native wildlife nursery sites"). The EIR must specifically analyze and mitigate for impacts to mountain lions to ensure any such impacts would be less than significant.

p. 228, Table 3.4-3. Potential Special-status Plants.	The table identifies the potential habitat for special-status plants in the planning area, but it fails to disclose where potential impacts might overlap with areas within the Specific Plan. For example, there is no way to tell based on the EIR where the areas of potential development (including uses permitted within "Preserve Open Space" such as indoor crop cultivation and utility development) would occur in relation to the habitat for special-status plants. Nor is it possible to discern what the potential impacts to special status plants and their habitat might be, or what specific mitigation would reduce those impacts. As drafted, substantial evidence and analysis do not support the EIR's conclusion that impacts to special status plants would be less than significant.
p. 234, Sensitive Habitats.	The EIR fails to clearly evaluate sensitive plant communities other than wetlands. The scientific community considers several other habitat types that are present at SDC to be sensitive. See PCI (2018); see also comment on p. 214 and following, above. The EIR cannot justify its conclusion that impacts on sensitive habitats will be less than significant without clearly analyzing and mitigating impacts to all relevant sensitive plant communities.
p. 235, Wildlife Corridors, last sentence, and Impact 3.4-4 p. 254-255	Riparian corridors serve as important movement routes for many species other than steelhead, including many mammals, birds, amphibians, and reptiles. Please adjust wording. Mill and Asbury Creek serve as important corridors as well. The EIR must fully identify and analyze the impacts to all wildlife corridors on the SDC site, including Mill and Asbury Creeks. This section fails to provide a map of all wildlife movement corridors showing where all proposed plan development may be located in relation to the corridors and the EIR fails to identify what, specifically, the direct and indirect impacts on wildlife use of the existing corridors might be under Impact 3.4-4 starting on page 254. What are the potential impacts from habitat loss or alteration, noise, light, human presence, dog presence, and fragmentation by roads that may impact wildlife use of the corridor and what mitigation measures are proposed to reduce the specific impacts? Without identifying, analyzing, and mitigating specific impacts to wildlife corridors, the EIR lacks substantial evidence or explanation to justify its conclusion that those impacts would be less than significant. How will the proposed Class I pathway indicated on Figure 3.2-1, shown leading toward Sonoma Creek from Walnut Street, affect the wildlife corridor and sensitive riparian habitat? What measures will be in place to limit or mitigate for these impacts? Without identifying, analyzing, and mitigating specific impacts of the Class I pathway, the EIR lacks substantial evidence or explanation to justify its conclusion that those impacts would be less than significant. Two options for connector roads are shown in Specific Plan Figure 3.1-1, and three types of facilities (a direct connection to Highway 12, an emergency access connection, and a pedestrian/bike connection) are all alluded to in accompanying text. In addition, Policy 3-44 calls for development of the Sonoma Valley Trail (multi-use path) parallel to Highway 12. However, the EIR does not disclose or analyze the specific impacts of each of those proposed options. What will be the direct, indirect,

	and cumulative impacts of all these elements on biological resources, including wetlands, drainages, Butler Canyon Creek, and wildlife movement through existing undercrossings? Without identifying, analyzing, and mitigating specific impacts of the connector road(s), the EIR lacks substantial evidence or explanation to justify its conclusion that those impacts would be less than significant.
p. 236 Evaluation Criteria	The EIR's chosen thresholds of significance are not sufficiently specific to enable decision-makers or the public to understand, in practical terms, what it means for the Specific Plan to have a significant or less-than-significant impact on biological resources. Further, the EIR fails to explain how the County chose or developed its significance criteria, or to justify why these specific criteria were selected while others were omitted. The EIR cannot fulfill its role as an informational document unless it provides additional information regarding its significance thresholds. For example: Criterion 1. How does the EIR define substantial adverse effect for *each* candidate, sensitive, or special-status species present or potentially present in the Specific Plan area? What was the process used to determine if implementation of the proposed Plan will substantially affect specific species? How does this criterion address a potential change in species diversity and abundance that could occur from the implementation of the Specific Plan? How is a potential change in the quantity and quality of native habitat used by the biological resources addressed under this criterion and what is the significance threshold to evaluate impacts of a change? Criterion 2. What does the EIR evaluation consider a substantial adverse effect on riparian habitat or other sensitive natural communities? This is not articulated, and therefore, how can impacts be determined? What are the sensitive natural communities present in the planning area and within the development area, including the Highway 12 connector? Criterion 5. How is a potential conflict with policies and ordinances evaluated in terms of protected biological resources? What would constitute a significant impact and how would the impacts be mitigated to less-than-significant levels?
p. 236. Methodology and Assumptions, first sentence.	Why was the analysis of impacts limited to a comparison against Figure 3.4-1 when there are additional resources presented in the EIR? Figures 3.2-1 through 3.2-4 provide significantly more information for use in the analysis of impacts in the Biological Resources section. These figures illustrate locations within the planning area that support riparian forest types, evergreen and redwood forest types, and oak woodlands at a scale far more useful for impact evaluation. Portions of 3.4-1 also to be incorrect (see comment above on p. 212).
p. 236. Methodology and Assumptions, third sentence.	This section states that the plans' land use designations would not directly, adversely affect areas of natural vegetation. This conclusion is inappropriate for the "Methodology and Assumptions" section. Where is the analysis of how land use designations would relate to natural vegetation? For instance, how will land use types such as managed landscape and fire buffer affect natural vegetation? How will permitted uses in "Preserved Open Space" such as crop production, keeping of confined farm animals, and wine tasting facilities (as stated in Table 4.3-1) affect

	natural vegetation? Without first answering these and other questions, the EIR cannot support its conclusion with analysis and substantial evidence. The impacts of the proposed Plan's land use designations are the only aspect of the Plan evaluated in the Biological Resources Section. This approach is inconsistent with other sections of the EIR that evaluate potential impacts from construction of projects within the Specific Plan area. For instance, construction emissions are evaluated in the Air Quality section addressing potential construction emissions from a new road connection to Highway 12. The fact that the proposed Plan is programmatic and does not include any specific development projects does not excuse the EIR from including an evaluation of any specific potential construction/development on biological resources. The potential locations of specific development types are shown on figures included in the EIR and the Specific Plan. The draft Specific Plan is, therefore, sufficiently detailed to allow analysis of at least some of these specific impacts at the programmatic stage. The EIR needs include potential impacts from construction and use of a connector to Highway 12 so that decision-makers and the public can determine now—when the County is proposing to lock in these uses—whether these uses will have significant impacts to biological resources and how those impacts could be mitigated.
p. 236. Section 3.4.3.2, fourth sentence.	How can the EIR make the conclusion that the proposed Highway 12 connector and the upgraded wastewater treatment plant would not adversely affect areas of natural vegetation? There is no analysis or substantial presented to support the conclusion. In addition, how can potential conditions of approval reduce impacts? Please articulate why BIO 1 through 14 are not considered mitigations. What are the potential impacts should the County not include the conditions of approval as proposed, and what mitigation measures would be needed to reduce impacts to less-than significant-levels?
p. 237 Goal 2-D.	While the methods of "intentional water and energy conservation, sustainable food productions, top-tier sustainable building practices, and aggressive waste reduction" seem like valuable strategies for general sustainability of site operations, it is not clear whether or how these methods would "promote conservation of existing habitat" on the site. Further, the EIR does not clearly evaluate the details or efficacy of any of these methods with respect to whether or how they could reduce impacts to biological resources. Please clarify and address.
p. 238 Policy 2-9	The policy states that the defensible space requirements of the County Fire Department should be met but not exceeded in the wildlife corridor. What are the County standards for defensible space and what are the impacts on biological resources from implementation of the defensible space requirements? The impacts should be evaluated under Impact 3.4-4 and 3.4-2 at a minimum but may also require evaluation for potential impacts on special-status plants. What mitigation measures would be needed to reduce impacts on biological resources from implementation of defensible space requirements? What could be the impact is defensible space standards must be exceeded and what mitigation would be needed if the impacts are significant?
p. 238 Policy 2-11	Policy 2-11. Dark skies standards need to apply to the private realm as well as public setting, and should apply all new lighting, not just for new buildings. See comments

	on Specific Plan p. 2-11, above. The impacts of lighting on wildlife need to be addressed in the EIR. The EIR must evaluate how wildlife species modify their behavior as a result of increased nighttime light within wildlife corridors and other habitat and how increased light may alter nocturnal ecology within the Specific Plan area. Studies indicate increased light can disrupt foraging behavior and increase the risk of predation, increase roadkill of mammals, and disrupt dispersal movements and corridor use (Rich & Longcore eds. 2006). Nighttime light may prevent wildlife from fully using habitat available to them and light can prevent mammals from moving along wildlife corridors. Nighttime light can attract animals and result in altered wildlife movement patterns; these changes can expose prey to predators and make them more vulnerable to capture, thereby reducing species abundance and diversity in the area. See comment on Specific Plan, p. 2-11, above. This comment provides a partial list of potential wildlife impacts from increased light; many other potential impacts may occur. The EIR must evaluate potential impacts and evaluate what level of light pollution might trigger impacts to sensitive species or species movement. How are the potential changes evaluated for the potentially affected species? Habitat modifications must be evaluated in Biology Criteria 1 and 4 to determine how the project may affect wildlife species and how changes may affect the use of movement corridors. The analysis must identify how these potential impacts were evaluated and what mitigation measures are needed to reduce impacts to less-than-significant levels.
p. 238. Policy 2-16.	This fencing standard will be very important in reducing impacts to wildlife. Will this be required for all agricultural uses within the "Preserved Open Space" as well? Please state if so. If not, impacts on wildlife movement should be re-evaluated to ensure that fencing-related impacts will remain less than significant. Are there locations where fencing will not be allowed because potential impact on wildlife movement cannot be reduced to less-than-significant levels? These areas must be identified in the EIR as a means to reduce impacts to less-than-significant levels.
p. 239 Policy 2-17,	This noise standard is vague and unenforceable. It does not include a specific commitment to lower noise levels. Requirements to meet residential noise standards, during both day and night, need be addressed and the impacts of not meeting such standards needs to be evaluated. Biology Criterion 1 says a significant impact would occur if the Project would have a substantial adverse effect on any special-status species; therefore, the EIR must address the biological impacts resulting from noise and specifically address the impacts of non-attainment of noise standards. How will increased noise impact species that communicate acoustically such birds and bats that use habitat at SDC? How will noise affect animal physiology and behavior, and how would those changes impact special-status species? These impacts must be addressed in Biology Criterion 1 to understand how noise may impact special-status species, what noise levels would cause the impact, and what mitigation measures would be used to reduce the impacts to less-than-significant levels. Noise impacts on potential changes in wildlife use of corridors must be addressed under Biology Criterion 4 to provide an understanding of how noise may affect movement, and what mitigation measures are proposed to reduce the potential impacts to less-than-significant levels. How will the County determine if

	noise impacts occur? Without this critical information, the EIR does not have sufficient evidence to conclude that impacts to special status species would be less than significant.
p. 239 Policy 2-24 Policy 2-25.	Why is Asbury Creek not included as protected with a 50' buffer? What are the potential impacts to Asbury Creek from the lack of an adequate buffer? This stream provides significant habitat values and merits protection. It needs to be protected. If it will not be included within a buffer, the EIR must analyze and mitigate impacts to Asbury Creek to ensure those impacts remain less than significant.
p. 240, Section 3.4.3.4 Impacts Summary of Proposed Plan.	The EIR's summary of impacts in the Biology Section does not permit the level of granular analysis that is required to fully understand the impacts of the draft Specific Plan, particularly in light of the Specific Plan's level of detail and specificity. As such, the analysis of impacts on biological resources risks is missing key impacts that may not be analyzed fully in later environmental review.
p. 241. First full sentence	The first full sentence on this page states that "development is not proposed to occur within Preserved Open Space." However, this conflicts with the Specific Plan (p. 4-14 and following), which permits certain uses in that zone including tasting rooms, mushroom farms, utility development, and parking. Which is correct? If the Specific Plan is correct, the EIR must analyze the biological impacts from those permitted uses and mitigate any impacts to less-than-significant levels. Similarly, the EIR fails to explain how the Conditions of Approval would mitigate the negative impact of the Highway 12 connector on wildlife movement. Nor does the EIR disclose the potential impacts of the wastewater treatment plant, or what types of mitigation would be appropriate to reduce those impacts. Without an analysis and supporting evidence, decision-makers and the public cannot independently judge the EIR's unsupported conclusion that these impacts would be less than significant.
p. 241. Impact 3.4-1. Paragraph 1 last sentence.	This sentence states that future development under the Proposed Plan could have a significant direct or indirect impact on any special-status species if it would result in removal or degradation of a species or potentially suitable habitat. But the EIR does not contain any performance standards by which one could judge whether removal or degradation of a species or potentially suitable habitat has occurred. Please define what is meant by removal and what is meant by degradation. Does removal mean loss of one individual special-status plant or animal? Would a significant impact occur should a special-status species no longer utilize habitat following increased human-animal interactions following site development? This is only an example of how impacts may be defined and how the undefined terms of removal or degradation are problematic as used in the EIR context.
p. 241. Impact 3.4-1, Construction third sentence.	The EIR states that potentially significant impacts could occur if *significant* amounts of habitat loss occurs. But what constitutes "significant" amounts of habitat loss varies by species? What does the EIR consider to be significant habitat loss for the special-status species present and potentially present at the site? How will the County determine whether a significant amount of habitat loss has occurred for each species? Without this critical information, the EIR does not have sufficient evidence to conclude that impacts to special status species would be less than significant. Why are all species lumped into a single evaluation paragraph and not discussed individually? The impacts to special-status species will vary on a species-by-species

	basis and need to be analyzed individually. Without species-by-species analysis, the EIR cannot disclose what the specific impacts to each species might be or determine how those impacts should be mitigated. Where will grading, excavation, and construction activities likely occur and what species may be affected in these locations? The Specific Plan clearly identifies where development should be sited. The EIR needs to be at least as detailed as the Specific Plan in order to capture the known foreseeable impacts of the project. What specific species could be impacted with construction of the Highway 12 connector? How can the species be impacted from this activity and what are the mitigation measures needed to reduce the potential impacts to less-than-significant levels? Once mitigation measures are identified, the EIR must address how the mitigation measures reduce the impact on a measure-by-measure basis.
p. 241. Construction.	How does the EIR evaluate the potential biological resource impacts of the alternatives in relation to the potential construction impacts from the proposed plan?
p. 241. Operations.	What specifically are the potential increased risks to special-status species from the operation of individual parts of the Proposed Plan? Individual special-status species occur in different locations around the SDC site. Some will necessarily be more affected by particular aspects of the Specific Plan depending on where the Specific Plan locates particular uses. The location of proposed uses is known based on the current draft Specific Plan. The EIR therefore needs to analyze the operational impacts of specific proposed uses on the special-status species in their vicinity before it can draw any conclusions about the significance of those impacts. What are the potential impacts from increased vehicular traffic and recreational use and to which species may these impact occur? What mitigation measures are needed to reduce these impacts? Multiple studies have found that increased vehicle traffic, increased density of human uses, and increased human activity levels, including trail development and use and dog presence, can reduce or alter habitat use by key wildlife species on SDC including mountain lions and bobcats (see for example Wilmers et al. 2021, Serieys et al. 2021, Smith et al. 2019, and Nickel et al. 2020). Increased visitor use along trails across SDC may alter behaviors and cause some species to avoid those areas. Mitigation measures may include visitor education and requiring all visitors stay on established trails, minimize excessive noise, and keeping dogs on leash at all times. The County must identify areas where mitigation measures may not reduce impacts to less-than-significant levels and consider other means to reduce impacts, such as prohibiting dogs in areas that cannot accommodate their presence. Identification of areas where trail densities might already impact wildlife and identifying redundant trails to eliminate must be explored and analyzed in the EIR. What proposed plan elements have the potential to directly impact streams and the surrounding habitats and how might this impact individual species that depend on

	the habitat impacted? How do the policies presented protect these resources and what are the remaining impacts following implementation of the policies? What are the mitigation measures proposed to reduce the potential impacts and how will the mitigation measure reduce the impact?
p. 242. Operations.	What elements of the proposed plan might result in a significant reduction in forest extent and quality and how will these potential impacts be reduced to less–than-significant levels? How does the County define a “significant” reduction in extent and quality? Do these potential impacts vary by alternatives to the proposed plan?
p. 242. Operations.	What proposed plan elements in open grasslands might impact American badger and burrowing owls? Development and increased human use in open grassland that support habitat for these species may result in the loss of nesting and foraging habitat, and direct mortality. BIO-3 identifies means to avoid American badger dens during development to avoid direct mortality; however, it does not address the impacts associated with loss of habitat. BIO-5 includes relocation measures for burrowing owl; however, the EIR does not address potential impacts from loss of habitat, such as reduced population numbers and the potential for burrowing owls to avoid use of potential nesting and foraging habitat located adjacent to developed areas. The EIR must evaluate impacts that result from human presence, such as loss of habitat and potential abandonment of nests resulting from human presence. How will the County determine if these impacts occur following development and how will the County protect the species? What are the mitigation measures needed to reduce the potential impacts on American badger and burrowing owl habitat loss?
p. 242. Operations, second paragraph.	The EIR states that “Outside of the developed areas, the Proposed Plan establishes dedicated open space areas. Managed open space in these areas would preserve and, in some cases, enhance the quality of sensitive habitats such as wetlands, native grasslands and oak woodlands. Several special-status wildlife and some plant species would be positively impacted by the preservation of these habitats. The open space would preserve the Sonoma Valley Wildlife Corridor and maintain its permeability for the movement of wildlife at a regional scale.” .
p. 242, third paragraph.	How do policies reduce impacts on special-status species? The EIR makes statements without providing supporting discussion or explaining the methods used. As a result, decision-makers and the public cannot independently evaluate the adequacy of the EIR’s analysis or the veracity of its conclusions. What are the impacts from development that the policies address and what impacts remain after the policies are all implemented? What mitigation measures are proposed to address impacts remaining after implementation of policies? How will the County measure the efficacy of the policies and any mitigation measures?
p. 242. Last paragraph.	Why are the requirements listed as conditions of approval and not as necessary mitigation measures and how does each condition of approval reduce specific impacts? The EIR effectively admits that these requirements are needed to reduce impacts to less-than-significant levels. The EIR needs to analyze the project’s unmitigated impacts and then identify impact-reducing policies as mitigation measures. It must also include those mitigation measures in a mitigation monitoring and reporting program to ensure they are effective and enforced. The approach used

	in the Biological Resources section failed to do this and is inexplicably inconsistent with the methodology used in other sections of the EIR.
p. 242	Conditions of Approval policies appear to relate only to the construction phase. Where is the analysis of impacts on special-status species associated with operations? How will the effects of ongoing site use and facility operation be reduced to less than significant? Without clearly defined and enforceable mitigation, the EIR provides no assurance that the operational impacts of the Specific Plan would be reduced to less-than-significant levels. The EIR fails to identify potential impacts on special-status species from dog use at Suttonfield Lake. As such, the EIR cannot determine what mitigation measures are necessary to reduce those impacts to less-than-significant levels.
p. 245. Standard Conditions of Approval BIO-2.	The EIR fails to identify which proposed plan elements could impact special-status bats and their habitat. What happens if the survey indicates that bats inhabit a building that is scheduled for demolition? How will the bats be evacuated from the building and how will they be prevented from reoccupying the site? How will the proposed mitigation prevent impacts?
p. 245. Standard Conditions of Approval BIO-3.	The EIR fails to identify which proposed plan elements could impact American badger. What are the potential impacts in open grassland? How will this mitigation prevent impacts and how will the County evaluate the efficacy of the measure?
p. 246. Standard Conditions of Approval BIO-4.	Is BIO-4 only needed during construction? Are there any potential impacts on nesting raptors from project operations? How will the proposed mitigation prevent impacts and how will the County determine the efficacy of the measure? BIO 4 does not specify that pre-construction survey work needs to be completed by a qualified biologist. All construction-related wildlife surveys needs to be completed by a biologist. The measure defines an “active nest” as having eggs or nestlings present. Some interpretations of the Fish and Game Code include nest building as active nesting. The definition of “active nest” here needs to incorporate nest building.
p. 246. Standard Conditions of Approval BIO-5.	The EIR fails to identify the specific potential impacts to burrowing owls. What are the potential impacts in owl habitat and what habitat do they use in the proposed plan area? How will the proposed mitigation prevent impacts? BIO 5 does not specify that pre-construction survey work needs to be completed by a qualified biologist. All construction-related wildlife surveys need to be completed by a biologist. The measure defines an “active nest” as having eggs or nestlings present. Some interpretations of the Fish and Game Code include nest building as active nesting. The definition of “active nest” here needs to incorporate nest building.
p. 247. Standard Conditions of Approval BIO-6.	The EIR fails to identify proposed plan activities that might impact northern spotted owls. What activities might occur within riparian, evergreen and/or oak forests where owls may nest? Please explain how the acquisition of a permit reduces the impact on owls to less-than-significant levels.
p. 247. Standard Conditions of	What is the proposed work that might occur near Fern Lake and Suttonfield Lake that might impact tricolored blackbird? How will the mitigation measure prevent impacts?

Approval BIO-7.	
p. 247. Standard Conditions of Approval BIO-8.	The measure defines an "active nest" as having eggs or nestlings present. Some interpretations of the Fish and Game Code include nest building as active nesting. The definition of "active nest" here needs to incorporate nest building.
p. 248 – 249. Standard Conditions of Approval BIO-9 through BIO 11.	The EIR fails to identify which proposed plan elements could result in direct impacts to aquatic features and result in the loss of habitat or cause harm to individuals. What will those direct impacts be and how will the mitigation prevent these impacts?
p. 249. Standard Conditions of Approval BIO-11.	Why are the measures limited to potential work within 300 feet of a channel when USFWS mandates measures to protect California red-legged frogs across CRLF habitat, not only within 300 feet of an aquatic feature? The EIR needs to identify protection measures for CRLF habitat outside 300 feet.
p. 250. Standard Conditions of Approval BIO-9 through BIO 12.	The EIR fails to identify which proposed plan elements could result in direct impacts to freshwater shrimp and salmonids and result in the loss of habitat or cause harm to individuals. How will the mitigation prevent these impacts? Why are the requirements listed not considered mitigation? What is necessary to prevent the loss of freshwater shrimp habitat and what compensatory mitigation may be necessary in the event a proposed planned element results in loss of habitat?
p. 250-251. Standard Conditions of Approval BIO-13.	What process will be required if a special-status plant cannot be avoided? What specific mitigation is necessary and how will that mitigation reduce the potential impact? How will the County monitor the efficacy of the mitigation?
p. 251. Impact 3.4-2. Construction. Sentence 1.	The EIR notes development would take place in previously developed portions and concludes that will limit potential for disruption to undeveloped habitats. Where within the SDC property will riparian habitat and other sensitive natural communities be directly or indirectly impacted by implementation of the proposed plan? The EIR must support its conclusions with substantial evidence and thorough analysis.
p. 252 Construction	The first full sentence states that no new building development is proposed to occur within open space areas. However, this conflicts with the Specific Plan (p. 4-14 and following), which permits uses in that zone including tasting rooms, mushroom farms, utility development, and parking. Which is correct? This section must analyze the specific impacts from all uses permitted under the Specific Plan. The first paragraph states that "implementation of the Proposed Plan may result in the degradation or removal of riparian habitat" and that such projects will require measures to reduce, avoid, or compensate for impacts. The EIR needs to identify these impacts as potentially significant, and must design and analyze appropriate mitigation measures. At present, the EIR does nothing to ensure that these impacts would actually be mitigated to less-than-significant levels.

p. 252. Paragraph 2.	BIO-1 though BIO-14 address special-status wildlife species. It is not clear from the EIR whether or how these policies would reduce the impact on riparian habitat or other sensitive natural communities to less-than-significant levels. The EIR needs to explain how individual species protection measures protect riparian or sensitive natural communities in general? What are the mitigations necessary for the loss of riparian habitat? How will development impact sensitive valley oak habitat? What will the impacts from the increased presence of people and pets be on wildlife in valley oak habitat? The EIR needs to discuss these impacts and analyze in sufficient detail how these impacts will be mitigated to less-than-significant levels.
p. 252. Paragraph 3.	The EIR fails to identify the specific impacts on riparian and sensitive natural communities from the two public infrastructure projects? What specifically could be impacted and which sensitive natural communities could be present in the construction area? How would BIO-1 through BIO-14, which address special-status species, reduce these impacts? What are the specific mitigations needed in the event the project results in the loss of riparian habitat or sensitive natural communities? How specifically do the policies listed reduce the impacts?
p. 252. Operations.	Is there new trail construction included as part of the project? If so, the potential impacts on riparian and sensitive natural vegetation must be analyzed and mitigated.
p. 252. Operations.	The EIR fails to disclose the potential impact of increased vehicle trips be on individual wildlife species. This impact must be analyzed fully. At present, there is not sufficient evidence or analysis to indicate whether or how this impact would be mitigated to a less-than-significant level.
p. 253. BIO-14.	BIO-14 is deferred mitigation. The EIR must expand on what might be included in an aquatic resources mitigation plan and describe how development of this plan will reduce impacts to less-than-significant levels. The EIR must provide clear performance standards that any future mitigation plan must meet.
p. 253. Impact 3.4.3, Construction, paragraph 1.	The analysis indicates a potentially significant impact could occur if construction impacts federally protected wetlands. This analysis improperly excludes wetlands that fall under State jurisdiction without justification. Figure 3.4-1 serves as the basis for the location of known wetlands and vernal pools (but see comments on potential errors in that figure, above). What are the proposed plan elements that could potentially cause the impact and why was this analysis not provided? It further appears the Highway 12 connectors could impact a large mapped wetland (incorrectly shown as vernal pool). These potential impacts are not analyzed in the EIR. The EIR must analyze and mitigate all foreseeable potentially significant impacts, including impacts related to the Highway 12 connector(s).
p. 253. Construction, paragraph 2.	The EIR fails to identify performance standards for its de factor proposed mitigation. What are the requirements in the permits that would mitigate impacts? Why are these measures not included as mitigation(s) in the EIR? How, specifically, will these measures mitigate the impact?
p. 254	Operation. The first sentence states that no new building development is proposed to occur within open space areas. However, this conflicts with the Specific Plan (p. 4-14 and following), which permits uses in that zone including tasting rooms, mushroom farms, utility development, and parking. Which is correct? The EIR must

	analyze the specific impacts from all uses permitted under the Specific Plan before it can determine whether those impacts will be significant.
p. 254-255. Impact 3.4-4	The introductory paragraph does not discuss the Sonoma Valley Wildlife Corridor. The paragraph also notes there will be a significant impact on migratory species, corridors, and nursery sites; however, the impact analysis does not support this statement. The EIR states that implementation of the Proposed Plan would have a significant impact on migratory species, corridors, or nursery sites if the siting, construction, or operation of develop allowed under the Proposed Plan would impede on or remove migratory corridors or nursery sites. The EIR must define what is considered impede on and what might trigger an individual species to not fully use or stop using habitat for migration. The Proposed Plan would impact species differently. The EIR must evaluate how the potential impacts on individual species resulting from development identified in the Specific Plan and addressed under Impact 3.4-1 potentially alter wildlife movement and migration patterns across the property and across the larger corridor. How would the introduction of light sources, noise, human activity, domestic animals, trails, new roadways and increased use of existing roadways directly and indirectly impact permeability of the wildlife corridor and alter use pattern? The EIR must identify mitigation measures for any significant impacts on migratory species, use of migration corridors, or nursery sites to less-than-significant levels?
p. 255. Construction, paragraph 1.	It is an error to assume trails and use of trails would not impact wildlife movement simply because the use is consistent with open space management. Trails and trail use, especially increased use, can directly impact individual species. The EIR must analyze the specific impacts of the proposed trail and explain how those impacts will relate to wildlife movement through the SDC property. How will new trails be designed to minimize impacts to wildlife movement and prevent habitat fragmentation? What mitigation measures are needed to reduce the impacts to less-than-significant levels?
p. 255. Construction, paragraph 2.	The EIR does not explain why the requirements of a 401 or 404 permit or CDFW authorization would fully protect fish and wildlife resources in terms of wildlife movement and wildlife corridors. The EIR must support its conclusions with analysis and substantial evidence, and the current EIR does not do so.
p. 255. Construction, paragraph 3.	The EIR fails to identify what specific policies would minimize impacts on wildlife migration or explain how implementation of each individual policy listed in the analysis would mitigate those impacts. The EIR states that the proposed plan preserves a majority of the site within the Sonoma Valley Wildlife Corridor. What is the impact caused on the portions of the migration corridor that are not preserved? Will access be limited and how will access impact wildlife use? What other impacts could occur and how will these impacts be mitigated? The EIR must specifically identify impacts and analyze their potential for mitigation in order to comply with CEQA.
p. 255. Operations.	The EIR fails to analyze the potential wildlife migration issues associated with the increased daily vehicle trips for each length of roadway and for each scenario presented in Table 3.14-3: Projected Traffic Volumes in Plan Area (page 440). It

	appears the proposed plan would result in 13 percent more vehicular traffic than historic uses. What effect could this increase have on biological resources?
p. 256. Operations, 2-11.	The EIR fails to explain what specific impact(s) the implementation of the “dark skies” standards would address in terms of wildlife movement. The potential impact from increased light is not addressed in the wildlife impacts analysis. The EIR must analyze unmitigated impacts before defining mitigation measures. The EIR fails to analyze light impacts on wildlife movement or explain why, based on substantial evidence, it believes that dark sky standards would reduce those impacts to less-than-significant levels. What are the potential impacts on biological resources from residential housing, buildings and other facilities in terms of nighttime lighting?
p. 256. Operations, 2-12 and 2-13.	The EIR fails to explain how these general policies apply specifically to the Sonoma Valley Wildlife Corridor and what potentially significant impacts these policies address. What proposed plan elements could encroach on the wildlife corridor and into existing open space, and what are the potential impacts on wildlife?
p. 256	Operation. The addition of 1,000+ housing units and 900 jobs will substantially increase the number of recreational users. The EIR fails to quantify or analyze the effect of this increase. What is the anticipated increase in recreational use? Will this increase have a significant impact on wildlife usage? How will the impacts of this greater human and pet presence on trails be mitigated? Similarly, the increase in housing and jobs will increase vehicle traffic. The EIR fails to analyze the effect of this increase on wildlife corridor permeability. How will the increase in vehicle traffic generated by 1000 new homes and 900 jobs affect wildlife corridor permeability? How will these impacts be mitigated? Research has found a strong negative correlation between wildlife corridor use and traffic quantity and development intensity (see, for example, Charry and Jones 2009, and Smith 2019).
p. 257. Operations, 2-17.	The EIR provides no justification for limiting restrictions on nighttime noise based on feasibility. Nor does the EIR analyze or disclose how frequently adherence to residential nighttime noise standards would be infeasible or discuss what additional impacts would occur and mitigation would be required in that case. What are the potential impacts on wildlife migration should adherence not be feasible and what are the proposed mitigation measures to reduce the impact?
p. 258. Paragraph 1.	The EIR fails to identify what plans were evaluated to determine the proposed plan would not conflict with any local, regional, or state habitat conservation plan. The EIR must document its analysis and support its conclusions with substantial evidence.
p. 524, Section 4.1 Alternatives, paragraph 4.	The proposed plan would result in significant and unavoidable impacts related to transportation (Impact 3.14-2) and historic resources (Impact 3.5-2). The biological resources impact evaluation does not address potential wildlife impacts resulting from the increased traffic; therefore, the alternatives may not adequately address potentially significant and unavoidable impacts on biological resources. Traffic volume and density of development are key factors that must be addressed in evaluating impacts to wildlife movement.
p. 524, Alternatives: No Project	It is unclear what the no project alternative is and how the EIR evaluates it. It appears the no project alternative is development without a Specific Plan but following the County General Plan. Does the EIR evaluate a true no action alternative (no development)? If not, why not? It appears the EIR concludes that State law

Alternative paragraph 2.	requires development of the site, and this is not adequately explained in the text. Discussion of a no project alternative does not provide a complete picture without a true "no development" alternative.
p. 524, Alternatives.	The EIR does not adequately explain how the impact of increased vehicle trips on individual special status species and wildlife corridor permeability would differ between the proposed buildout and its project alternatives. Different types and magnitudes of uses in different locations would likely have different impacts on individual special-status species, since special-status species are not uniformly distributed throughout the SDC site. So it is foreseeable that a given alternative could improve impacts on one special-status species while worsening impacts on another. These distinctions and impacts must be analyzed and fleshed out in the EIR in order for decision-makers and the public to fully understand the merits of each of the alternatives presented.
p. 589, Cumulative Impacts, Section 5.2.4, Biological Resources.	The assessment for cumulative impacts on biological resources is simply a summary of the project impacts and fails to identify other projects or impacts to which the Specific Plan will add or compound impacts. What other projects in the geographical context of biological resources could have similar impacts as the proposed plan? Is there an existing cumulative impact on biological resources throughout the County and does the proposed plan have a considerable contribution to a cumulative impact on biological resources? These questions are particularly relevant to the EIR's analysis of the Sonoma Valley Wildlife Corridor, which spans a significant east-west divide and is subjected to impacts from a broad range of projects across its geographic range. The EIR must consider the Project's cumulative impacts to the wildlife corridor in light of the corridor's full geographic range.

PCI appreciates this opportunity to provide input on the planning process for this ecologically important site.

Sincerely,

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Joan Schwan, Principal Ecologist

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PRUNUSKE CHATHAM, INC.

Carrie Lukacic
Principal Environmental Planner

Carrie Lukacic has worked in the environmental planning field for over 30 years in the public and private sectors. Her work focuses on Master Planning, landscape analysis, CEQA/NEPA compliance, and environmental permitting for a wide range of land management projects including recreation and public access, both large- and small-scale infrastructure projects, and water quality improvement and watershed restoration projects. She specializes in the evaluation of environmental impacts in sensitive resource areas and is known for working with stakeholders, project designers, engineers, and resource agency staff to develop creative solutions to avoid impacts and meet stringent regulatory requirements. Carrie maintains a strong working relationship with staff from the regulatory community, which translates into successful authorization and implementation of even the most complex projects. She is also skilled at the development of reasonable and feasible mitigation measures to protect resources while meeting project goals and agency standards.

Selected Professional Experience

Principal Environmental Planner, *Prunuske Chatham, Inc., February 2015 – present*

- The Nature Conservancy South Fork Ten Mile Habitat Restoration Project. Lead planner responsible for development and implementation of a regulatory compliance strategy to construct the first four of the 20 identified projects in the SF watershed. Coordinated with and secured permits for TNC from federal and state agencies including US Army Corps of Engineers, NOAA Fisheries, California Coastal Commission, California Department of Fish and Wildlife, North Coast Regional Water Quality Control Board, and the State Historic Preservation Officer. 2017 to 2018.
- Sonoma Land Trust, Lakeville Creek Restoration Planning. Lead environmental planner for grant-funded effort to restore Stage 0 stream restoration project, linking uplands and baylands in southern Sonoma County. Goals include restoration of channel complexity and hydrologic function. 2020-ongoing.
- The Nature Conservancy, Garcia River Estuary Restoration Project. Lead planner responsible for all elements of regulatory compliance including NEPA, CEQA, and permitting for the large-scale estuary enhancement project. The project is in the BLM-managed California Coastal National Monument; designs include floodplain reconnection and large wood habitat structures. 2020-present.
- Sonoma County Regional Parks, North Sonoma Mountain Regional Park and Open Space Preserve Master Plan. Lead environmental planner for development of public access alternatives, assisting SCRP in preparing a Master Plan, and preparing natural resource management plans for an 800-acre landmark property. 2019-ongoing.
- Trout Unlimited Mill Creek Dam Removal Project. Lead planner responsible for applying for and securing permits from the US Army Corps of Engineers and California Department of Fish and Wildlife.
- City of Healdsburg Fitch Mountain Park and Open Space Preserve Management Plan and CEQA Compliance for City of Healdsburg. CEQA compliance and permitting lead for the development and evaluation of the management plan elements including public access improvements. Included public meeting participation to address resource and access issues. 2016 to 2018.
- Sonoma County Agricultural Preservation and Open Space District Wright Hill Ranch Open Space Preserve Management Plan and CEQA compliance Document. Responsible for development of the CEQA Initial Study/Mitigated Negative Declaration preserve, protect, and enhance the property's biological, ecological, and cultural and historical resources while allowing public access and continued grazing. 2016 to 2017.

Senior Environmental Planner, *GHD, Inc., Santa Rosa, CA, 2004 to 2015*

Carrie managed numerous multi-disciplinary teams performing technical studies, CEQA/NEPA evaluations and securing State, federal, and local authorizations for large- and small-scale infrastructure projects.

Education, Professional Development and Affiliations

- Bachelor of Science in Natural Resources Planning & Interpretation, Humboldt State University, 1987
- California Association of Environmental Professionals, North Bay CEQA and NEPA training coordinator
- American Planning Association
- Facilitation Skills for Scientists and Resource Managers, 2016
- Burn Area Emergency Response (BAER) Fire Assessment Team Leader

PRUNUSKE CHATHAM, INC.

Joan Schwan
Principal Ecologist

Joan Schwan has over 25 years of experience in ecological research, conservation, restoration, and monitoring programs. Her work focuses on natural resource assessment and planning for parks and preserves, and planning and implementation of habitat restoration projects. Joan leads the science team at PCI, providing project oversight and guidance for other staff members. She has worked in settings ranging from the dunes of the Sonoma County coast to vernal pools, oak woodlands, redwood forests and riparian habitats of the greater Bay Area, Central Valley riparian habitats and forests of the lower Sierra. Joan brings a broad ecological perspective to her work, and a commitment to helping people enjoy and engage with the natural world while sustaining natural systems and functions.

<u>Selected Professional Experience</u>

Ecologist, *Prunuske Chatham Inc., 2008 to present*, *Principal, 2016 to present*

- Mill Bend Conservation Plan, Redwood Coast Land Conservancy. Lead ecologist and project manager for assessing natural and cultural resources of 113-acre property on the Gualala River estuary, planning public access, and developing restoration plans and long-term stewardship guidance. (2020-ongoing)
- Lakeville Creek Restoration Planning, Sonoma Land Trust. Lead ecologist and project manager for grant-funded effort to restore Stage 0 stream, linking uplands and baylands in southern Sonoma County. Goals include restoration of channel complexity and hydrologic function. (2020-ongoing)
- Garcia River Estuary Restoration Design Project, The Nature Conservancy. Lead vegetation ecologist for botanical assessment of project site, development of rare plant protection and mitigation plan, and advisor on revegetation design and implementation. Project is in the BLM-managed California Coastal National Monument; designs include floodplain reconnection and large wood habitat structures. (2020-ongoing)
- North Sonoma Mountain Regional Park and Open Space Preserve Master Plan, Sonoma County Regional Parks. Lead ecologist and project manager for development of public access alternatives, assisting SCRP in preparing Master Plan, and preparing natural resource management plans for 800-acre landmark property. (2019-ongoing)
- Sonoma Developmental Center Existing Conditions Assessment – Natural and Recreational Resources, WRT. Lead ecologist on team of consultants, led by WRT, to California Department of General Services for analysis of sensitive resources, protection needs and enhancement opportunities on 945-acre property planned for redevelopment in the Sonoma Valley. (2017-2018)
- Revegetation planning and implementation:
  - PG&E Riparian Mitigation – Sonoma, Fresno, and San Benito counties, multiple sites. Project manager and lead ecologist for revegetation of riparian sites; work includes design, implementation, community engagement, monitoring, adaptive management. (2016-ongoing)
  - PG&E Crane Valley Dam retrofit project, including planning and coordination of restoration of pine forest habitat to 40 acres of quarry and other impacted areas on USFS lands. (2012-2018)
  - PG&E Pit River hydroelectric facility relicensing, including project management of spoils piles revegetation effort and development of seed collection plan, monitoring plans, and roadside revegetation plan for coniferous forest, riparian, and oak woodland settings. (2010-2018)

Botanical and Ecological Consulting, *1992-2008*

- Range-wide Endangered Species Survey Program. Developed a program to engage expert volunteers in collecting data on endangered plants of the Santa Rosa Plain, for the Laguna de Santa Rosa Foundation.
- Vernal pool vegetation monitoring. Monitored hydrology and vegetation, including listed species, of vernal pools undergoing restoration.
- Oak woodland restoration. Managed oak and native grassland restoration on Stanford University open space lands, including community education and volunteer management components.

<u>Education</u>

- M.S. Biology, Sonoma State University, 2006. Thesis: Effects of Livestock Grazing on Native and Exotic Vegetation in Vernal Pools.
- B.A. Human Biology, Stanford University, 1992

Celia Chatham
Biologist/Ecologist II

PRUNUSKE CHATHAM, INC.

Celia Chatham has nine years of experience working as an ecologist in a range of habitats including the Sonoran desert, estuaries along the Gulf of California, and northern California settings from the coast to the Sierra. Her expertise spans both plant and wildlife realms. Before she came to PCI, Celia monitored seabird and estuarine bird populations and behavior in northern Mexico. Her work at PCI focuses on surveys for fish and wildlife, monitoring of wildland habitat restoration, vegetation mapping, biological resource assessment, wetland delineation, construction monitoring and assistance with aquatic species rescue.

Selected Professional Experience

Ecologist, *Prunuske Chatham, Inc., 2013 to present*

- Fish, amphibian, and other aquatic species surveys, dewatering, relocations, and construction monitoring, including:
  - Matanzas Creek Dam Watershed Rehabilitation Project, Sonoma Water and AECOM. Conduct protocol-level California red-legged frog amphibian night and day surveys. 2022.
  - Oken Conservation Easement stream restoration, Sonoma Ag + Open Space. Conduct construction oversight for California tiger salamander protection. 2021.
  - Taylor Mountain Regional Park and Open Space Preserve Trail Construction Project, Sonoma County Regional Parks. Conduct biological resources training and pre-construction surveys for special-status wildlife including breeding birds and California red-legged frog. 2022.
  - Mainstem Ten Mile River Habitat Enhancement Project, The Nature Conservancy. Assist TNC biologist team in relocation of juvenile coho salmon, steelhead, northern red-legged frogs, and other aquatic species for river dewatering prior to construction. 2018.
  - Furlong Culvert Replacement Project, private owner. Assist lead qualified biologist with relocation of California freshwater shrimp and other aquatic species. 2018.
  - Pine Gulch Creek Watershed Enhancement Project, Marin Resource Conservation District. Assist senior wildlife biologist with construction oversight and relocations of California red-legged frog, northwestern pond turtles and other aquatic species. 2015-2018.
  - Mill Creek Fish Passage Restoration Project. Assist lead qualified biologist with aquatic species relocations and construction monitoring. Species relocation included capturing and handling of steelhead, coho salmon, and other wildlife species working closely with CDFW. 2015-2016.
  - Stuart Creek Fish Passage Project, Sonoma Land Trust. Assist senior wildlife biologist with relocation of aquatic species prior to fish passage construction. 2014.
- Breeding bird, bat, and other surveys, including:
  - Sonoma Ag + Open Space. American badger, nesting bird, bat roost, and botanical surveys for mowing and shaded fuel break projects. 2016-present.
  - Sonoma County Regional Parks breeding bird surveys for fuel reduction projects. 2021-present.
- Revegetation monitoring and reporting, including:
  - PG&E native vegetation restoration projects. Plant layout, monitoring, data analysis, and reporting for projects in Sonoma, San Benito, Fresno, and Shasta counties. Assessing plant health and maintenance or remedial needs. Settings include oak woodland, riparian, and coniferous forest. 2013-present.
  - URJ Camp Newman Dam Removal and Stream Reconstruction. Development of vegetation monitoring plan and vegetation monitoring and reporting of reconstructed riparian upland habitat. 2015-2018.
  - Bambury Riparian Restoration Project, project manager; revegetation monitoring and reporting of reconstructed riparian habitat in Sonoma. 2018-present.
- Biological resources assessments and wetland delineation, including:
  - Wetland delineation and biological resources assessment, Petaluma River Park. 2022.
  - Biological resources assessment, Dinner Property, Sonoma Land Trust. 2022.

  - Baseline and current conditions assessment and reporting for Sonoma Ag + Open Space easements and properties. Conduct field surveys, mapping and report preparation for conservation properties. 2018- present.
- Vegetation mapping, Sonoma County Vegetation Mapping Program, Sonoma Ag + Open Space. Ecologist and GIS technician for team led by Tukman Geospatial to develop county-wide vegetation classification and detailed vegetation mapping. 2015-2016.

Conservation Fellow, *Prescott College Kino Bay Center for Cultural and Ecological Studies, 2013-2014*

- Waterbird Monitoring Program. Conducted bird field surveys, data analysis and reporting for four negative estuaries and one island as part of an ongoing waterbird, seabird and shorebird monitoring effort in the region. Bahia de Kino, Sonora, Mexico.

Education

- B.S., Natural History and Ecology, Prescott College, 2013
- B.F.A., Studio Art, Prescott College, 2013

Selected Professional Training

- California Tiger Salamander Workshop. Elkhorn Slough Coastal Training Program. April 2015. Included in-classroom handling of adults and seine sampling larvae in nearby ponds with permitted instructors.
- California Red-legged Frog Workshop. Elkhorn Slough Coastal Training Program. May 2015. Included in-classroom handling of adults and positive night-time eye shine observations.
- Wildlife Biologist Construction Awareness Training (WildC.A.T.). The Wildlife Society Western Section Annual Meeting. February 2018
- Wetland Delineation Training. Wetland Science and Coastal Training Program, SF Bay National Estuarine Research Reserve. March 2018.
- Identifying and Appreciating the Native and Naturalized Grasses of California. California Native Grassland Association. May 2018.
- California Rapid Assessment Method (CRAM) for Wetlands Practitioner Level Training. San Francisco Estuary Institute. April-May 2022.

PRUNUSKE CHATHAM, INC.

Erynn Rebol
Biologist II

Erynn Rebol has 10 years of experience in biological research. Her work has included assisting with, designing, and leading field research and working on habitat restoration projects. She has experience in settings ranging from California to the Arctic to the Amazon with numerous organisms including venomous snakes, small mammals, birds, and plants. Erynn brings a broad biological perspective to the science team at PCI where she assists with natural resource assessment, monitoring, and planning and implementation of habitat restoration projects. She is committed to protecting wildlife, land, and ecological processes so people can responsibly enjoy them for generations to come.

Selected Professional Experience

***Biologist**, Prunuske Chatham Inc., 2022 to present*

- McCormick Ranch Acquisition, Sonoma County Regional Parks. Assisting with a wildlife resources assessment of potential trail alignments and providing recommendations for best management practices for designing a wildlife-friendly trail within a 242-acre property connecting Sugarloaf Ridge State Park and Hood Mountain Regional Park. (2022-ongoing)
- North Sonoma Mountain Regional Park and Open Space Preserve Master Plan, Sonoma County Regional Parks. Assisting with preparation of Master Plan for 800-acre landmark property. (2022-ongoing)
- Mill Bend Conservation Plan, Redwood Coast Land Conservancy. Assisting in development of conservation plan for 113-acre property on the Gualala River estuary. (2022-ongoing)
- Petaluma River Park Biological Resources Assessment, Petaluma River Park Foundation. Prepare wildlife elements of biological assessment to support park development on the McNear Peninsula. (2022-ongoing)
- PG&E Riparian Mitigation Monitoring – Monitoring and reporting on restoration success on multiple riparian revegetation projects. (2022-ongoing)

***Research Assistant**, California State University Long Beach* – Cocha Cashu, Peru *July 2019*

- Collected live insect samples, trained & supervised two field technicians, designed and constructed herbivore exclosures, and collected data on native plant herbivory.

***Project Volunteer**, U.S. Fish & Wildlife Service* – Alaska, USA *Sep-Oct 2017*

- Collected data on polar bear-viewing, took island-wide bear surveys, performed public outreach with educational lectures for tourists, and collaborated with local native schoolteachers to create lesson plans.

***Research Intern**, Wake Forest University* – Galápagos, Ecuador *Oct 2014-Jan 2015 | Mar-May 2015*

- Collected behavioral, survival, positional, and reproductive data; banded and gathered diet samples from multiple seabird species; completed colony-wide species surveys. Installed and monitored camera traps and deployed GPS tags on seabirds.

***Volunteer**, U.S. Fish & Wildlife Service* – Alaska, USA *May-Sep 2014*

- Collected survival and reproductive data for Kittlitz's murrelet, completed annual MAPS passerine mist-netting/ banding sessions, completed avian offshore surveys, and wrote sections of USFWS reports.

***Field Technician**, San Diego State University* – California and Nevada, USA *May-Aug 2012*

- Completed behavioral experiments and took tissue and blood samples from small mammals and venomous snakes, took GPS points, and tracked snakes using telemetry.

Education

- M.S. Biology, Wake Forest University, 2020. Thesis: Sex-specific aging in bite force in a wild vertebrate.
- B.A. Biology, Willamette University, 2013

Publications

Rebol, EJ and Anderson, DJ. 2022. Sex-specific aging in bite force in a wild vertebrate. *Experimental Gerontology*, *159*, 111661.

ATTACHMENT C

Tanya Diamond, Co-Principal & Wildlife Ecologist. MS in Conservation Biology and Ecology.

Contact info: tanya@pfwildlife.com

Phone: (408) 891-9833.

Letter of Regarding: Sonoma Development Center DEIR comments

Date: September 1, 2022

To: Brian Oh, Comprehensive Planning, Permit Sonoma, 2550 Ventura Avenue, Santa Rosa, CA 95403

From: Tanya Diamond

Dear Mr. Oh,

Pathways for Wildlife was asked by Sonoma Land Trust to review the Draft Environmental Impact Report ("EIR") and Draft Specific Plan for the Sonoma Development Center ("Specific Plan" or "Project"). Our review and comments focus on the Project's impacts on wildlife connectivity in the proposed Project area and the impacts of the proposed Project within the Sonoma Valley Wildlife Corridor. Our comments identify inadequacies in the EIR's treatment of wildlife connectivity impacts as well as deficiencies in the Specific Plan.

FIRM OVERVIEW AND QUALIFICATIONS

Pathways for Wildlife is a research organization developed by Wildlife Ecologist Tanya Diamond and Wildlife Researcher Ahíga Snyder in 2013. Pathways for Wildlife works with land trusts, conservation organizations, and transportation agencies to help identify important wildlife and habitat linkages for land conservation efforts by conducting wildlife connectivity surveys and implementing connectivity designs for wildlife movement within a landscape. Data collection used to develop wildlife connectivity plans include data from field cameras, roadkill surveys, tracking data, GIS habitat suitability modeling, and linkage analyses.

Several Pathways for Wildlife projects have resulted in significant funding for land conservation to protect wildlife linkages that animals have been documented using to travel through in various landscapes. Pathways also work with Caltrans and local transportation authorities to implement connectivity designs along highways, such as installing culverts as wildlife crossing structures.

Pathways for Wildlife provides these comments on the Draft EIR and Draft Specific Plan based on the professional expertise and opinion of its Co-Principal and wildlife ecologist, Tanya Diamond. These professional opinions and expertise are informed by over ten years of experience analyzing wildlife connectivity and impacts thereto, application of established scientific principles, and a robust knowledge of the resources and environment at the SDC site.

A resume for Tanya Diamond and Pathways for Wildlife is included herewith as Attachment 1.

COMMENTS ON THE SPECIFIC PLAN AND DRAFT EIR

The Draft EIR and Specific Plan fail to clearly or thoroughly address a number of important considerations related to wildlife movement and the Sonoma Valley Wildlife Corridor. As a result, some aspects of the Specific Plan conflict or potentially conflict with wildlife movement and thus conflict with the Project's stated goal to preserve and protect wildlife mobility through the Sonoma Valley Wildlife Corridor and the SDC site more broadly.

As detailed below, the Draft EIR's lack of analysis of key impacts to wildlife mobility prevents the EIR from identifying which impacts are likely to occur, where such impacts are likely to occur, what species those impacts are likely to affect, or how significant those impacts will be. Further, because the EIR does not clearly identify or analyze relevant impacts, it cannot fully develop or analyze effective mitigation measures. The EIR does not propose clear, tailored, and enforceable mitigation measures to ensure that the SDC site will remain permeable to the specific species that move through it. Further, to the extent the EIR proposes to mitigate potentially significant impacts through Specific Plan policies and conditions of approval, the EIR provides no supporting data or analysis to indicate whether or how its proposed mitigation would actually reduce impacts to wildlife mobility. Without complete analysis and enforceable mitigation supported by substantial evidence, the EIR cannot support its conclusion that impacts to wildlife mobility would be less than significant, and the Specific Plan cannot reliably achieve its goals to "protect[] natural resources, foster[] environmental stewardship, and maintain[] and enhance[] the permeability of the Sonoma Valley Wildlife Corridor for safe wildlife movement throughout the site." Draft Specific Plan at 1-9.

Comment: The DIER states that the project will not interfere substantially with the movement of any wildlife species with an established native resident or migratory wildlife corridors (Figure 1; EIR at 19). This conclusion is not supported by substantial evidence and is likely incorrect. For example, there has been documented mountain lion movement through the Sonoma Development Center property (Figure 2). Two mountain lions in particular, P1 and P5, have been recorded traveling through the SDC property routinely throughout the study period and the property is part of these two mountain lions' home range (Figure 2). Mountain lions are also of particular concern when designing new development because they are uniquely threatened by human activity and encroachment into their habitat. Mountain lions are known to be sensitive to human disturbance, light, and noise (Suraci, Justin P., et al 2019, Wilmers et al. 2013). Largely as a result of increasing development pressures, local mountain lion populations in California are increasingly under threat, and some—including populations within the Bay Area—are currently under review by CA Dept. of Fish and Wildlife to be a listed species for special protection under State law (Yap, TA, JP Rose, and B Cummings. 2019). It is therefore foreseeable that the Project, which would site more than 1,000 residential units and additional commercial and recreational uses immediately adjacent to a bottleneck in the Sonoma Valley Wildlife Corridor—will impede mountain lion movement through this corridor and negatively impact the resident mountain lion population (Wilmers et al. 2013). Impeding mountain lion movement would constitute significant impacts under Biological Resources significance Criteria 1 and 4.

Notwithstanding this foreseeable impact, however, the EIR fails to identify or analyze the Project's impacts to mountain lions. It does not discuss how the Project's uses and associated impacts, including light and noise, would carry into the corridor and influence mountain lion behavior or other species. Nor does the EIR discuss movements of particular species, including mountain lions, through the corridor. As a result, decisionmakers and the public neither know where and how frequently mountain lions or other wildlife species occur on the SDC site or whether and to what degree the development proposed under the Specific Plan would impact their behavior. The Project's impacts to mountain lion and other species mobility could thus be significant, but decisionmakers and the public have no way to know because the EIR failed to include necessary data and studies.

In fact, there have been no wildlife connectivity studies conducted to document what wildlife species are traveling through or residing on the SDC property. *See* EIR at 236 ("No new field studies were conducted for the preparation of this EIR."). This type of study must be conducted to be able to analyze what the project's impacts will be to wildlife movement and resident wildlife populations, and therefore to determine whether the project's impacts would be significant or could be mitigated. *See* EIR at 236 (Criterion 4, providing that impacts would be significant if the project would "[i]nterfere substantially with the movement of any native resident or migratory fish or wildlife species or with established native resident or migratory wildlife corridors"). How will the FEIR resolve this issue?

The EIR also does not include any specific mitigation measures that would reduce impacts to mountain lion and other species mobility to less-than-significant levels. For example, while the EIR acknowledges that wildlife and their habitat may be sensitive to noise impacts (EIR at 337-338), and while mountain lions in particular are known to be sensitive to noise, the EIR does not include any mitigation measures that are designed to or capable of mitigating noise impacts to mountain lions to less-than-significant levels. Instead, the EIR relies on Specific Plan policies that regulate noise and vibration-based thresholds for humans and buildings. EIR at 347-349. This approach does not and cannot ensure that noise impacts to mountain lions would be sufficiently mitigated.

Similarly, the de facto mitigation included in the Biological Resources section of the EIR fails to address mountain lions. For example, Conditions of Approval BIO 1 through BIO 14 ostensibly address construction impacts to special-status plants and wildlife. As discussed in the letter prepared by Prunuske Chatham, Inc., which comments are incorporated herein by reference, these conditions are not sufficiently detailed or enforceable to ensure that impacts would actually be reduced to less-than-significant levels. But even if they were sufficient for the species identified, Conditions of Approval BIO 1 through BIO 14 do not require mitigation specific to mountain lions or mountain lion activity. *See* EIR at 243-251. The EIR thus cannot conclude that the Project's impacts to mountain lion mobility would be less than significant because those impacts have neither been studied nor mitigated.

Comment: The SDC project will further constrain Sonoma Valley Wildlife Corridor. The landscape is already fragmented for wildlife movement Because of the existing infrastructure and roads, the wildlife corridor within the project area already constrains the corridor, resulting in a bottleneck of the linkage. Any further development or increase in people, cars, or intensity of land use would further constrain the linkage. The proposed project could ultimately sever this critical linkage and result in isolating wildlife populations, their ability to find resources like food and water, the ability to find mates, or juveniles dispersing out of their parental home range to establish their own. **How does the County propose to avoid or mitigate the foreseeable constricting effects of increased human activity on the wildlife corridor?**

The proposed project will further constrict the wildlife corridor by significantly increasing the amount and intensity of human activity in and immediately adjacent to the corridor. The Specific Plan proposes more than 1,000 units of residential development in addition to commercial and visitor-serving development. By contrast, in recent years, the human activity at SDC has been considerably reduced. Even before facility closure, the site only supported approximately 415 clients living there, 470,000 sf of client housing, 49,000 sf staff housing, and 643,400 sf offices, shops, etc. California Department of Developmental Services. (2012). Sonoma Developmental Center Building Use Survey. Department of Developmental Services. October 2012. The increase in activity from new construction and occupation of the SDC site would therefore represent a sizeable increase in human activity encroaching on the Wildlife Corridor. Loss of habitat, increased noise and light disturbance within the Corridor, and human or domestic animal intrusion could reduce the width of animal dispersal corridors and disrupt movement through the Wildlife Corridor.

The EIR's failure to describe the already fragmented nature of the landscape results in an incomplete picture of the environmental setting of the Project and prevents decisionmakers and the public from understanding fully the consequences of the Project's impacts. Without a complete understanding of how development will further constrict the Wildlife Corridor, the EIR cannot develop adequate mitigation to reduce the Project's constricting impacts. And without targeted and enforceable mitigation, the Wildlife Corridor would predictably see an increase in potentially significant impacts from noise, light, habitat loss, and other consequences of development.

That analytical and informational gap is apparent on the face of the EIR. For example, as discussed above, the EIR admits that wildlife and their habitat may be sensitive to noise impacts. EIR at 337-338. But the EIR fails to quantify or otherwise describe how construction and operational noise might impact wildlife, including the use of the Wildlife Corridor by relevant species. The species that populate the Wildlife Corridor may respond to noise and other impacts in unique ways. For example, noise has been shown to impact wildlife usage of habitat, resulting, for example, in reduced foraging time and efficacy, and reduced nesting use, in birds (Burger and Gochfeld 2002, Stone 2000, Aubrey and Hunsaker 1997, Shannon et al. 2016). Other species may respond differently. The EIR must therefore analyze noise impacts on the Wildlife Corridor on a species-by-species basis if it is to provide a full understanding of the Project's potentially significant impacts to wildlife and wildlife mobility. The EIR does not provide that analysis. Nor does the EIR mitigate for effects to the wildlife corridor. For example, as discussed above, noise impacts are addressed based on thresholds for human and building exposure; the EIR does not contain performance standards relevant to wildlife or explain why thresholds for human and building exposure are applicable to wildlife. *See* EIR at 347-349.

The EIR's remaining analysis and mitigation similarly fails to ensure that the Project's impacts on the wildlife corridor will be less than significant. For example, Conditions of Approval BIO 1 through BIO 14 require future mitigation for construction-related impacts to specific special-status species. EIR at 243-251. But none of those conditions specify what "impacts" to those special-status species might entail. EIR at 243-251. Nor do any of the conditions establish performance standards related to wildlife movement within the corridor. EIR at 243-251.

The fourth significance criteria chosen by the EIR requires the EIR to demonstrate that "Implementation of the Proposed Plan would not interfere substantially with the movement of any native resident or migratory fish or wildlife species or with established native resident or migratory wildlife corridors, or impede the use of native wildlife nursery sites." EIR at 254-255. But the EIR does not specify what species constitute "native resident or migratory fish and wildlife species" that could be impacted. The EIR also does not explain how much interference with species' movement would constitute "substantial" interference or how the County would determine whether "substantial" interference has occurred. The EIR cannot treat the Wildlife Corridor or the species that use it as a monolith. Different species use the wildlife corridor in different ways. Different species are also differentially impacted by various elements of human development and activity. An impact that is insignificant for one species may be extremely significant for another. Thus, before the EIR can claim that impacts to the wildlife corridor are less than significant, the EIR must first identify the species that use the corridor and identify the specific impacts of the Project that are likely to affect those species. Vague and generalized mitigation, such as the policies referenced on pages 255 to 256 of the EIR, are not sufficient to ensure that impacts to wildlife movement in the wildlife corridor will categorically be less than significant. For example:

2-12 Restrict development in the wildlife corridor and creek corridor to limited trails/paths and informational signage, and design trail networks to minimize travel through wildlife and creek corridors.

The EIR cannot assume that limiting development in the wildlife corridor to trails and paths would not significantly impact wildlife movement. Wildlife is known to respond to human activity, even when that activity is restricted to trails. For example, mountain lions are known to avoid trails where domestic dogs are present. Since the corridor is going to be significantly impacted and restricted by the proposed developments, the only habitat left will be the creeks and rivers for wildlife to travel along. Trails should be set back from creeks and the EIR must analyze the impacts of trails and trail use on surrounding wildlife. **Allowing limited development could have impacts on the wildlife corridor, and the EIR must analyze the significance of those impacts.**

2-13 Restrict access to the wildlife corridor and creek corridor to designated pedestrian paths marked with clear signage and delineated by strategic wildlife-permeable fencing.

The same principles apply here. **Allowing limited access could have impacts on the wildlife corridor, and the EIR must analyze the significance of those impacts.**

2-14 Prohibit all unleashed outdoor cats, and restrict off-leash dogs and other domestic animals to private fenced yards and designated areas.

How will this policy be enforced? Prohibiting off-leash pets is important to do but can be difficult to enforce. The EIR and Specific Plan must include an enforcement mechanism to ensure that this policy would actually reduce impacts to wildlife.

2-15 Collaborate with local wildlife protection groups to create and distribute educational information and regulations for residents and employees to guide safe interactions with wildlife onsite. Materials should be accessible to all ages and abilities and could include posted signs, disclosures, fliers, or informational sessions, among other things.

This policy does not clearly mitigate for any of the project's impacts and habitat loss of the wildlife corridor. What specific regulations would be developed? Until the County knows what regulations will be imposed, it cannot analyze whether those regulations would be sufficient to avoid negative interactions between people and wildlife. Further, this policy fails to specify how regulations would be enforced. Major national parks such as Yellowstone struggle with enforcement of regulations regarding interactions with wildlife despite having a full-time staff of rangers patrolling and enforcing those regulations. The EIR cannot conclude that information and regulations would reduce impacts to wildlife without providing clear standards and a mechanism for enforcement.

2-16 All fencing within the open space must be wildlife permeable, with at least 18 inches of clearance between the ground and the bottom of the fence, and shall not cross or bisect streams or otherwise discourage wildlife movement. For any barbed wire fences, a smooth bottom wire at least 18 inches above the ground must be used.

The EIR and Specific Plan fail to explain how this policy would be enforced. In my professional experience, these types of guidelines are often ignored. For example, ranchers often do not adhere to fencing guidelines because of the risk that calves or smaller farm animals might get out onto the roads, which is dangerous both for the animals and for drivers. How will the County enforce these critical fencing requirements? Further, because the Specific Plan permits agricultural uses within the "Preserved Open Space," this policy must make clear that these fencing standards apply throughout areas shown as Preserved Open Space in Figure 2.2-2.

2-17 Adhere to residential nighttime noise standards to the extent feasible.

This policy is vague and unenforceable. It states that occupants of the SDC site must adhere to residential nighttime noise standards only to the extent feasible. It does not specify who determines whether compliance is feasible or indicate how frequently compliance may not be feasible. Further, this policy does not provide for any additional mitigation that may be required if and when adhering to residential nighttime noise standards is not feasible.

There is simply no basis on which the EIR can conclude that this policy would reduce noise impacts to wildlife.

Why did the DEIR fail to analyze specific impacts to the wildlife corridor?

Why is there no formal mitigation set up for the impacts to the wildlife corridor? Even if the mitigating policies are baked into the Specific Plan, mitigation measures need to be included in a mitigation monitoring and reporting program to ensure they are effectively followed.

Why was there no study developed to determine impacts to wildlife movement within the wildlife corridor?

Without a detailed analysis, how will the FEIR evaluate and set up mitigation for impacts to the wildlife corridor?

SDC SPECIFIC PLAN OUR VALLEY OUR FUTURE

Sonoma Developmental Center Specific Plan
DRAFT Environmental Impact Report

Table ES-2: Summary of Impacts

Impact	*Mitigation Measures*	*Significance before Mitigation*	*Significance after Mitigation*
3.4-2 Implementation of the Proposed Plan would not have a substantial adverse effect on riparian habitat or other sensitive natural community identified in local or regional plans, policies, regulations or by the California Department of Fish and Game or US Fish and Wildlife Service.	None required	Less than significant	Not applicable
3.4-3 Implementation of the Proposed Plan would not have a substantial adverse effect on state or federally protected wetlands (including, but not limited to, marsh, vernal pool, coastal, etc.) through direct removal, filling, hydrological interruption, or other means.	None required	Less than significant	Not applicable
3.4-4 Implementation of the Proposed Plan would not interfere substantially with the movement of any native resident or migratory fish or wildlife species or with established native resident or migratory wildlife corridors, or impede the use of native wildlife nursery sites.	None required	Less than significant	Not applicable

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Figure 1. SDC EIR Summary of Impacts, 3.4-4.

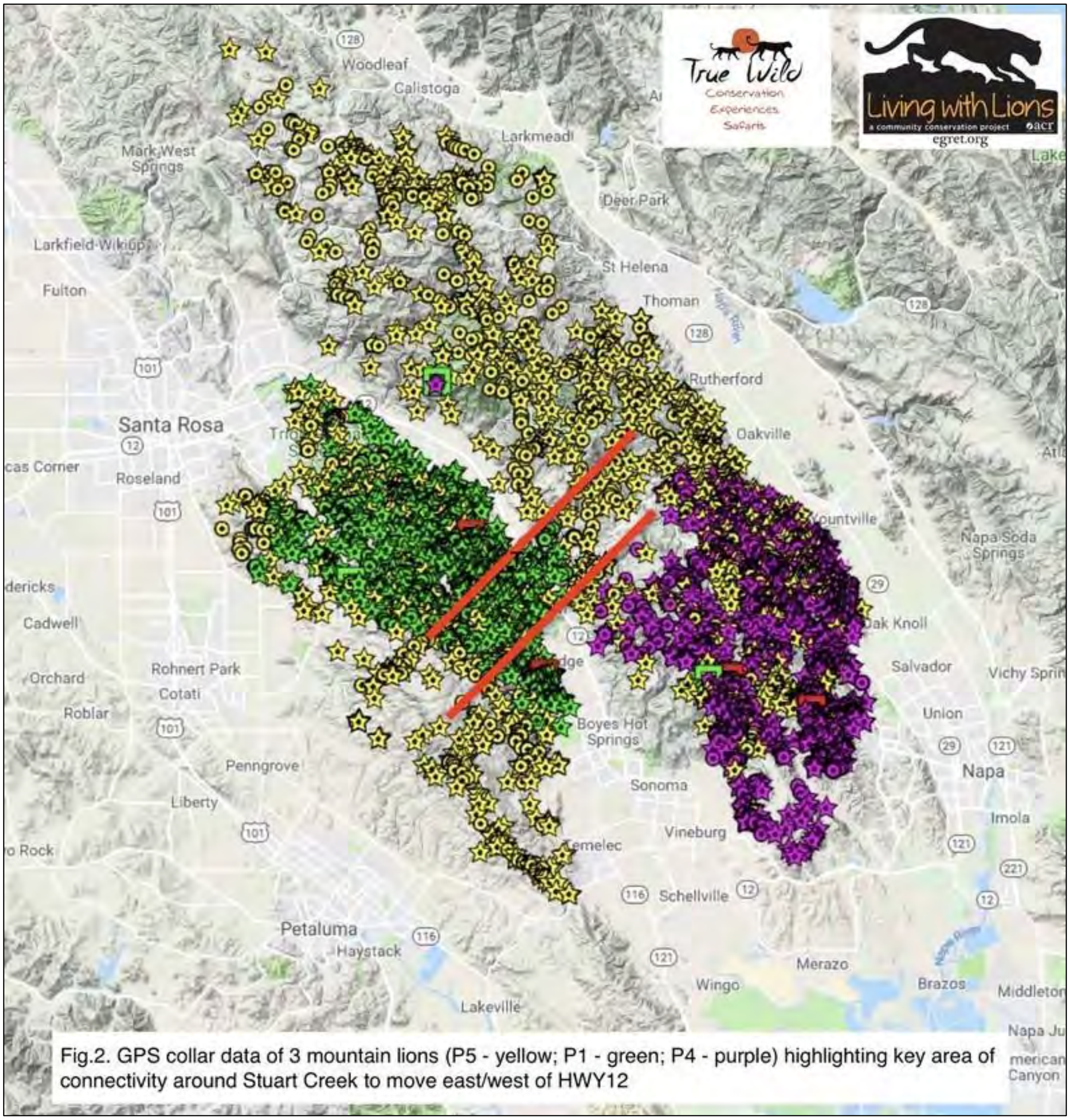

Fig.2. GPS collar data of 3 mountain lions (P5 - yellow; P1 - green; P4 - purple) highlighting key area of connectivity around Stuart Creek to move east/west of HWY12

Figure 2. Mountain lion GPS collar data of 3 mountain lions recorded by ACR, Living with Mountain Lions. Two mountain lions, P1 and P5, were recorded traveling through the SDC property.

Comment: During a site visit, Pathways for Wildlife observed tracks and scat from multiple species, including deer, bobcat, coyote, and gray fox, throughout the main sections of the proposed development site. Yet the EIR does not disclose whether these species or others are present at the site because the County has not conducted the necessary surveys to document the site's biological resources. A site survey is a simple and necessary tool to confirm the presence of special-status species and other plants and wildlife at the Project site. A survey would allow the County to identify not only whether species are present on the site, but also where those species are documented to occur.

A spatial understanding of species distribution at the SDC site is key to understanding the full scope and intensity of impacts to plants and wildlife, because the impacts of development will vary based on what types of development the Specific Plan permits at different locations around SDC. While a specific development proposal has not yet been selected by the State, the Draft Specific Plan is sufficiently detailed and development plans are sufficiently congealed to know where certain types of development would be permitted under the Specific Plan. *See, e.g.,* Draft Specific Plan Figs. 1.6-1, 3.1-1, 3.1-2, 4.1-1, and 4.1-2. Therefore, a major roadblock standing in the way of a complete understanding of the Project's impacts to biological resources is the EIR's failure to collect relevant data about the occurrence and distribution of species at the SDC site. Until those data are collected, the EIR cannot fully analyze the Specific Plan's impacts to biological resources or intelligently mitigate for the effects.

Why were simple data like these not collected and analyzed by the authors of the DEIR? Comments on the Notice of Preparation, including those by Sonoma Land Trust, identified the need for this type of data collection to support any analysis or mitigation in the EIR. In addition, prior comments identified the need for an in-depth wildlife linkage assessment to fully characterize the scope, use, and impacts to the Sonoma Valley Wildlife Corridor. The Sonoma Valley Wildlife Corridor broadly recognized as a critical and regional linkage. An analysis of the impacts of the proposed development needs to be conducted so that the EIR can identify linkage-level impacts and develop appropriate mitigation measures to reduce those impacts to less-than-significant levels. CDFW expects all DEIRs for projects that impact that impact documented wildlife corridors to include this analysis. The EIR must include surveys of biological resources so that it can fully analyze and mitigate impacts to less-than-significant levels.

Comment: Pathways for Wildlife also conducted a wildlife connectivity study along Hwy 12, adjacent to the prosed development (Sonoma Valley Wildlife Corridor Road Underpass Use Report 2013-2014). We recorded multiple species' movements under the highway on a consistent basis throughout the study period. These species included bobcat, coyote, deer, gray fox, mountain lion, raccoon, skunk, and opossum. This study illustrated the importance of the wildlife movement with the Sonoma Valley Floor and documented that the highway is currently permeable for wildlife movement. However, no equivalent study was prepared for or included the DEIR. There is no actual analysis of wildlife movement in the DEIR, and therefore there is no evidence on which to base the EIR's so-called "analysis" of impacts. *See* EIR at 254-257 (concluding that impacts to wildlife movement would be less than significant without studying or fully describing how wildlife actually moves through or around the SDC site). In order to understand how the Project will impact wildlife movement, the DEIR first needs to study and analyze how wildlife actually use the SDC property. Only after comparing actual wildlife movement against the Specific Plan's development proposal can the EIR begin to determine what the specific impacts and magnitude of impacts to wildlife movement will occur as a result of that development. A thorough study is therefore a predicate to impact analysis or mitigation. The final EIR must incorporate all relevant studies and data.

The EIR's conclusion that the proposed project will not impact wildlife movement is completely unsupported and false as there is no data or documentation to support an assumption of that magnitude. An adequate wildlife connectivity study needs to be conducted to mitigate the project's impacts and to ensure that they are less than significant. The study proposal that Pathways for Wildlife prepared for Sonoma Land Trust, which was included in Sonoma Land Trust's comments on the Notice of Preparation and which is reproduced as Attachment 2 to this letter, is representative of the vetted and scientifically proven methodology for conducting wildlife connectivity studies to be able to analyze any types of development impacts on a wildlife corridor. This type of study is necessary to be able to determine and analyze the impacts to wildlife corridor by the proposed project (Safe Passages, Beier, P. & Loe. S. 1992, Forman, R. T. 2012).

Finally, the DEIR is clear that important riparian corridors run through the SDC project area. Why was there no study or analysis of wildlife movement within these important riparian corridors? How will the FEIR avoid or mitigate impacts to these key riparian corridors in light of the current absence of data about wildlife movement in those corridors?

Wildlife Corridors

The northern portion of the SDC property is identified as a regionally important wildlife corridor. This corridor is approximately ¾ of a mile wide and its southern edge slightly infringes into the northern portion of the Core Campus on the site. In total, the SDC property extends across about the southern half of the width of the corridor, which is generally oriented in an east-west direction, linking large habitat blocks to the west, with large habitat blocks to the east. In addition to this regionally significant corridor, the riparian corridors along the streams that run through the SDC, in particular Sonoma Creek, serve as wildlife corridors for several species that use streams to transit from one habitat to another (e.g. steelhead).

3.4.3 Impact Analysis

Sincerely,

Tanya Diamond

Tanya Diamond

Attachments

Attachment 1: Pathways for Wildlife Resume

Attachment 2: Sonoma Developmental Center Wildlife Connectivity Proposal. originally submitted as Attachment C to Sonoma Land Trust's comments on the Notice of Preparation

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ATTACHMENT 1

Pathways for Wildlife Resume

Firm Overview for Pathways for Wildlife

Pathways for Wildlife is a research organization developed by Wildlife Ecologist Tanya Diamond, and Wildlife Researcher Ahíga Snyder in 2013. Pathways for Wildlife works with land trusts, conservation organizations, and transportation agencies, to help identify important wildlife and habitat linkages for land conservation efforts by conducting wildlife connectivity surveys and implementing connectivity designs for wildlife movement within a landscape. Data collection used to develop wildlife connectivity plans include; data from field cameras, roadkill surveys, tracking data, GIS habitat suitability modeling and linkage analyses.

Several projects have resulted in significant funding for land conservation to protect wildlife linkages that animals have been documented using to travel through in various landscapes. Pathways also work with Caltrans and local transportation authorities to implement connectivity designs along highways, such as installing culverts as wildlife crossing structures.

Pathways Team

1. **Co-Principal, Wildlife Ecologist & GIS Analyst:** Tanya Diamond: Wildlife Ecologist, MS Conservation Biology & Ecology and GIS Analyst, Co-Principal: of Pathways for Wildlife, and Certified Wildlife Tracker.
2. **Co-Principal, Field Researcher & Field Operations Manager :** Ahiga Roger Snyder: Wildlife Researcher, Co-Principal of Pathways for Wildlife.

Professional Experience and Demonstrated Knowledge:

1. American Badger and Burrowing Owl Habitat Suitability Study conducted for Midpeninsula Regional Open Space District (2019-present).

2. Highway 17 Wildlife Connectivity Study conducted for Midpeninsula Regional Open Space District and the Land Trust of Santa Cruz County (2014-present).

3. SR-152 Pacheco Pass and Pacheco Creek Wildlife Connectivity Study for the Santa Clara Valley Habitat Agency (2020-present).

4. The Southern Santa Cruz Mountains Wildlife Connectivity Study conducted for POST, the Santa Clara Valley Habitat Agency, and Caltrans (2018-present).

5. SR 68 Monterey-Salinas Scenic Highway Plan: Wildlife Connectivity Analysis conducted for Caltrans and the Transportation Agency of Monterey County (2016-2017).

6. Coyote Valley Linkage Assessment Study conducted for POST and Santa Clara Valley Open Space Authority (2015-2016).

7. Sonoma Land Trust Hwy 12, 116 & 101 Wildlife Connectivity Study for Sonoma Land Trust (2013-2014).

8. CA Central Coast Wildlife Connectivity Study conducted for the Big Sur Land Trust (2013-2014).

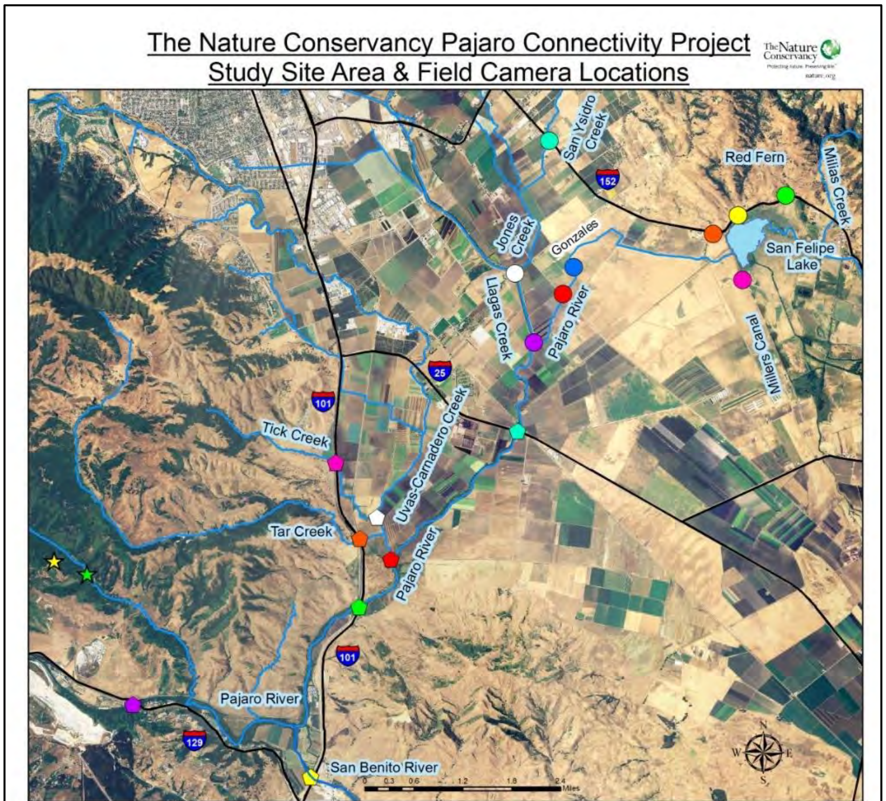
9. The Pajaro Wildlife Connectivity Study conducted for The Nature Conservancy (2012-2013).

Selected Project Descriptions

1.The Nature Conservancy's Pajaro Wildlife Connectivity Study (2012-2013).

The objective of this study was to identify wildlife movement and presence along riparian systems and underneath roads through wildlife surveys using digital infrared (no flash) field cameras in partnership with Caltrans District 5. The goals of this project was to increase our understanding of wildlife movement through the entire Pajaro Valley floor which is a primary connection, habitat linkage, between the Diablo and Santa Cruz ranges (Figure 1). Road kill data was also collected to identify hot spot locations in which animals were routinely being hit at.

This data was used by Santa Clara Valley Transportation Authority for a potential US-101 and SR-152 widening project. Mitigation measures would include installing directional fencing to known bridges and culverts that animals were documented using during the study, along with increased culvert sizes in which animals were using to cross underneath the highway.



Camera Name	Camera Site	Total Number of Detections	Bobcat	Coyote	Deer	Raccoon	Skunk	Opossum	Gray fox	Mountain lion	Burrowing Owl	Dusky footed Woodrat	Red Fox	Wild Pig	Domestic Dog	Domestic Cat	Months of Monitoring
C1	Hwy 25 Pajaro River	82	33	8	30	4	1	6									12
C2	Gonzalez Pajaro Cam 1	73	13	54	2	3	1										12
C3	Gonzales Bridge	66	46			18		2									6
C4	Llagas Creek Cam 1	516	45	97	117	204		52							1		12
C5	Llagas-Pajaro Cam 2	124	31	4	87	1		1									2
C6	Hwy 152 San Ysidro	91		4		60		5					1		3	18	4
C7	Wildlands Wetland	51	1	24	12		1				12				1		12
C8	Wildlands Main Gate by 152	10		6	4												2
C9	Tick Creek-Uvas Creek	706	143	397	17		126	8				2			13		12
C10	Hwy 101 Tick Creek	113	89	2		21	1										12
C11	Pajaro-Uvas Carnadero	776	33	599	72	50	1	2				16		3			12
C12	Hwy 101 Tar Creek	305	44	30	212	9	2	7						1			12
C13	Hwy 101 Pajaro River	186	63	3	15	53	2	50									12
C14	Hwy 101 San Benito River	104	43		59										2		12
C15	Hwy 129 Pajaro River	60	11	1	18	5	1	23	1								8
C16	Star Creek Main Gate	100	31		45		3	2	3	16							12
C17	Star Creek Ranch Ravine	289	82	2	95	1	28	7	47	19					8		19
C18	Red Fern Culvert 1	201	110	4	3	41	2	41									5
C19	Red Fern Culvert 2	86	13	27	14	3	10	4						14	1		5
	Total Detetions	3939	831	1262	802	473	179	210	51	35	12	18	1	18	29	18	

Map by:
Pathways for Wildlife

Figure 1. Field Camera Data Results from the TNC Pajaro Connectivity Study.

2. Highway 17 Wildlife Connectivity Study (2013-present).

In September 2013, Midpeninsula Regional Open Space District, Peninsula Open Space Trust, Land Trust of Santa Cruz County and Pathways for Wildlife joined as project partners to work with Caltrans District 5, Santa Clara Valley Transportation Authority ,the UC Santa Cruz Puma Project, the Department of Fish and Wildlife, and Santa Clara County Parks to identify the best locations for wildlife crossing structures on Highway 17.

Pathways for Wildlife was hired as the Project Manager to conduct the wildlife connectivity analysis and to develop the connectivity design to submit to Caltrans. Field camera, roadkill data, and mountain lion radio collar data were overlaid with GIS wildlife connectivity modeling to determine the optimum locations to install wildlife crossing structures for animals to travel underneath Highway 17 (Figure 2).

Caltrans District 5 has integrated the connectivity design into a project design, that is currently in the process for installing a wildlife crossing structure at Hwy 17 at the Laurel Curve Study site, which includes the installation of a 10'h by 20'w open span bridge with directional fencing to guide animals to the crossing structure.

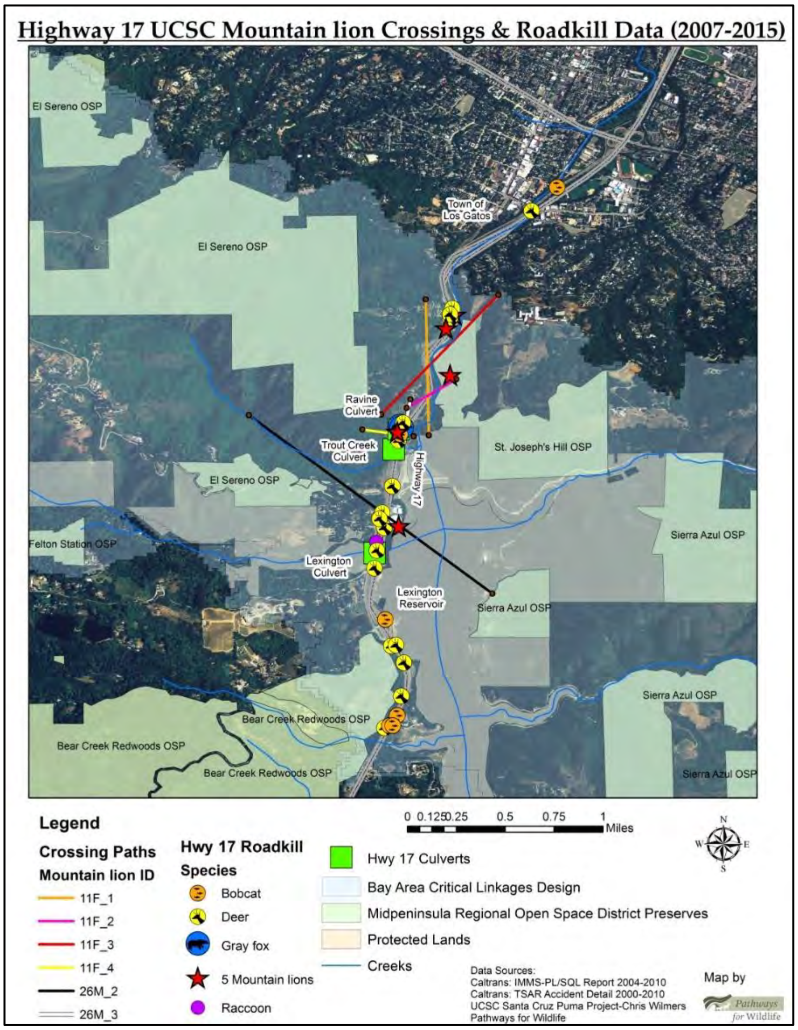


Figure 2. Hwy 17 Lexington Study Site: Roadkill and UCSC Mountain lion Radio Collar Data.

3.CA Central Coast Wildlife Connectivity Project: Northern Monterey-Sierra de Salinas (2007-2009, 2013-2014).

Wildlife Ecologist, Big Sur Land Trust: Principal Investigator for the California Central Coast Connectivity Project. Project Manager, Rachel Saunders (BSLT). Research involved performing a multiple species connectivity analyses in Northern Monterey County. Through wildlife surveys which include, data collected by field camera stations, wildlife track and sign surveys, and documented road-kill incidents combined with Geographic Information System (GIS) mapping. Field data was then integrated into focal species habitat suitability maps, which include areas wildlife are moving through and also barriers to wildlife movement (Figures 3 and 4). The reports and data produced from this project were integrated into Caltrans's District 5 Regional Wildlife Corridor and Habitat Connectivity Plan and Scenic Plan. 3/07-3/2014.

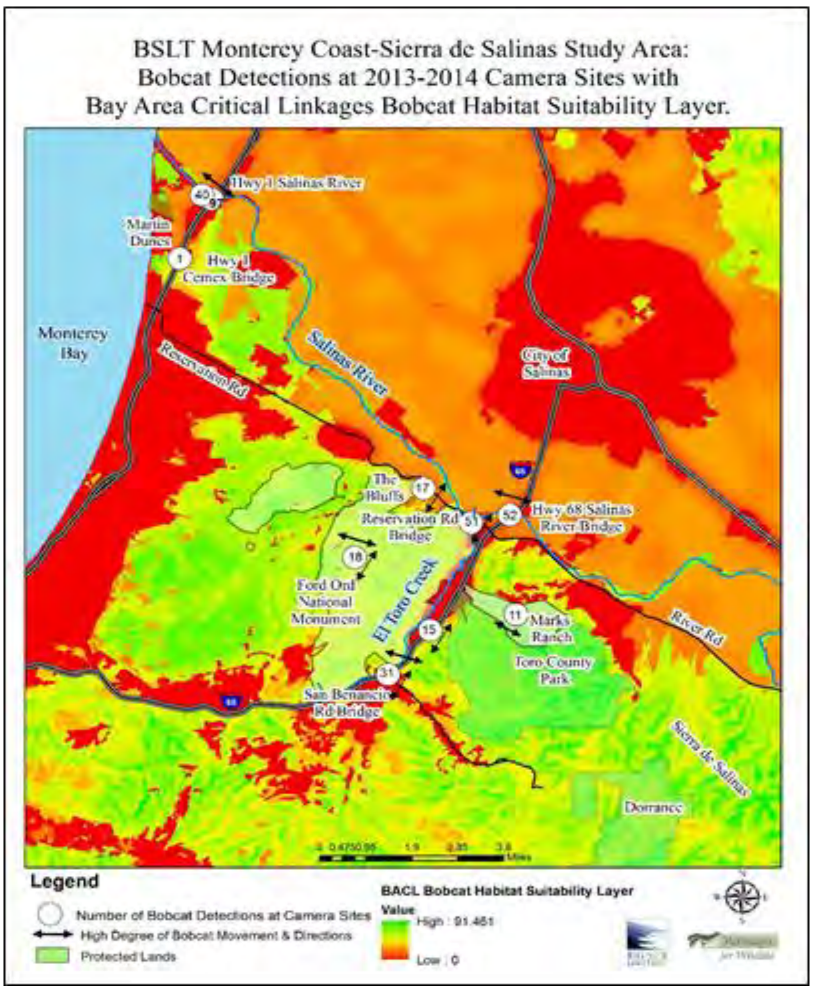


Figure 3. Bobcat Habitat Suitability Layer & Number of Bobcat Recorded at Camera Stations.

Pathways for Wildlife

Highway 68 Wildlife Crossing Data

BIG SUR LAND TRUST

Hwy 68 El Toro Creek Bridge: Bobcat w/ Kittens

Hwy 68 San Benancio Bridge: Deer

Hwy 68 El Toro Creek Underpass– Deer Herd

Hwy 68 Salinas River Underpass: Coyotes

Hwy 68 El Toro Creek Underpass-Mountain lion

Gray fox hit on Hwy 68 across from El Toro County Park

Figure 4. Examples of Highway 68 Wildlife Crossing Data collected from BSLT 2008-2009 & 2013-2014 Studies.

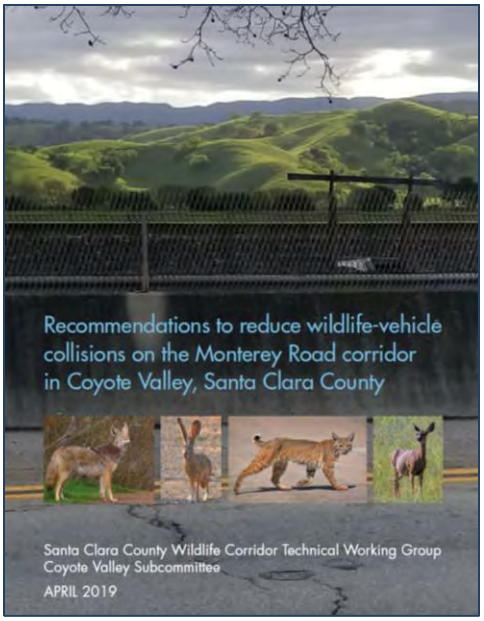
4. Coyote Valley Road Ecology Study and Long-Term Wildlife Vehicle Collision Monitoring Strategy (CV Road Ecology Study)

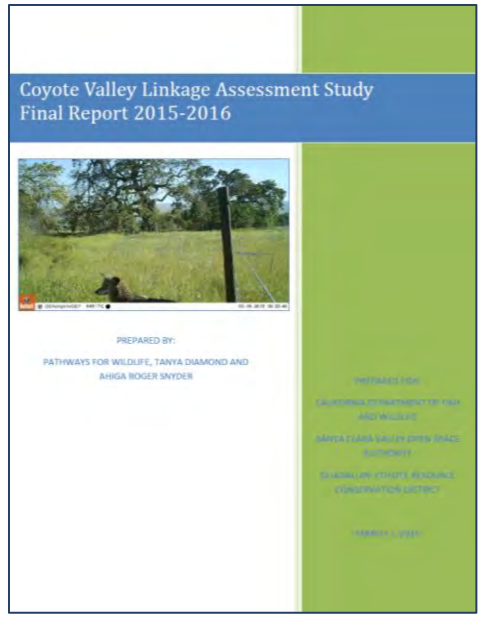
Pathways for Wildlife are currently conducting the new Coyote Valley Road Ecology study with POST, OSA, and the Santa Clara Valley Habitat Agency to help inform future planning efforts to enhance wildlife movement between the newly protected properties. This project will explore and characterize the interactions between wildlife and roadways in Coyote Valley, with a particular focus on the North Coyote Valley Conservation Area (NCVCA) properties. The resulting findings and recommendations are intended to inform the Coyote Valley Master Planning process and ongoing land conservation work including land acquisition, habitat restoration, land management, and wildlife crossing infrastructure. We will monitor and characterize wildlife use of undercrossing features (e.g. culverts and bridges) as well as successful and unsuccessful crossings at-grade. Based on the findings of the analysis, we will provide data-driven recommendations to reduce wildlife-vehicle collisions and maintain or increase permeability of the landscape for wildlife, as appropriate.

The project scope will include roadkill surveys and the development of a long-term wildlife-vehicle collision monitoring strategy for the greater Coyote Valley to inform ongoing efforts to preserve and/or enhance the permeability of the landscape for wildlife use. Protocols for conducting roadkill surveys will be developed with the intention for sharing with agency staff and/or qualified volunteers.

This study will build upon previous studies that explored the relationships between wildlife movement and various roads that intersect with the Coyote Valley wildlife linkage area.

Pathways for Wildlife are co-authors on the Coyote Valley Linkage Assessment Report and Recommendations to reduce wildlife-vehicle collisions on the Monterey Road corridor in Coyote Valley. Data from their Coyote Valley Linkage Assessment study with OSA and DFW helped inform the wildlife connectivity strategies outlined in the reports.





5. Sonoma Land Trust Hwy 12, 116 & 101 Wildlife Connectivity Study for Sonoma Land Trust (2013-2014).

The Sonoma Valley Wildlife Corridor (SVWC) connects the Sonoma Mountains and the Mayacamas Mountains through the Sonoma Valley floor (Figure 5). In 2013 Sonoma Land Trust (SLT) began a multi-year study, to determine whether mobile wild animals are able to move freely through the designated corridor. The study includes a remote camera grid across the corridor landscape, cameras at bridges and culverts along Highway 12, and roadkill surveys. The objective in placing cameras at underpasses is to determine if these structures are facilitating wildlife movement under Highway 12 and Arnold Drive within and adjacent to the SVWC.

Pathways for Wildlife was hired to set up the cameras along Highway 12, enter camera data, analysis the results, and write the final project report, Sonoma Valley Wildlife Corridor Road Underpass Use Report 2013-2014. This report describes and summarizes data and findings from the first year of data collected at several underpasses within and adjacent to the SVWC.

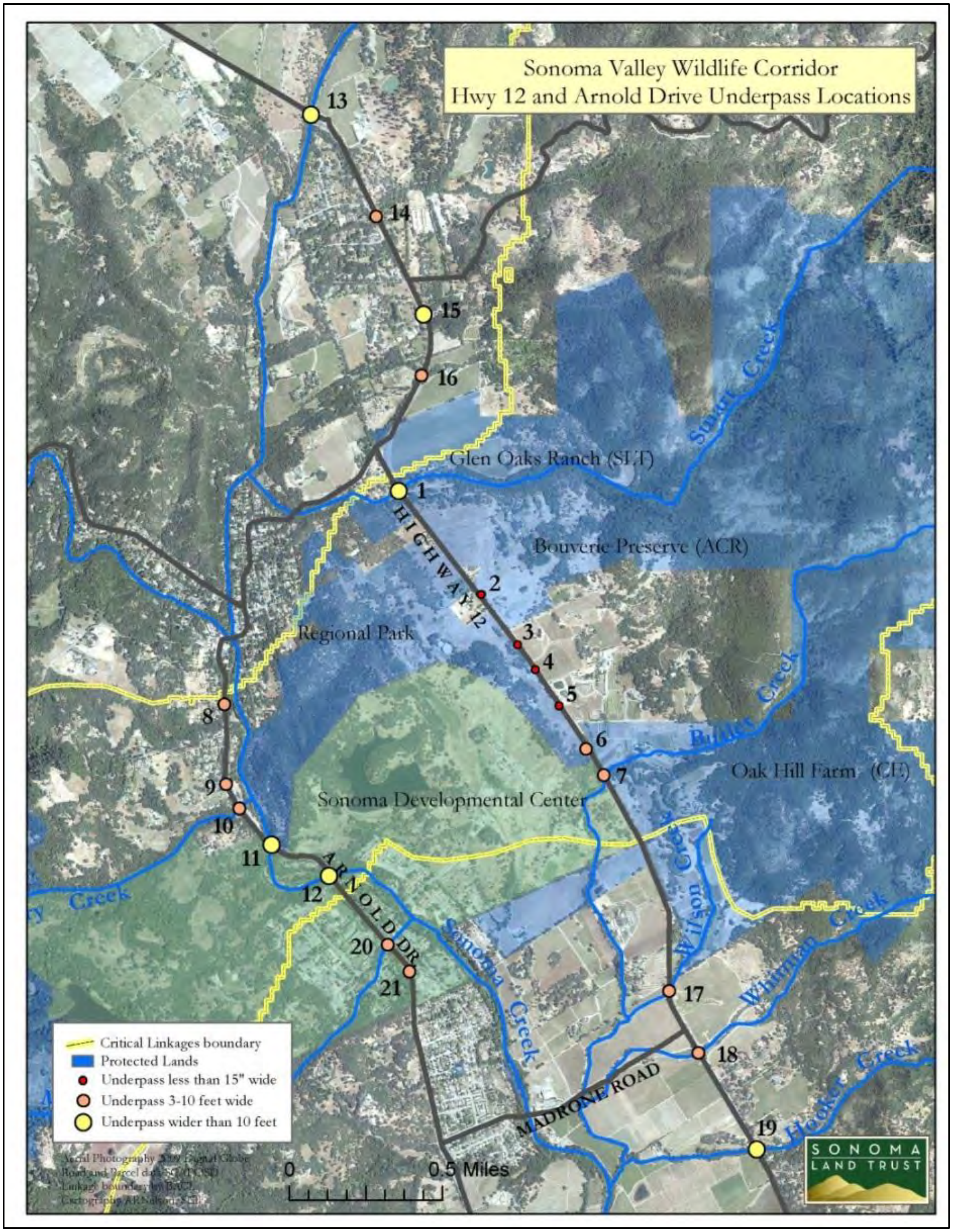


Figure 5. Roadkill Data Results from the TNC Pajaro Connectivity Study.

ATTACHMENT 2

Sonoma Development Center

Wildlife Connectivity Study Proposal

By Pathways for Wildlife

1.0 Introduction: Purpose and Need

To evaluate and implement science-based management, the development of a DEIR for the Sonoma Development Center needs to understand and document where species occur within the property and how wildlife are traveling throughout the property to be able to evaluate the impacts of the proposed development within this critical wildlife linkage. Additional data necessary for evaluating the proposed impacts include the habitat characteristics that are facilitating wildlife movement throughout the property and information about the existing populations of each species. The information obtained through this study can then inform how best to minimize the biological impacts of development at SDC.

The Sonoma Land Trust would like to hire consulting experts in this field, Pathways for Wildlife and Prunuske Chatham, Inc. (PCI) to construct a Habitat Suitability and Wildlife Linkage (Corridor) model for several focal species to create maps depicting levels of habitat suitability for each species. These models will then be used to run fine scale linkage analysis to create a multiple species linkage design for the property. Field-based surveys for each species would then be conducted in areas with high probability of occurrence and control areas (low probability of occurrence) to ground-truth the linkage design.

Pathways for Wildlife developed the following project approach based on our team's understanding of the project area and twelve years of wildlife connectivity experience which includes identifying wildlife linkages and the development of wildlife connectivity enhancement recommendations throughout the Bay Area. The proposed wildlife connectivity study includes robust monitoring and analyses methods that are well-vetted in previous research and publications.

2.0 Connectivity Modeling

2.1 Introduction

Connectivity models are used for identifying important habitat linkages and areas for highway mitigation. Recent attention has focused on the use of habitat suitability and linkage models to guide highway mitigation efforts (Landguth et al. 2012). These types of connectivity models are particularly well-suited for identifying important landscape linkages as they model large, landscape scale processes (i.e., wildlife movement and dispersal patterns).

We propose to create several GIS habitat suitability and cost surface models for the Sonoma Development Center (SDC) property. The models will produce a habitat linkage analyses for a set of four focal species. These models will then be ground-truthed using field survey methods such as wildlife camera monitoring and wildlife tracking transects.

2.2 Model Comparisons

In 2013, the Bay Area Critical Linkages (BACL) created several species habitat suitability maps, however these maps resulted in coarse-scale, low-resolution maps that do not reflect the current level of available wildlife presence, habitat use, and land use layers (Penrod, K et al. 2013). The proposed study will use a much more detailed and current land use layer to produce fine scale species suitability maps that includes rankings for various types of human land use. This analysis will use a map resolution of 10m versus the BACL maps that used 30m resolution GIS layers.

Other improvements will include using a much finer scale habitat types GIS layer, which will include ranking habitat suitability for wildlife movement in agricultural lands based on documented wildlife movement through agricultural lands from previous studies (Nogeire et al. 2013). The BACL ranked agricultural lands as poor habitat for wildlife movement. Pathways for Wildlife has found through several different wildlife connectivity studies in Coyote Valley and the Pajaro Valley that landscapes featuring agricultural uses provide suitable habitat for certain wildlife to both reside in and travel through (Pathways for Wildlife, Coyote Valley Linkage Assessment Study 2016).

This study will also highlight sensitive species and bottleneck areas that could be negatively affected by an increase in human recreational effects (Larson, C. L. et al. 2016).

3.0 Methods

3.1 Habitat suitability and Cost Surface Development

Habitat suitability and cost surface models will be developed for four focal species and include an analysis of habitat variables. These habitat variables include; vegetation, habitat types, hydrology, land use, and roads. Each habitat variable will be reclassified to reflect the suitability of a habitat feature for focal species presence and movement using ArcMap 10.2. The resulting models will reflect a range of habitats from highly suitable (low cost for movement) to poor habitat (high movement costs).
A cost surface layer is a raster grid in which the value in each cell is the cost of movement through the landscape for a given species. The cost for each cell is developed by the cell's characteristics, such as land cover or housing density, combined with species-specific landscape resistance models. For example, a cell that has high use roads or high-density housing will have a higher cost for movement for the animal to travel through that cell within the grid. A cell that contains highly suitable habitat and open space for a particular focal species will have a lower cost of movement for traveling through that cell.

As animals move away from specific core areas, a cost-weighted distance analyses produces a map of total movement cost accumulated. Core areas are defined as habitat that is most preferred by a species and consists of habitat that provides resources such as food and water, breeding and dispersal habitat for that particular species (Corridor Ecology 2019). This analysis will result in a model which reflects a range of highly suitable habitat with low cost for movement for focal species to poor habitat with high movement costs within the study area. The process for developing a habitat suitability and cost surface model in outlined in Figure 1.

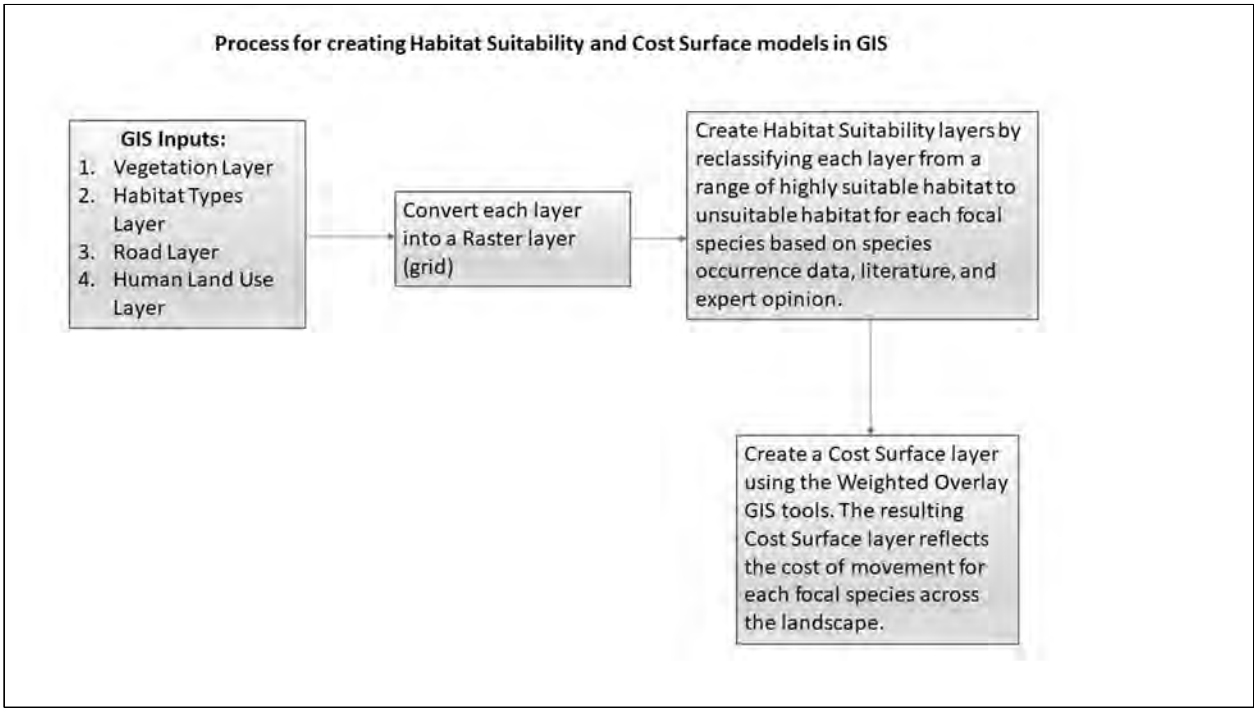


Figure 1. Habitat suitability and cost surface model development.

3.2 Linkage Model Development

The study will then run the Linkage Pathways program, for each focal species cost surface layers to identify and map least-cost linkages between core areas (Washington Connected Landscape Project 2010). Each cell in a resistance map (cost-surface layer) is attributed with a value reflecting the energetic cost, difficulty, or mortality risk of moving across that cell. An example of the steps involved in the Linkage Pathways analysis is illustrated in Figure 2 below. The Linkage Pathways program is an advanced version of least-cost path analysis and uses Circuitscape programming, which runs a fine scale linkage analysis between a network on core areas.

The resulting focal species linkage designs will then be overlaid together to identify linkages that may be facilitating multiple species movement through the landscape.

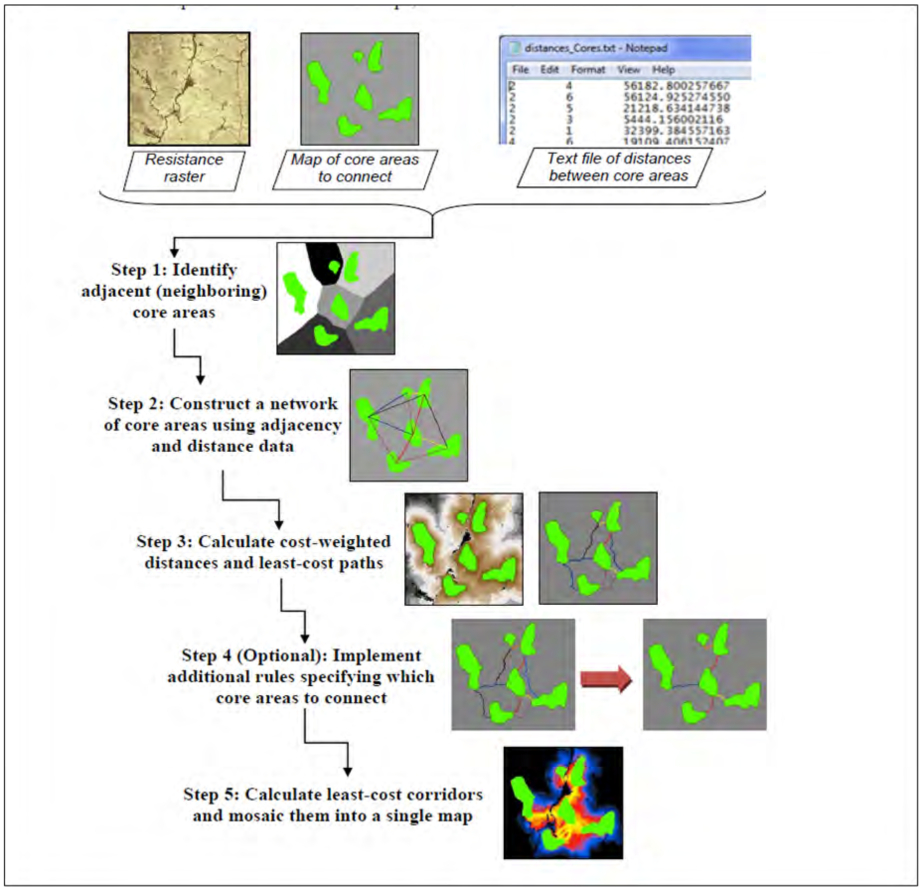


Figure 2. Linkage Pathways analysis steps.

3.3 Focal Species Selection

Landscape permeability analysis is a GIS method that models the relative cost for a species to move between core areas based on how each species is affected by habitat characteristics, such as slope, elevation, vegetation composition, land use, and road density. This type of analysis identifies the best potential movement corridors for each species between core areas and across highways in our study area (Craighead et al. 2001, Singleton et al. 2002). The purpose of the analysis is to identify critical habitat linkages within the SDC property.

Focal species will be selected based on the following: 1. habitat preference for both residing in and traveling through the study area; 2. sensitivity regarding human presence and land use; and 3. keystone and/or umbrella species.

Our goal will be to include a large range of habitat preferences and habitats wildlife travel through to identify important core locations and linkages that connect these sites. The focal species approach recognizes that species move through and utilize habitat in a wide variety of ways (Beier and Loe 1992). Species used in landscape permeability analysis must be carefully chosen, and will be included in this analysis only if:

- Sufficient data is available about the movement of the species to reasonably estimate the cost-weighted distance using the data layers available for our analysis.

- Data layers in the analysis reflect the species' ability to move.
- The focal species could potentially move between cores, at least over multiple generations.

i. Selected Focal Species Selection Criteria

We define focal species as a set of terrestrial mammal, amphibian, and bird species that collectively serve as an umbrella for all native species and ecological processes of interest in our study area. Our use and selection of focal species intended to capture the ecological attributes we list below.

Area-Sensitive: Species that need connectivity for dispersal, seasonal migration and or home range connectivity, which include many carnivore species.
Barrier-Sensitive: Species most reluctant to traverse roads, canals, urban areas or other barriers, such as tule elk.
Corridor-Dwellers: Species with limited dispersal, may take days or generations to move between target areas, such as California tiger salamander.
Habitat Specialists: Species strongly associated with specific habitat types or topographical elements, such as some songbirds, raptor species, and American badgers.
Ecological Indicator: Species tied to important ecological process whose presence indicates the health of the system, such as mountain lions.

3.3 Modeling Summary

A habitat suitability and cost surface model are created as inputs for the Linkage Mapper analysis. The steps of the overall process are illustrated below in Figure 3. Our models will also include land use and hydrology layers.

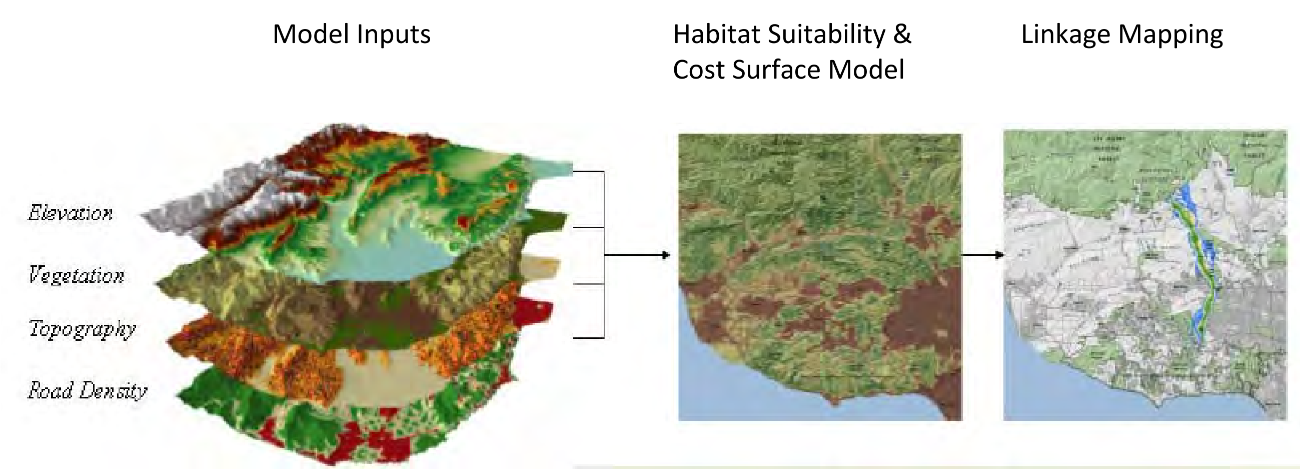


Figure 3: Cost surface modeling Summary

4.0 Model Validation: Ground-truthing with Data Collection

Linkages will then be ground-truthed by overlaying data collected from field surveys. To validate the focal species habitat suitability models and linkage design, we will employ two types of surveys—wildlife tracking transect surveys and camera trapping.

i. Transect Surveys

Systematic searches along established transects have been used in other studies to establish species presence in an area (Lay 2008, Quinn 2008). Surveys will be conducted by having at least two qualified wildlife trackers to walk the transects to record, GPS and photograph wildlife track and sign. The transects will be set up in a range of highly suitable habitat to poor habitat for each focal species to test the habitat suitability models along with the linkage design.

ii. Camera Trapping

Camera monitoring stations will be set up within both the habitat suitability models and linkage design to test the models. Camera arrays will be set by qualified biologists and with permission and permits pending approval of the project. Camera data will be entered into a master database. Data results will then be mapped out in GIS, as a data layer to overlay with the habitat suitability models and linkage design for model validation. This study will build on the data collection from the Sonoma Valley Wildlife Corridor Road Underpass study conducted by Pathways for Wildlife and the Sonoma Land Trust from 2013-2014 (Figure 4). This study proposes to expand this wildlife connectivity study beyond Hwy 12 to incorporate a critical part of the linkage to understand and document wildlife movement within it.

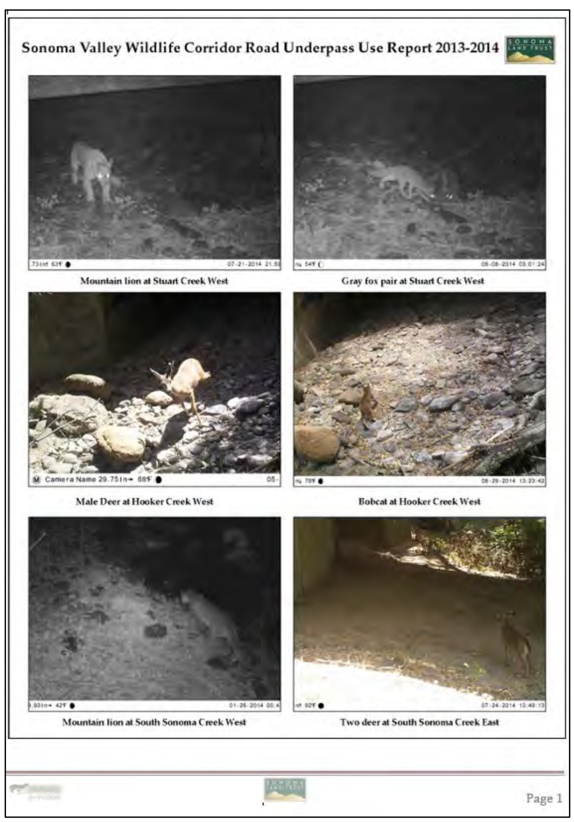


Figure 4. Sonoma Valley Wildlife Corridor Road Underpass Use report cover.

5.0 Analysis and Interpretation

The model will provide gradients of habitat suitability for a species for the entire property from the types of habitats a species prefers to habitat they typically do not use and travel through. The linkage analysis will then analyze how the highly suitable (preferred) habitats are connected.

The field component of the project will then document sites where the species are traveling through to validate if the model accurately depicts suitable habitats and if species are in fact traveling through the linkage design.

Linkages that have documented wildlife use will then be assigned appropriate buffers to ensure the linkage will not be negatively impacted by human development that would impede wildlife movement through the linkages. **Validated linkages and highly suitable habitat will inform the proposed development plan to identify important locations that should not be impacted by development and be designated as open space.**

The ground-truthed data will also result in developing wildlife connectivity enhancement recommendations such as fencing improvements that would be beneficial as wildlife friendly fencing designs, directional fencing to culverts and bridges we record wildlife using to travel underneath roads, culvert retrofits to facilitate wildlife passage, or new locations for wildlife crossings structures, along with removal of buildings that create bottlenecks and pinch-points within the linkage design, and modifications of proposed developments and roads to include safe passage for wildlife movement through the linkage design.

Figures 5 and 6 includes examples of models developed and then ground-truthed by Pathways for Wildlife.

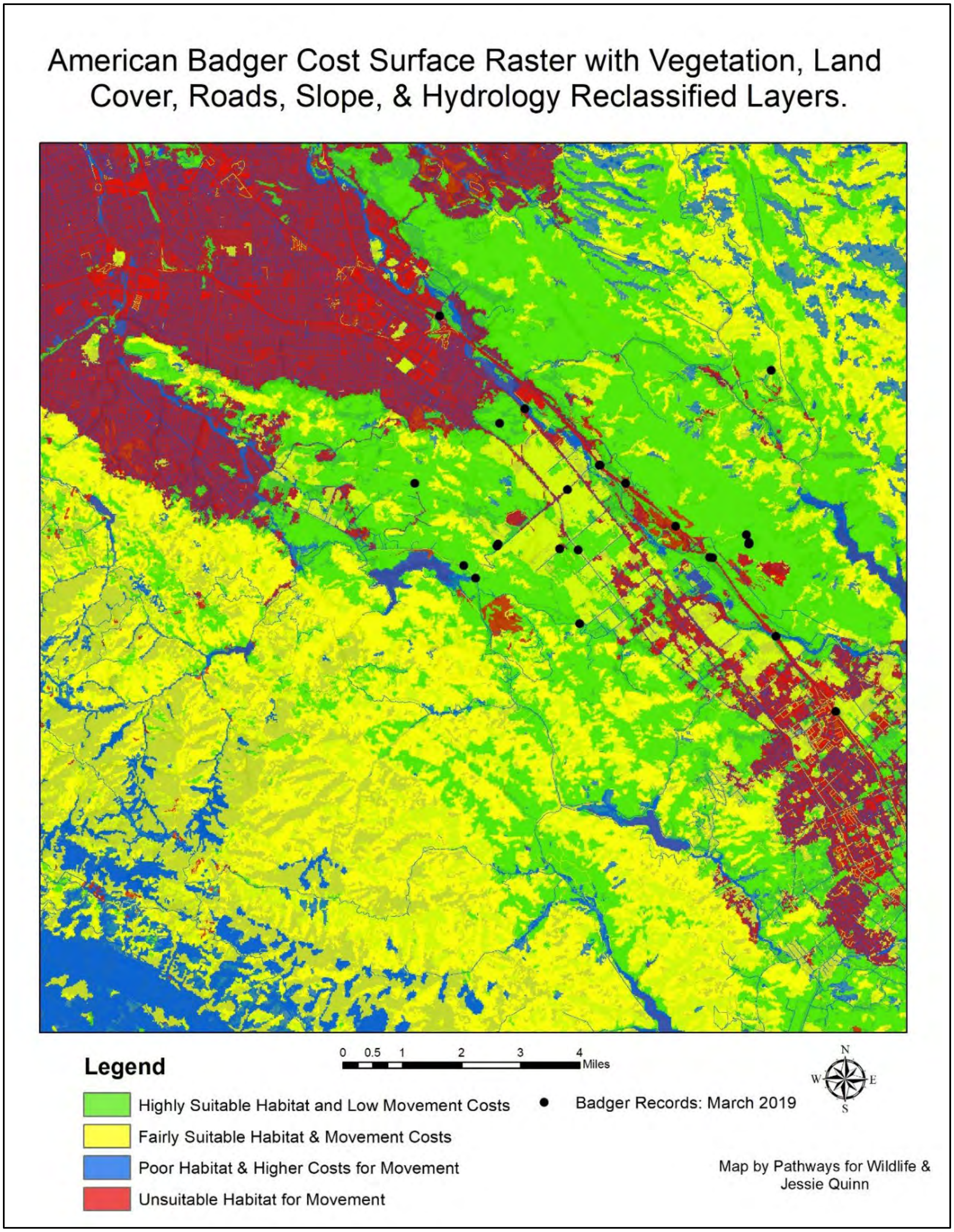


Figure 5. American badger habitat suitability & cost surface model for Coyote Valley. Collected badger records were then overlaid to ground-truth the model. Data records include badgers that were hit by cars on US-101. Developed by Pathways for Wildlife.

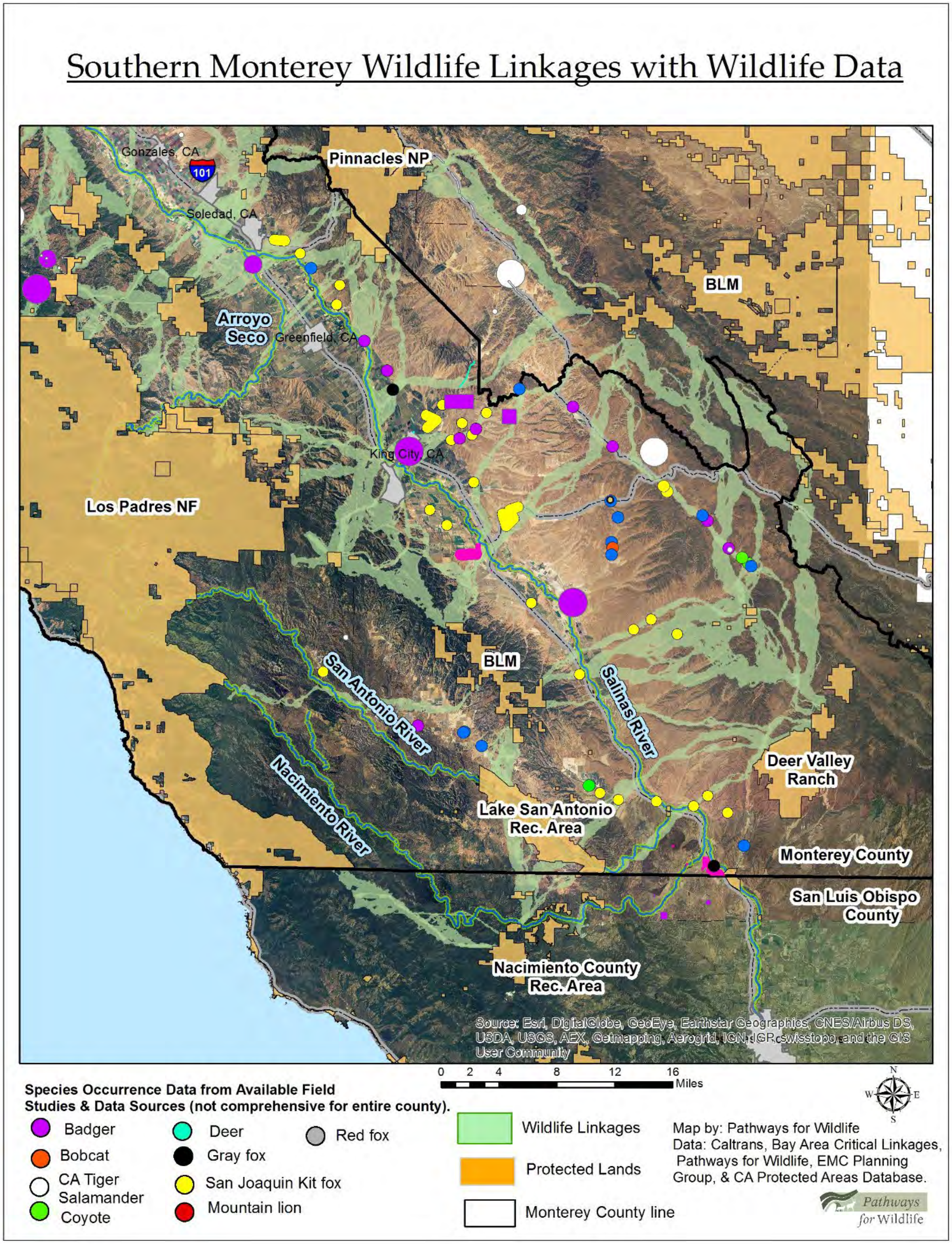


Figure 6. Multiple species linkage model for Monterey County developed by Pathways for Wildlife for the Monterey County Planning Department. Collected wildlife records were then overlaid to ground-truth the model.

5.0 Literature Cited

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ATTACHMENT D

September 26, 2022

Mr. Brian Oh, Comprehensive Planning Manager — Via E-mail Only
Permit Sonoma County of Sonoma
2550 Ventura Avenue
Santa Rosa, CA 95403
Brian.Oh@sonoma-county.org

Subject: ***Review of Draft Environmental Impact Report Transportation Analysis***
Sonoma Developmental Center Specific Plan, Sonoma County, California

Dear Mr. Oh:

Griffin Cove Transportation Consulting, PLLC (GCTC) has completed a review of the transportation analysis completed with respect to the proposed Sonoma Developmental Center Specific Plan project (Project) in Sonoma County, California. Details regarding the Project are presented in the *Sonoma Developmental Center Specific Plan Public Review Draft* (Dyett & Bhatia, August 2022).

The proposed Project is the subject of a Draft Environmental Impact Report (DEIR) prepared for the County of Sonoma (Reference: Dyett & Bhatia, *Sonoma Developmental Center Specific Plan Draft Environmental Impact Report*, August 2022). Section 3.14 of the DEIR presents the transportation analysis. No separate technical report was prepared, although Appendix F to the DEIR is labeled "Traffic Model Data." We should note, however, that no traffic model data are actually presented in that appendix; instead, it simply provides a table that is virtually identical to DEIR Table 3.14-3: Projected Traffic Volumes in Plan Area. (DEIR p. 441)

Our review focused on the technical adequacy of the transportation analysis presented in DEIR Section 3.14, including the detailed procedures and conclusions documented there.

BACKGROUND

The proposed Sonoma Developmental Center (SDC) Specific Plan project involves the potential redevelopment of the 180-acre "Core Campus" within the overall SDC site. According to the DEIR Executive Summary (p. 7), the Project would result in buildout of 1,000 housing units, 2,400 residents, and 940 jobs. More specific development plans are described in DEIR Section 3.14 – Transportation, as follows:

- 435 single-family residential units,
- 345 multifamily residential units,
- 220 senior residential units,
- 40,000 square feet (SF) of commercial/retail space,
- 190,000 SF of office space,
- 70,000 SF of institutional space (described in DEIR Table 2.5-3 – Planning Area Non-Residential and Employment Buildout Summary (p. 80) as 30,000 SF of public space and 40,000 SF of institutional space),
- 120 hotel rooms, and
- 12.1 acres of recreational uses.

We note that the specific breakdown of housing unit types addressed in the transportation analysis is not presented in either the DEIR Project Description or in the Specific Plan document. Questions regarding the specific development plan are discussed in our comments below.

TRANSPORTATION ANALYSIS REVIEW

Our review of the DEIR transportation analysis for the proposed Sonoma Developmental Center Specific Plan project revealed several issues that must be addressed prior to certification of the environmental document and approval of the project by the County of Sonoma. These issues are presented below.

1. ***Flawed Analysis of Plan Consistency*** – Impact 3.14.4.5 (DEIR p. 443) addresses the issue of potential Project-related conflicts with "a program, plan, ordinance, or policy addressing the circulation system." Among the plans considered here is the Sonoma County General Plan 2020. The DEIR states that:

   > *Objectives CT-4.1 and CT-4.2 of the Sonoma County General Plan pertain to upholding vehicle level of service standards. As individual development projects occurring within the Proposed Plan complete traffic impact studies as required by the Sonoma County Department of Transportation and Public Works (DTPW), the potential exists for identification of locations where LOS* [Level of Service] *targets would be exceeded.*

   The General Plan objectives referenced here require operation at LOS C on roadway segments (except where exceptions have been adopted) and LOS D at intersections. Attachment 1 contains an excerpt from the General Plan, including the figure illustrating where LOS exceptions have been approved.

   The DEIR (p. 444) goes on to state:

   > *. . . while traffic congestion effects of the Proposed Plan or development of individual sites within the Planning Area may not comply with the LOS targets established in Sonoma County General Plan Objectives CT-4.1 and CT-4.2, for the purposes of the Proposed Plan's CEQA assessment this would not be considered an adverse environmental impact.*

   We believe this conclusion is erroneous. In fact, we believe that the failure to conform to level of service standards established within the County's adopted General Plan constitutes a clear "conflict with a program, plan, ordinance, or policy addressing the circulation system." Further, the failure to include any documentation within the DEIR regarding conformance to the General Plan LOS objectives is a significant deficiency.

   We note that a detailed traffic impact analysis has been conducted for the Project, although that document has not been included in the DEIR. Specifically, Footnote 118 (DEIR p. 410) references the *Focused Traffic Operations Analysis for the SDC Specific Plan* (W-Trans, August 2022 [actually July 6, 2022]). Although the traffic analysis is not part of the DEIR, we reviewed it to establish whether the Project conforms to General Plan Objectives CT-4.1 and CT-4.2. Our review revealed that the W-Trans report (p. 3) states:

   > *Under future conditions with implementation of the SDC Specific Plan, two intersections are projected to operate unacceptably if no modifications to the current roadway configurations are made. The intersection at Arnold Drive/Harney Street would operate unacceptably at*

> *LOS F during the p.m. peak hour . . . The future new intersection on SR 12 at the new SDC Connector Road would have unacceptable LOS E operation on the stop-controlled connector road approach . . .*

Although improvements are identified that would remedy these deficiencies, no assurance is provided that those measures would be implemented.

The focused traffic study (p. 5) also says:

> *With the additional traffic generated by the buildout of the SDC Specific Plan, the segment of SR 12 between Arnold Drive and Trinity Road would continue to operate below the County's standard at LOS D, as would the segment of Arnold Drive between SDC and Madrone Road.*

Although these road segments are also identified as falling short of the County LOS standard without the Project, no mitigation measures were proposed to allow operation at an acceptable LOS. In any event, it is clear that these two roadway segments will fail to meet the County LOS standard upon completion of the Project, thereby violating the General Plan objectives.

In conclusion, the information necessary to address conformance with General Plan Objective CT-4.1 and CT-4.2 exists, but was not included within the DEIR, which would have allowed public review. As described here, that information indicates that the Project fails to conform to the County's LOS standard, as two intersections and two road segments will operate at unacceptable levels of service upon completion of the Project, and no assurance was provided that these deficiencies will be remedied. Thus, a significant impact exists with respect to conflicts with the adopted General Plan.

Finally, the focused traffic study must be incorporated into the DEIR. The provision of this new information within the DEIR provides grounds for recirculation of the document.

2. ***Project Trip Generation is Underestimated*** – The DEIR (p. 440) states that the Project will generate 5,736 daily trips. Of that total, 1,398 of those trips (i.e., 24.4 percent of the total) will be "captured within the campus itself," resulting in net external trip generation of 4,338 trips. We believe the DEIR has substantially underestimated the volume of traffic associated with the Project.

   The DEIR's Project trip generation estimate was developed using the SCTM19 travel demand forecasting model maintained by the Sonoma County Transportation Authority (SCTA). The specific trip generation factors employed were not revealed in the DEIR. Consequently, it is impossible for the reviewing public to evaluate the reasonableness of either those factors or the resulting trip generation estimates.

   Traffic impact analyses for proposed development projects commonly use information presented in the Institute of Transportation Engineers (ITE) document ***Trip Generation Manual*** (Eleventh Edition, 2021) to develop project-related trip generation estimates. Although we acknowledge that the ITE trip rates often differ from corresponding rates contained within travel demand forecasting models such as the SCTM19 model, comparison of an estimate based on the ITE information versus the estimate documented in the DEIR provides a valuable perspective on the credibility of the DEIR Project's transportation analysis.

Two scenarios are addressed here. The first employs the Project plan as described in DEIR Section 3.14 - Transportation, and the second considers a maximum residential development scenario based on information in the Specific Plan document.

DEIR Section 3.14 – Transportation Project Plan Scenario

Table 1 provides a trip generation estimate for the Project based on the plan as described in DEIR Section 3.14 - Transportation and on commonly-accepted procedures documented in the ITE *Trip Generation Manual*. That estimate reflects the following parameters:

- The land use values described in DEIR Section 3.14 – Transportation, including the specific housing type breakdown, were evaluated.
- The ITE *Trip Generation Manual* typically provides two methods to develop an estimate of project-related traffic: one using an average rate and one using a fitted curve equation. For this analysis, we have reported whichever of those two methods provides a lower value, so as to provide a conservative estimate of Project trips. The trip generation data sheets for this estimate are presented in Attachment 2.
- Within each housing type, it was assumed that 25 percent of the residential units would be inclusionary income-restricted units, in order to conform to Specific Plan Policy 4-14 (Specific Plan, p. 4-25). Because these units generally produce lower volumes of traffic, this assumption again results in a conservative trip generation estimate.
- Because the specific uses included within the public/institutional land use are not currently well-defined, no trip generation estimate was included for that land use category.

As shown in Table 1, the Project is estimated to generate 12,253 daily trips. This is obviously substantially (i.e., 114 percent) greater than the DEIR estimate of 5,736 daily trips. As we stated above, model-based trip generation factors often differ from the ITE trip rates. However, a difference of this magnitude is exceptional and is greater than we have ever seen. Consequently, we question the validity of the DEIR trip generation estimate.

Table 1
Daily Trip Generation[1]
1,000 Dwelling Units (25 Percent Inclusionary Income-Restricted)

Land Use		Size	Daily Trips
Residential			
Single-Family Residential	Market Rate	326 DU[2]	2,993
	Affordable[3]	109 DU	524[4]
Multifamily Residential	Market Rate	259 DU	1,736
	Affordable	86 DU	414
Senior Residential	Market Rate	165 DU	711[5]
	Affordable	55 DU	178[6]
	Residential Subtotal	1,000 DU	6,556
Non-residential			
Commercial		40,000 SF[7]	2,701
Hotel		120 Rooms	959
Office		190,000 SF	2,028
Public/Institutional		70,000 SF	--[8]
Recreation		12.1 Acres	9
	Non-residential Subtotal		5,697
	TOTAL		**12,253**

Notes:
1 Reference: Institute of Transportation Engineers, *Trip Generation Manual*, 11th Edition, 2021.
2 Dwelling unit.
3 Affordable housing assumed to be 25 percent of all residential types.
4 Based on ITE Land Use Code 223 – Affordable Housing – Income Limits, which is defined as including only multifamily housing. This represents a conservative assumption regarding trip generation for this land use category.
5 Based on ITE Land Use Code 251 – Senior Adult Housing – Single Family.
6 Based on ITE Land Use Code 251 – Senior Adult Housing – Multifamily. This rate is conservative, since “Affordable Housing” rate is 48 percent higher than this.
7 Square feet.
8 No estimate is possible, given the lack of information regarding specific land uses in this category.

Maximum Residential Development Scenario

As we indicated above, we have questions regarding certain aspects of the proposed development plan. One such question concerns how many residential units will be constructed. Although the DEIR transportation analysis addresses development of 1,000 residential units, the Specific Plan indicates that a greater number of units is possible.

Table 4-2: Minimum and Maximum Housing Units by District (Specific Plan, p. 4-12) provides detailed information regarding how many housing units could be constructed within various subareas of the Project. That table reveals that the maximum number of housing units that could potentially be built is 1,210. Further, the notes to the table state that "[u]p to 10% deviations from the minimum and maximum by district are subject to approval by the Community Development Director." If such a deviation from the maximum values were to be approved, the total number of residential units would increase to 1,331 (1,210 X 1.10 = 1,331).

To assess the impacts of this maximum development scenario with respect to the volume of traffic associated with the Project we have performed a second trip generation analysis, as summarized in Table 2. The basic parameters of this analysis are similar to those described above for the Table 1 analysis. Attachment 3 contains the data sheets for the residential uses; the non-residential data sheets are unchanged from the previous analysis.

With consideration of the larger number of residential units, the Project's total daily trip generation increases to 14,290. This is 149 percent greater than the value claimed in the DEIR.

Summary

The analysis presented here indicates that the Project's daily trip generation has been substantially underestimated. This finding relates directly to the Project's impact with respect to vehicle-miles traveled (VMT). The DEIR acknowledges the relationship between trips and VMT at p. 447, where it says:

> *. . . trip reductions should in theory translate to roughly equivalent VMT reductions.*

Thus, trip increases, as we have described, will similarly translate to roughly equivalent increases in VMT. Further, as described at DEIR p. 425, the calculation of VMT:

> *. . . is based on the estimated number of vehicles* [actually, vehicle-trips] *multiplied by the distance traveled by each vehicle.*

If, as we have found, the number of vehicle trips is 2.14 – 2.49 times greater than the value considered in the DEIR, then the VMT values associated with the Project will also be 2.14 – 2.49 times greater than the DEIR findings.

Although the DEIR has already concluded that the Project's VMT impact will be significant and unavoidable, it has failed to accurately portray the magnitude of that impact. This is a serious deficiency in the DEIR, which suggests a need to reevaluate the Project's impact and recirculate the DEIR for further public review.

Table 2 Daily Trip Generation[1] 1,331 Dwelling Units (25 Percent Inclusionary Income-Restricted)			
Land Use		Size	Daily Trips
Residential			
Single-Family Residential	Market Rate	434 DU[2]	3,894
	Affordable[3]	145 DU	680[4]
Multifamily Residential	Market Rate	345 DU	2,287
	Affordable	114 DU	548
Senior Residential	Market Rate	220 DU	948[5]
	Affordable	73 DU	236[6]
	Residential Subtotal	1,000 DU	8,593
Non-residential			
Commercial		40,000 SF[7]	2,701
Hotel		120 Rooms	959
Office		190,000 SF	2,028
Public/Institutional		70,000 SF	???[8]
Recreation		12.1 Acres	9
	Non-residential Subtotal		5,697
		TOTAL	**14,290**

Notes:
1. Reference: Institute of Transportation Engineers, *Trip Generation Manual,* 11th Edition, 2021.
2. Dwelling unit.
3. Affordable housing assumed to be 25 percent of all residential types.
4. Based on ITE Land Use Code 223 – Affordable Housing – Income Limits, which is defined as including only multifamily housing. This represents a conservative assumption regarding trip generation for this land use category.
5. Based on ITE Land Use Code 251 – Senior Adult Housing – Single Family.
6. Based on ITE Land Use Code 251 – Senior Adult Housing – Multifamily. This rate is conservative, since “Affordable Housing” rate is 48 percent higher than this.
7. Square feet.
7. No estimate is possible, given the lack of information regarding specific land uses in this category.

3. ***Internal Trips are Substantially Overestimated*** – As described above, the DEIR transportation analysis (p. 440) claims that 1,398 of the Project's total 5,736 daily trips will occur completely within the Project site. In other words, 24.4 percent of the vehicle-trips resulting from the Project would never leave the Project site. These trips, which are typically referred to as internal trips, would have no impact on any element of the transportation system beyond the Project boundaries. Because this a substantial percentage, it seemed appropriate to test the validity of this claim.

   Various tools are available to develop estimates of internal tripmaking at mixed-use developments such as the proposed Project. Three such tools have been employed here:

   - Institute of Transportation Engineers/NCHRP 684 Internal Trip Capture Estimation Tool – As described in the ITE *Trip Generation Handbook* (Third Edition, September 2017, p. 46), this approach is based on procedures documented in National Cooperative Highway Research Program (NCHRP) Report 684: Enhancing Trip Capture Estimation for Mixed-Use Developments. That report documents the extensive research, data collection, and analysis undertaken in developing and validating the recommended procedure.
   - U.S. Environmental Protection Agency (EPA) Mixed Use Trip Generation Model – As described at the EPA website (https://www.epa.gov/smartgrowth/mixed-use-trip-generation-model), this model was developed cooperatively between EPA and ITE. Six metropolitan regions were evaluated in detail and the resulting model was validated against actual traffic counts at mixed-use developments across the country. This model is in use in California, Washington, and New Mexico, and according to EPA the model has been adopted as a statewide standard by the Virginia Department of Transportation.
   - San Diego Association of Governments (SANDAG) Smart Growth Trip Generation Spreadsheet Tool – Similar to the EPA method, this tool employs trip generation rates specific to the San Diego region. Although the trip rates vary from the ITE rates, the internal trip capture results should be representative of a development similar to the proposed Project.

   The results of these analyses are summarized below.

   ITE/NCHRP 684 Internal Trip Capture Estimation Spreadsheet Tool

   Attachment 4 contains a copy of the spreadsheet illustrating the results of this analysis procedure. Although the spreadsheet tool allows for adjustments to be made to reflect transit usage and changes to vehicle occupancy, no such modifications were made. Doing so would simply reduce the number of vehicle-trips estimated (internal, external, and total) with no effect on the resulting internal trip percentages.

   As shown in Attachment 4, the model projects an internal capture percentage of nine percent (actually 8.8 percent). The gross total of 12,256 daily trips would be reduced to 11,180, with 1,076 internal trips estimated. (Note that three of the individual daily trip totals were rounded up to ensure equal numbers of entering and exiting daily trips in the spreadsheet. Thus, the total trip generation in the model is 12,256 instead of the 12,253 described earlier.)

EPA Mixed Use Trip Generation Model

The results of this analysis are presented in Attachment 5. According to the EPA tool, the Project's 12,253 daily trips would be reduced to 11,291 external vehicle-trips (a difference of 962 trips). Those 962 internal trips include 796 vehicle-trips, 114 external walking trips, and 53 external transit trips.

Considering only vehicle-trips (and ignoring external walking and transit trips), the 796 internal vehicle-trips represent an internal capture rate of 6.5 percent.

SANDAG Smart Growth Trip Generation Spreadsheet Tool

As described above, the SANDAG tool is very similar to the EPA tool, but with minor modifications to reflect local San Diego conditions. Nonetheless, it is believed to provide valuable perspective regarding the level of internal tripmaking at the proposed Project. The SANDAG results are provided in Attachment 6.

The SANDAG model estimates that a total of 996 trips will be in the form of 821 internal vehicle-trips, 120 external walking trips, and 55 external transit trips. The 821 internal vehicle-trips constitute 6.7 percent of the 12,253 gross total daily trips.

Summary

The internal trip values derived from the three models presented here range from 6.5 to 8.8 percent, and all are substantially lower than the 24.4 percent value employed in the DEIR analysis. By substantially overstating the volume of traffic to be captured within the Project site, the number of external trips was excessively reduced. Consequently, the DEIR analysis has failed to accurately assess the off-site impacts of the Project.

Specifically, by underestimating the number of external trips, the analysis has similarly understated the Project-related VMT, which serves as basis for determining the significance of the Project's transportation impact. In short, the Project's transportation impact has been greatly understated due to a failure to provide an accurate estimate of the volume of traffic resulting from the Project.

Table 3
Internal Vehicle-Trip Percentage Summary

Source	Total Trips	Internal Vehicle-Trips	Net External Vehicle-Trips	Internal Vehicle-Trip Percentage
DEIR	5,736	1,398	4,338	24.4%
ITE Spreadsheet Tool	12,256	1,076	11,180	8.8%
EPA Mixed Use Trip Generation Model	12,253	796[1]	11,291	6.5%
SANDAG Smart Growth Trip Generation Spreadsheet Tool	12,253	821[2]	11,257	6.7%

Notes:
1 EPA model also projects 114 external walking trips and 53 external transit trips.
2 SANDAG model also projects 120 external walking trips and 55 external transit trips.

4. ***Flawed Project Traffic Assignment*** – DEIR Table 3.14-3: Projected Traffic Volumes in Plan Area (DEIR p. 441) presents traffic volume information for the three road segments that provide access to the site – Arnold Drive north and south of the site and the proposed Highway 12 connector. (Orchard Road connects to Jack London State Park to the west of the site, but would not be expected to carry a meaningful volume of Project traffic. That road is not included in the DEIR analysis.) Information is presented for various scenarios, both with and without the Project and with and without the Highway 12 connector. Based on this information, it is possible to derive the Project traffic assignment – that is, how many of the Project's claimed 4,338 external daily trips are estimated to be added to each of these three road segments. Table 4 below summarizes that information. (We should note that we were unable to confirm all of the existing traffic volumes, as DEIR p. 419, which apparently includes some of that information, was missing from the document that was available for downloading from the county website.)

   In each scenario analyzed, the volume of Project traffic assigned to the regional access roads falls substantially short of the 4,338 external trips claimed to be generated by the Project. In both scenarios involving implementation of the Highway 12 connector, the volume of traffic projected on Arnold Drive between Harney and Glen Ellen is actually shown to be reduced upon completion of the Project, which seems unlikely. The volume of Project traffic and its relationship to the claimed Project trip generation is summarized as follows:

   - Existing + Project (With Highway 12 Connector): 4,070 Daily Trips (93.8% of Project trips)
   - Existing + Project (No Highway 12 Connector): 3,410 Daily Trips (78.6% of Project trips)
   - Future + Project (With Highway 12 Connector): 3,320 Daily Trips (76.5% of Project trips)
   - Future + Project (No Highway 12 Connector): 2,650 Daily Trips (61.1% of Project trips)

   The DEIR analysis apparently fails to include a substantial portion of the Project traffic. Oftentimes, this sort of oddity is described as being due to existing or "background" traffic being diverted to other routes when the Project traffic demand is added to the study area roads. This can occur in a travel demand forecasting model when the added traffic causes a particular route to become congested and have high travel times, so the model redirects traffic to other, less congested routes so as to create an equilibrium condition on the study area road network with respect to travel time.

   In this case, though, no such alternative routes are available, so this explanation would not apply. The only explanation that does seem to apply is that the analysis is defective, and that it fails to accurately account for the full volume of Project traffic. The significance of this deficiency is magnified by the fact that the DEIR analysis only includes about 38 percent of the actual volume of Project traffic (i.e., 4,338 external trips compared to the corrected values of 11,180 – 11,291 documented in Table 3).

   The transportation analysis must be revised to remedy these substantial deficiencies, and the new analysis must recirculated for public review.

Table 4 Project Traffic Assignment Summary			
	Daily Vehicle-Trips		
Scenario	Arnold Drive – Harney to Glen Ellen	Arnold Drive – Harney to Madrone Rd.	Highway 12 Connector
Existing Conditions with Highway 12 Connector			
Existing No Project	6,330	7,150	--
Existing + Project	6,220	9,940	1,390
Project Only	-110	2,790	1,390
TOTAL PROJECT TRAFFIC	**4,070**		
Existing Conditions - No Highway 12 Connector			
Existing No Project	6,330	7,150	--
Existing + Project	7,400	9,490	--
Project Only	1,070	2,340	--
TOTAL PROJECT TRAFFIC	**3,410**		
Future Conditions with Highway 12 Connector			
Future No Project	6,730	7,670	--
Future + Project	6,310	9,960	1,450
Project Only	-420	2,290	1,450
TOTAL PROJECT TRAFFIC	**3,320**		
Future Conditions - No Highway 12 Connector			
Future No Project	6,730	7,670	--
Future + Project	7,410	9,640	--
Project Only	680	1,970	--
TOTAL PROJECT TRAFFIC	**2,650**		
Reference: DEIR, Table 3.14-3: Projected Traffic Volumes in Plan Area, p. 441.			

5. ***Defective Vehicles-Miles Traveled Analysis*** – The analysis of VMT impacts (Impact 3.14-2, DEIR p. 445) indicates that the Project will have a significant and unavoidable impact, with a significant impact relative to Household VMT and less than significant impacts regarding Employment VMT and Total VMT per Service Population. A significant impact was also found with respect to induced VMT associated with the proposed connector to Highway 12 (which is described as an "east-west emergency access connection from the site"). (DEIR p. 447)

   We believe the VMT analysis is flawed, as described in the following sections.

   Transportation Demand Management Effects

   The VMT analysis is summarized in DEIR Table 3.14-4: Planning Area VMT Metrics. (DEIR p. 446) That table includes a section labeled "Proposed Plan with 15% TDM Reduction," which is described as being for informational purposes and "reflect[s] a theoretical 15% reduction in VMT associated with required TDM measures." We believe this information is misleading, as no support is provided with respect to the feasibility of actually achieving a 15 percent reduction in VMT. Further, based on this "theoretical" information the DEIR makes the questionable and conclusory statement that (DEIR p. 447):

> *. . . it is likely that actual VMT will be less than the projections above.*

Our analysis has suggested that, to the contrary, the actual VMT will be substantially greater than those projections. In fact, only one paragraph later the DEIR contradicts itself and recognizes the questionable nature of the suggested TDM benefits (DEIR p. 447):

> *However, the ability for individual development projects to achieve a 15 percent reduction in VMT is uncertain.*

Clearly, any statement regarding the potential benefits of implementing TDM measures at the Project must be taken with a sizable grain of salt.

Employment VMT Analysis

As noted above, the DEIR analysis found a less than significant impact with respect to Employment VMT (also referred to as "Home-Work VMT per Worker" in the DEIR), with a finding of 4.8 home-based commute VMT per worker. (DEIR p. 445) Table 3.14-4 lists values for other pertinent geographical areas near the Project, as follows:

- Planning Area Baseline Average: 7.1 home-based commute VMT per worker,
- Countywide Baseline Average: 12.4 home-based commute VMT per worker, and
- Regional Baseline Average: 16.9 home-based commute VMT per worker.

These values raise questions regarding the validity of the DEIR's employment VMT finding of 4.8 home-based commute VMT per worker. This value is about 67 percent of the corresponding value for the Planning Area, 39 percent of the Countywide value, and only 28 percent of the Bay Area Region value. Without further substantiation of the DEIR's VMT analysis procedures and background parameters and inputs, it is difficult to readily accept that the Project's VMT result would be so vastly different from the other areas referenced above.

Unfortunately, the reviewing public is expected to blindly accept the output of the SCTM19 travel demand forecasting model even though, as described above, the model has obvious flaws with respect to its ability to estimate Project-related traffic volumes. In short, we question whether the employment VMT value derived for the Project is credible.

Proposed Policies Reducing VMT Impact

In recognition of the Project's significant and unavoidable VMT impact, the DEIR addresses ways to reduce that impact. The primary approach to achieving this goal is apparently Specific Plan Policy 3-41, which states, in part (Specific Plan p. 3-12):

> *Require all development to reduce vehicle trips by at least 15 percent below rates listed by the Institute of Transportation Engineers Trip Generation manual using transportation demand management strategies.*

As we described above, however, the Project's supposed trip generation, as reflected in Section 3.14 – Transportation, is already extremely low. According to the DEIR, the total daily trip generation is 5,736 trips/day. This includes trips associated with 1,000 residential dwelling units and substantial non-residential development types although, unfortunately, no trip generation breakdown is provided between the residential and non-residential land uses.

For perspective, if we totally ignore the non-residential development (a frankly ridiculous notion, given that this ignores 190,000 SF of office space and 40,000 SF of commercial space), the Project's trip generation rate would be 5.736 trips per dwelling unit (i.e., 5,736 trips / 1,000 DU = 5.736). If the non-residential land uses were included, the overall Project trip rate would be substantially lower.

For comparison, the current ITE daily trip generation rates for various types of residential uses that are potentially applicable to the Project are as follows:

- Single-Family Detached Housing: 9.43 daily trips/dwelling unit,
- Single-Family Attached Housing: 7.20 daily trips/dwelling unit,
- Multifamily Housing (Low Rise – Not Close to Rail Transit): 6.74 daily trips/dwelling unit.

Therefore, it appears that, if the Project's trip generation estimate is to be believed, the Project trip rate is already substantially less than 15 percent below the ITE trip rates. Two conclusions can be derived from this information:

- The Project's trip generation as presented in the DEIR is not to be believed, and
- Specific Plan Policy 3-14 is specious.

<u>Summary</u>

As we have described above, the DEIR transportation analysis is significantly flawed and those flaws relate directly to the validity of the VMT analysis. To briefly summarize:

- The Project trip generation estimate substantially understates the volume of traffic that will result from the Project.
- The internal trip capture rate is excessive, resulting in further reduction of the Project's traffic volumes.
- Only a portion of the Project's trips have actually been assigned to the study area roads.
- The purported benefits of implementation of TDM strategies are unlikely to be realized.
- The Project's derived Employment VMT value is highly questionable, when viewed in light of corresponding values for nearby geographical areas.
- Specific Plan Policy 3-41, which is claimed as a means to reduce Project VMT, is virtually meaningless, unless the Project's trip generation estimate is substantially modified to reflect reality.

The VMT analysis must be modified to correct the deficiencies described above. Upon completion of that revised VMT analysis, the DEIR must be recirculated for further public review.

CONCLUSION

Our review of the transportation analysis presented in the Draft Environmental Impact Report for the proposed Sonoma Developmental Center Specific Plan project in Sonoma County, California revealed several issues affecting the validity of the conclusions presented in that document. Particular deficiencies were identified with respect to the volume of traffic associated with the Project, how much of that traffic will be captured internally, the assignment of that traffic to the study area roads, and the validity of the estimate of Project-related vehicle-miles traveled. These issues must be addressed prior to approval of the proposed project and its environmental documentation by the County of Sonoma.

Sincerely,

GRIFFIN COVE TRANSPORTATION CONSULTING, PLLC

Neal K. Liddicoat

Neal K. Liddicoat, P.E.
Principal

Attachments

ATTACHMENT 1

Excerpt from Sonoma County General Plan 2020
Circulation and Transit Element

Sonoma County General Plan 2020

CIRCULATION AND TRANSIT ELEMENT

Sonoma County Permit and Resource Management Department
2550 Ventura Avenue
Santa Rosa, CA 95403

Adopted by Resolution No. 08-0808
of the Sonoma County Board of Supervisors
September 23, 2008

Amended by Resolution No. 10-0636 on August 24, 2010
Amended by Resolution No. 16-0283 on August 2, 2016

Policy CT-3ggg: Educate motorists, bicyclists, and pedestrians with regard to safety, rights, and responsibilities associated with use of the County transportation system.*

Policy CT-3hhh: Support constructive efforts from advocacy groups to address bicycle and pedestrian transportation issues.

Policy CT-3iii: Provide the option of flexible work schedules to County employees in order to accommodate commuting by bicycle, walking, or transit.*

Policy CT-3jjj: Develop a Guaranteed Ride Program for County workers and employees of other employers with participating programs who regularly bicycle, walk, vanpool, carpool, or use transit for their trip to work. The program would encourage use of alternative transportation modes by providing free transportation in the event of personal emergencies, illness, or unscheduled overtime.*

Policy CT-3kkk: Consider establishing greenhouse gas impact fees for new development. Use a portion of this fee to fund planning, design, and construction of bikeways and pedestrian facilities*.

Policy CT-3lll: Work with Federal, State, regional, and local agencies and any other available public or private funding sources to secure funding for bikeways and pedestrian facilities*.

Policy CT-3mmm: Encourage multi-jurisdictional funding applications for design, construction and maintenance of bikeways and pedestrian facilities that provide regional connectivity*.

Policy CT-3nnn: Develop a long range strategy to provide long term funding necessary to maintain and operate the Class I bikeway network*.

2.6 COUNTYWIDE HIGHWAY SYSTEM

GOAL CT-4: **Provide and maintain a highway system capacity that serves projected highway travel demand at acceptable levels of service in keeping with the character of rural and urban communities.**

Objective CT-4.1: Maintain LOS C or better on roadway segments unless a lower LOS has been adopted as shown on Figure CT-3.

Objective CT-4.2: Maintain LOS D or better at roadway intersections.*

Objective CT-4.3: Allow the above levels of service to be exceeded if it is determined to be acceptable due to environmental or community values, or if the project(s) has an overriding public benefit that outweighs lower

Footnote: *Mitigating Policy

levels of service and increased congestion.*

Objective CT-4.4: Utilize the American Association of State Highway Transportation Officials (AASHTO) functional classification system and guidelines for geometric design for the highway network.*

Objective CT-4.5: Consider developing a Heritage Road Program for Sonoma County. Heritage Roads would be subject to special design guidelines protecting their unique character, while meeting accepted AASHTO safety standards.

Objective CT-4.6: In recognition of the responsibility of the Cities and the County to contribute their fair share toward the mobility of County residents, coordinate with the Cities in the review of proposed development projects to identify a nexus between the project and impacts to the County transportation system, and to ensure that adequate mitigation is provided for impacts on the County transportation system.

Objective CT-4.7: Prioritize planned capacity improvements on Highways 101, 12, and 116 in recognition of the primary role that these highways play in providing mobility between communities. Prioritize capacity improvements to arterials over those for collector and local roads.

The following policies shall be used to achieve these objectives:

Footnote* Mitigating Policy

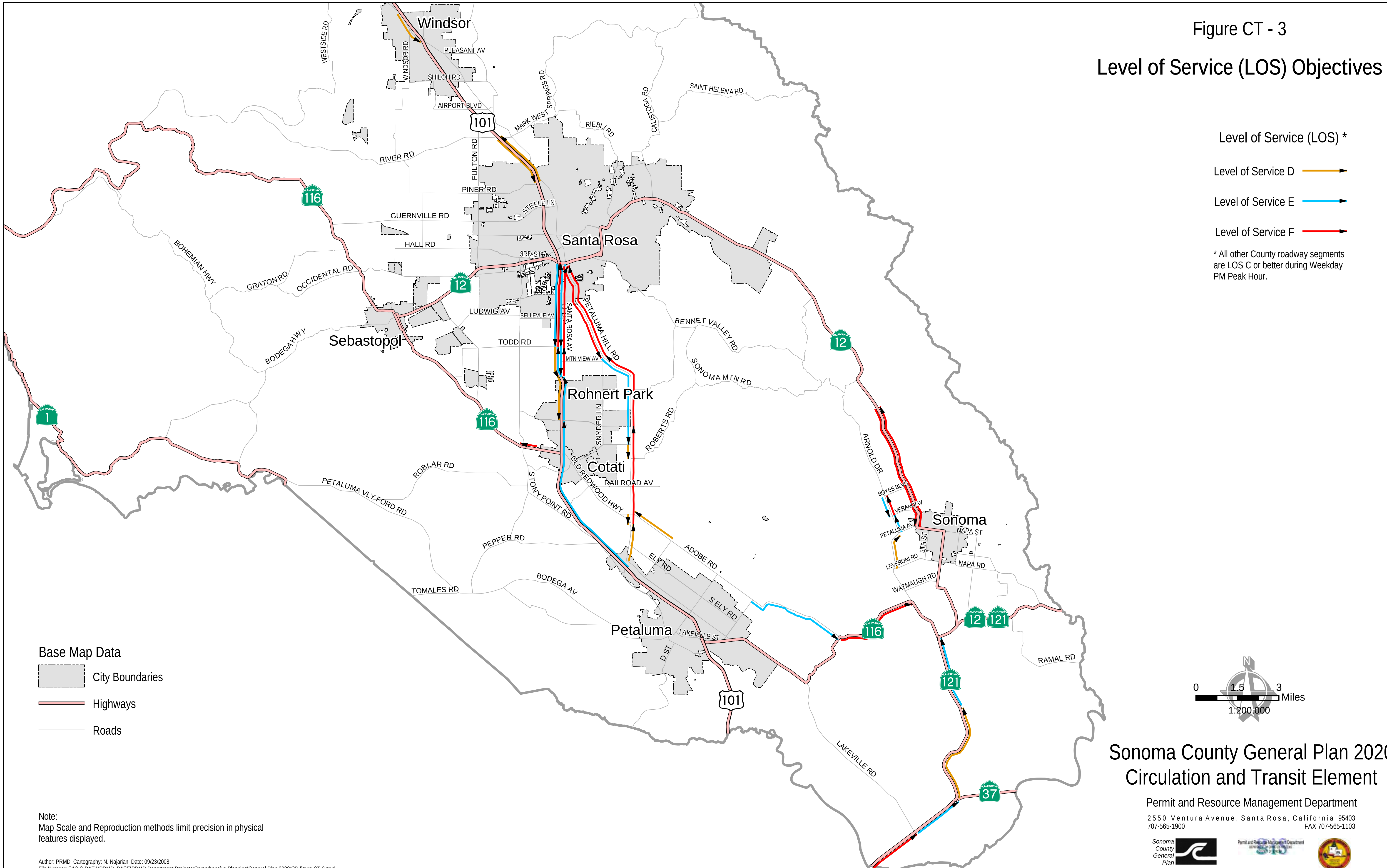


Figure CT - 3
Level of Service (LOS) Objectives
Level of Service (LOS) *
Level of Service D
Level of Service E
Level of Service F
* All other County roadway segments are LOS C or better during Weekday PM Peak Hour.
Base Map Data
City Boundaries
Highways
Roads
Windsor
Santa Rosa
Sebastopol
Rohnert Park
Cotati
Petaluma
Sonoma
WESTSIDE RD
WINDSOR RD
PLEASANT AV
SHILOH RD
AIRPORT BLVD
MARK WEST SPRINGS RD
RIEBLI RD
CALISTOGA RD
SAINT HELENA RD
RIVER RD
FULTON RD
PINER RD
STEELE LN
GUERNVILLE RD
HALL RD
3RD ST
BOHEMIAN HWY
GRATON RD
OCCIDENTAL RD
LUDWIG AV
BELLEVUE AV
SANTA ROSA AV
PETALUMA HILL RD
BENNET VALLEY RD
TODD RD
BODEGA HWY
MTN VIEW AV
SONOMA MTN RD
SNYDER LN
ROBERTS RD
ARNOLD DR
ROBLAR RD
OLD REDWOOD HWY
RAILROAD AV
STONY POINT RD
PETALUMA VLY FORD RD
BOYES BLVD
VERANO AV
PETALUMA AV
NAPA ST
5TH ST
LEVERONI RD
NAPA RD
WATMAUGH RD
ADOBE RD
ELY RD
S ELY RD
PEPPER RD
BODEGA AV
TOMALES RD
LAKEVILLE ST
D ST
RAMAL RD
LAKEVILLE RD
101
116
12
1
121
37
0
1.5
3
Miles
1:200,000
Note:
Map Scale and Reproduction methods limit precision in physical features displayed.
Author: PRMD Cartography: N. Najarian Date: 09/23/2008
File Number: S:\GIS-DATA\PRMD_BASE\PRMD Department Projects\Comprhensive Planning\General Plan 2020\GP figure CT-3.mxd
Sonoma County General Plan 2020
Circulation and Transit Element
Permit and Resource Management Department
2550 Ventura Avenue, Santa Rosa, California 95403
707-565-1900
FAX 707-565-1103
Sonoma County General Plan

ATTACHMENT 2

Project Trip Generation Data Sheets
1,000 Dwelling Units (25 Percent Inclusionary Income-Restricted)

(Source: Institute of Transportation Engineers,
***Trip Generation Manual*, Eleventh Edition, 2021.)**

Single-Family Detached Housing
(210)

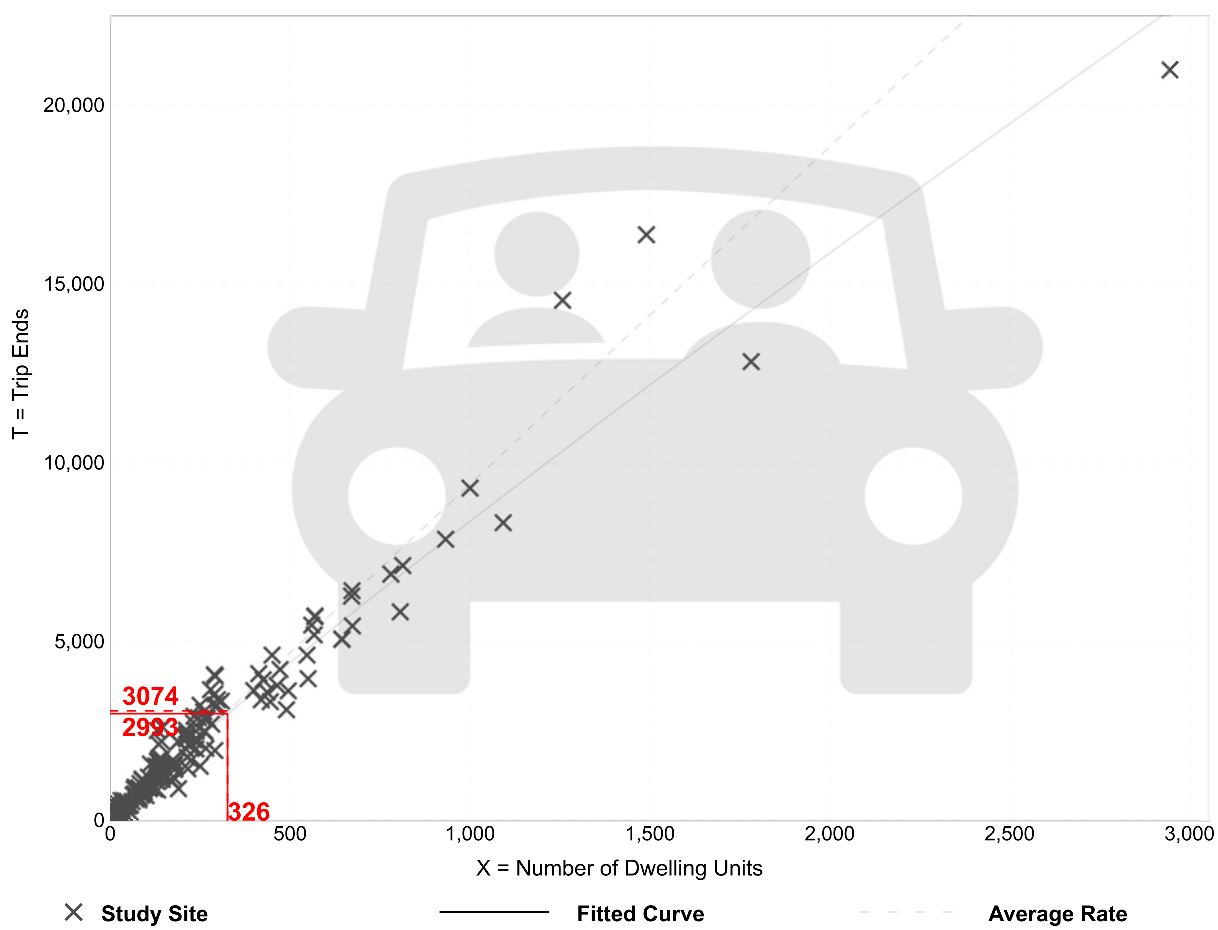
Vehicle Trip Ends vs:	**Dwelling Units**
On a:	**Weekday**

Setting/Location:	**General Urban/Suburban**
Number of Studies:	174
Avg. Num. of Dwelling Units:	246
Directional Distribution:	50% entering, 50% exiting

Vehicle Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
9.43	4.45 - 22.61	2.13

Data Plot and Equation



Fitted Curve Equation: $Ln(T) = 0.92 Ln(X) + 2.68$ **R^2= 0.95**

Trip Gen Manual, 11th Edition • Institute of Transportation Engineers

Affordable Housing - Income Limits
(223)

Vehicle Trip Ends vs: **Dwelling Units**
On a: **Weekday**

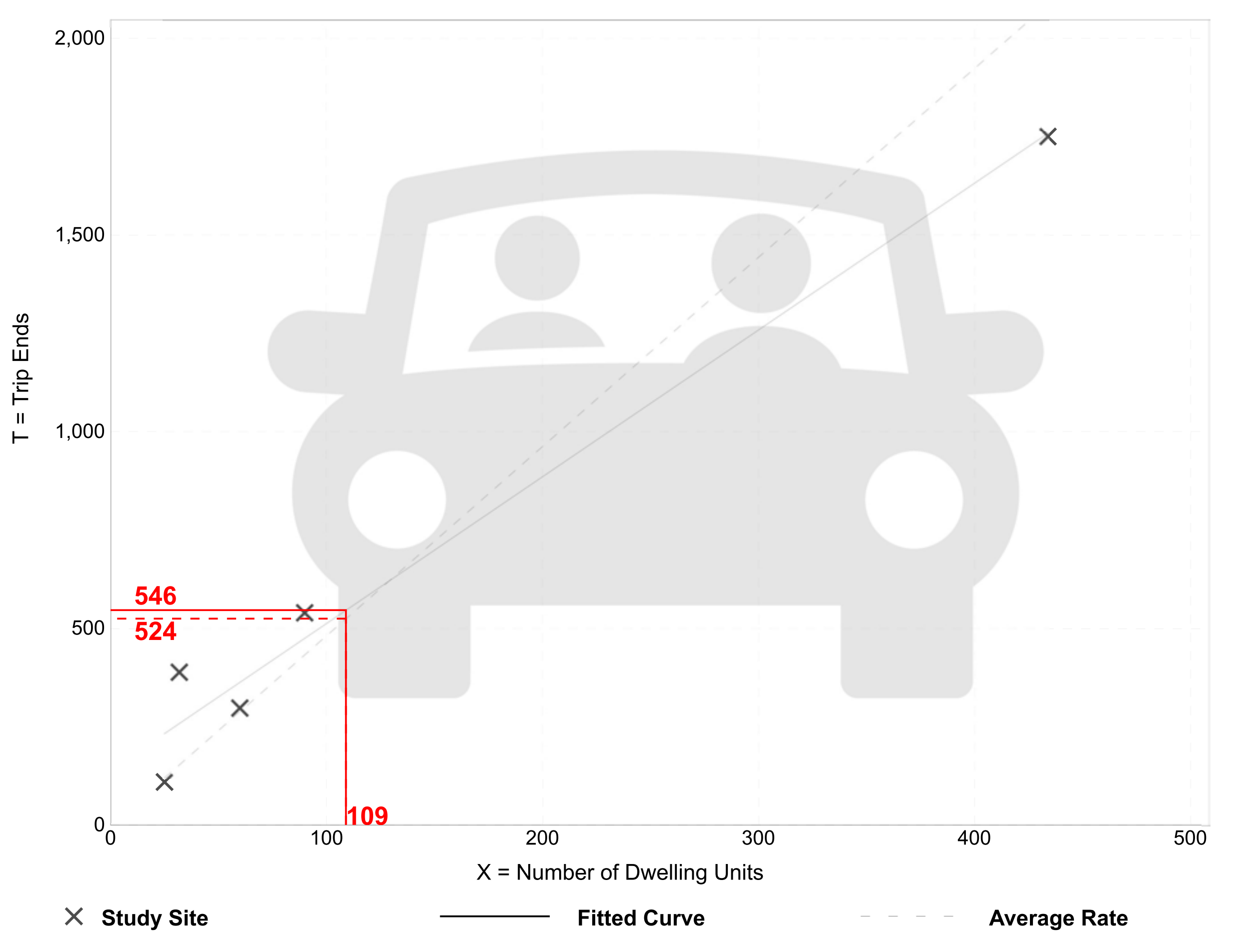
Setting/Location: **General Urban/Suburban**
Number of Studies: 5
Avg. Num. of Dwelling Units: 128
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
4.81	4.03 - 12.16	2.03

Data Plot and Equation

Caution – Small Sample Size



Fitted Curve Equation: $T = 3.73(X) + 139.35$

R^2 = 0.98

Trip Gen Manual, 11th Edition ● Institute of Transportation Engineers

Multifamily Housing (Low-Rise)
Not Close to Rail Transit (220)

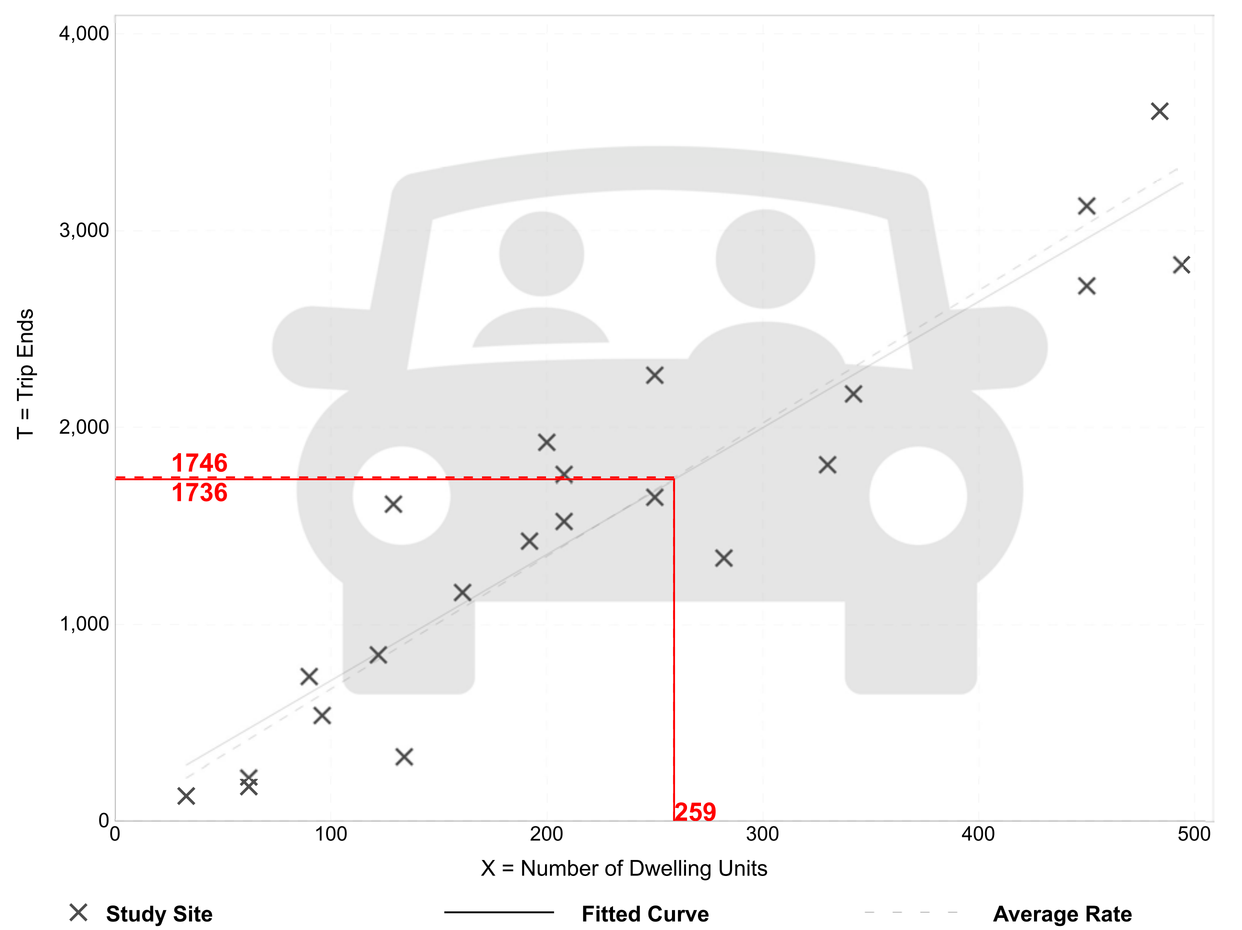
Vehicle Trip Ends vs: Dwelling Units
On a: Weekday

Setting/Location: General Urban/Suburban
Number of Studies: 22
Avg. Num. of Dwelling Units: 229
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
6.74	2.46 - 12.50	1.79

Data Plot and Equation



Fitted Curve Equation: $T = 6.41(X) + 75.31$ **$R^2 = 0.86$**

Trip Gen Manual, 11th Edition • Institute of Transportation Engineers

Affordable Housing - Income Limits
(223)

Vehicle Trip Ends vs: Dwelling Units
On a: Weekday

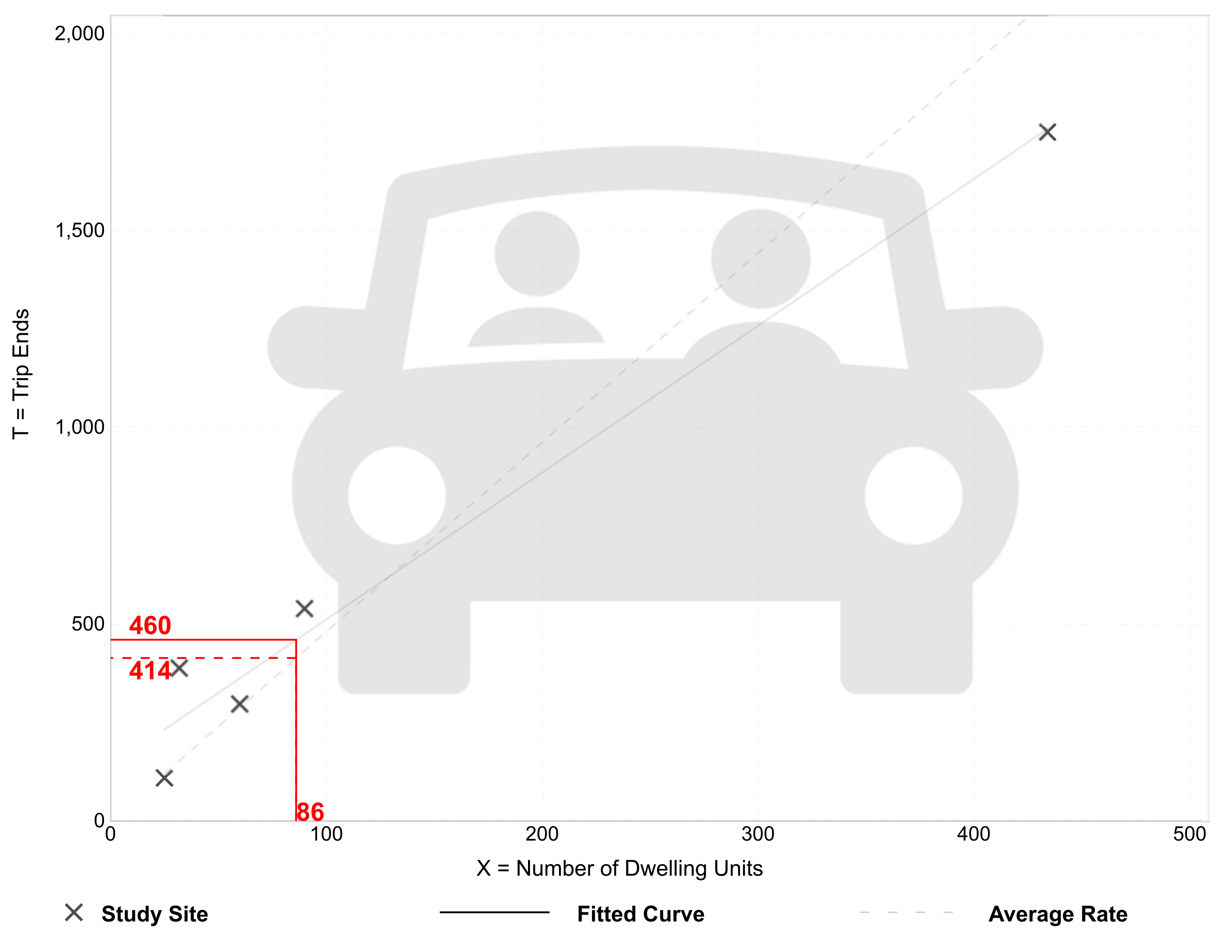
Setting/Location: General Urban/Suburban
Number of Studies: 5
Avg. Num. of Dwelling Units: 128
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
4.81	4.03 - 12.16	2.03

Data Plot and Equation

Caution – Small Sample Size



Fitted Curve Equation: $T = 3.73(X) + 139.35$

R^2= 0.98

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Senior Adult Housing - Single-Family
(251)

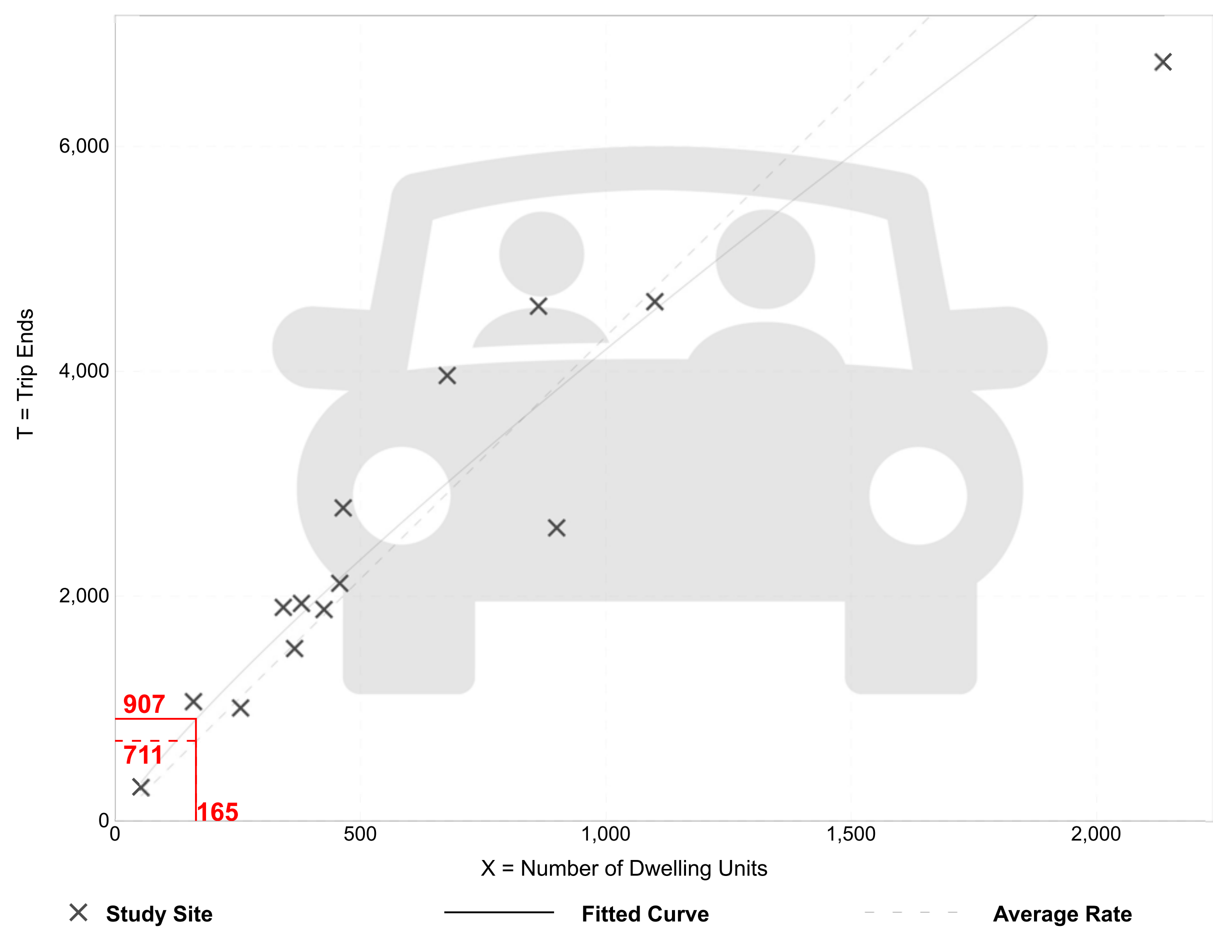
Vehicle Trip Ends vs: Dwelling Units
On a: Weekday

Setting/Location: General Urban/Suburban
Number of Studies: 15
Avg. Num. of Dwelling Units: 646
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
4.31	2.90 - 6.66	1.07

Data Plot and Equation



Fitted Curve Equation: $Ln(T) = 0.85\ Ln(X) + 2.47$

$R^2 = 0.94$

Trip Gen Manual, 11th Edition ● Institute of Transportation Engineers

Senior Adult Housing - Multifamily
(252)

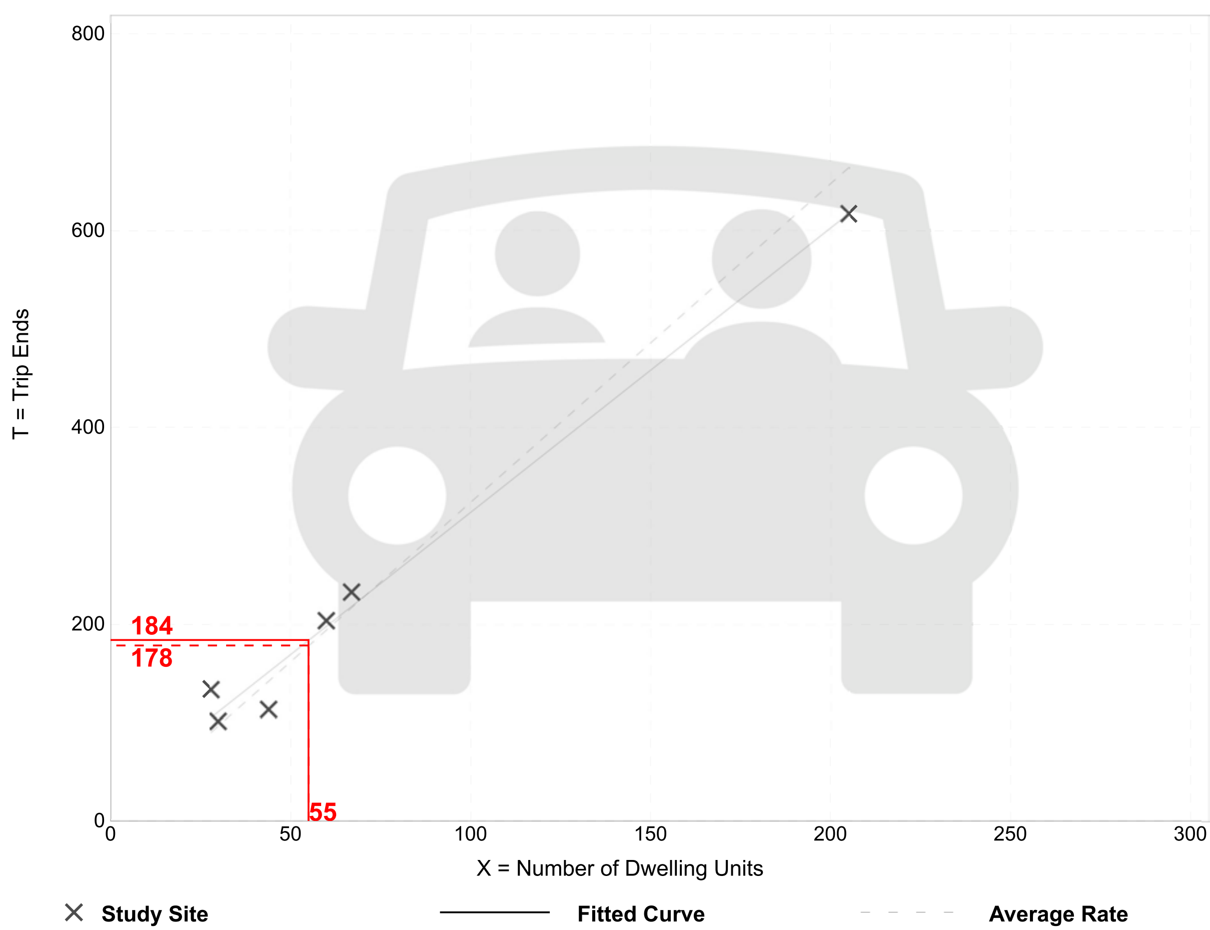
Vehicle Trip Ends vs:	**Dwelling Units**
On a:	**Weekday**

Setting/Location:	**General Urban/Suburban**
Number of Studies:	6
Avg. Num. of Dwelling Units:	72
Directional Distribution:	50% entering, 50% exiting

Vehicle Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
3.24	2.59 - 4.79	0.53

Data Plot and Equation



Fitted Curve Equation: T = 2.89(X) + 24.82 **R^2= 0.99**

Trip Gen Manual, 11th Edition • Institute of Transportation Engineers

Shopping Plaza (40-150k) - Supermarket - No
(821)

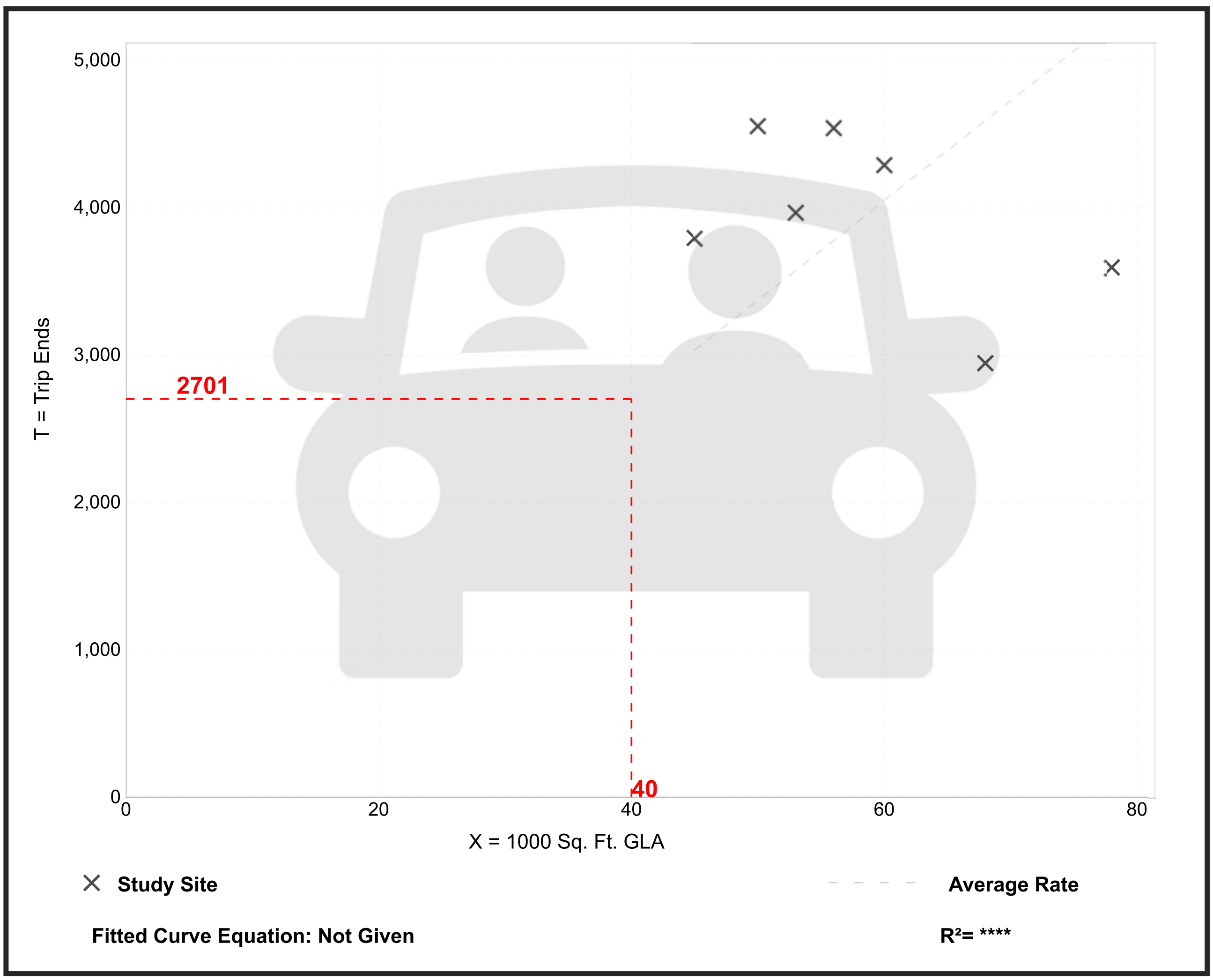
Vehicle Trip Ends vs: 1000 Sq. Ft. GLA
On a: Weekday

Setting/Location: General Urban/Suburban
Number of Studies: 7
Avg. 1000 Sq. Ft. GLA: 59
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per 1000 Sq. Ft. GLA

Average Rate	Range of Rates	Standard Deviation
67.52	43.29 - 91.06	19.25

Data Plot and Equation



Trip Gen Manual, 11th Edition • Institute of Transportation Engineers

Hotel
(310)

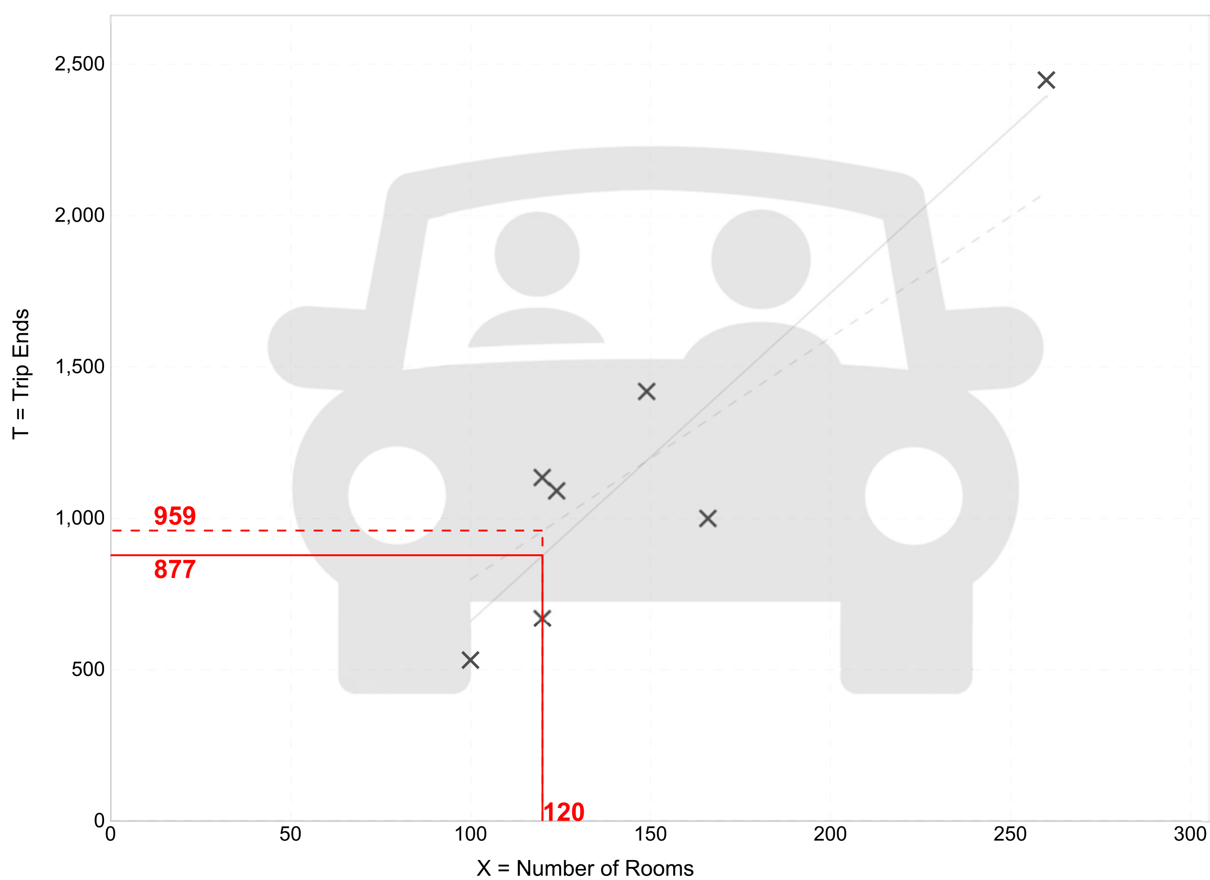
Vehicle Trip Ends vs: **Rooms**
On a: **Weekday**

Setting/Location: **General Urban/Suburban**
Number of Studies: 7
Avg. Num. of Rooms: 148
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per Room

Average Rate	Range of Rates	Standard Deviation
7.99	5.31 - 9.53	1.92

Data Plot and Equation



Fitted Curve Equation: T = 10.84(X) - 423.51 **R^2= 0.85**

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General Office Building
(710)

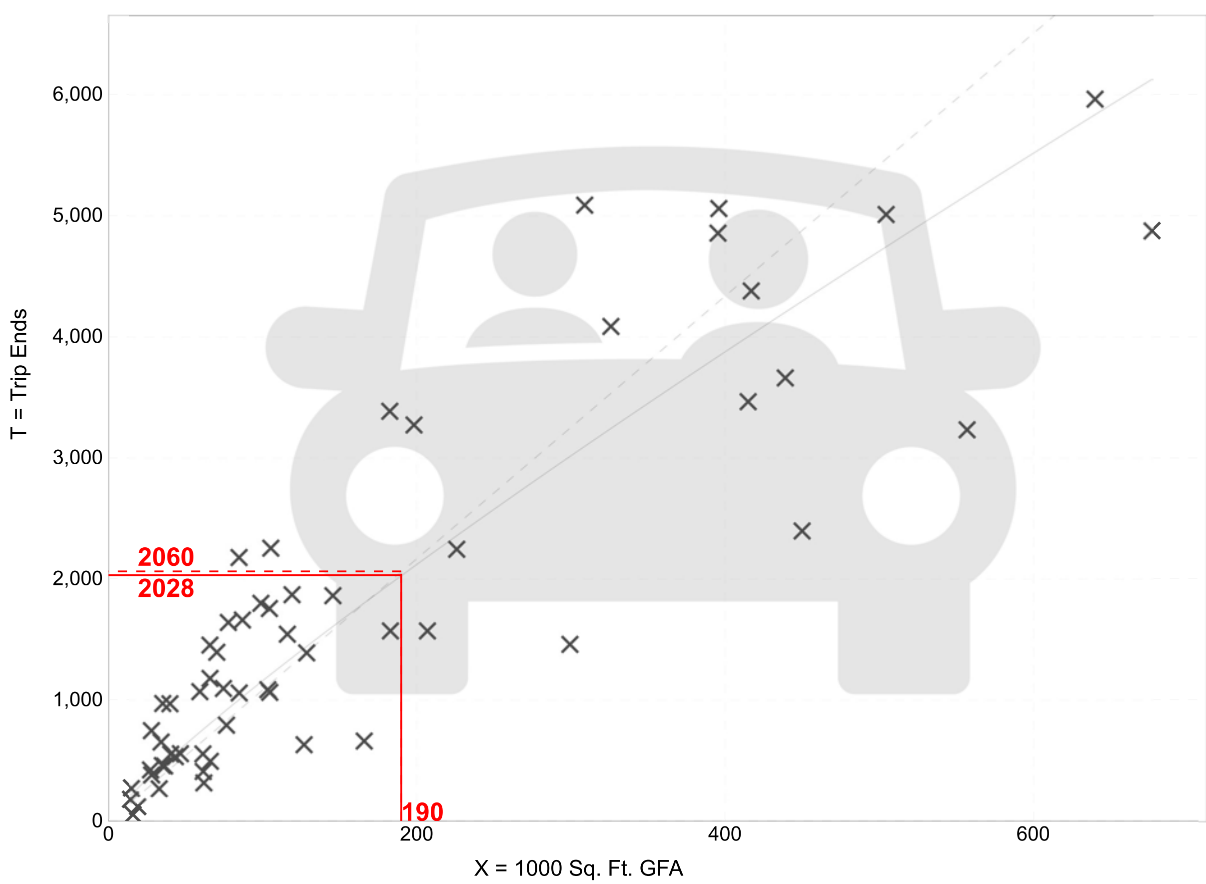
Vehicle Trip Ends vs: **1000 Sq. Ft. GFA**
On a: **Weekday**

Setting/Location: **General Urban/Suburban**
Number of Studies: 59
Avg. 1000 Sq. Ft. GFA: 163
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per 1000 Sq. Ft. GFA

Average Rate	Range of Rates	Standard Deviation
10.84	3.27 - 27.56	4.76

Data Plot and Equation



× **Study Site** —— **Fitted Curve** - - - **Average Rate**

Fitted Curve Equation: Ln(T) = 0.87 Ln(X) + 3.05 **R^2= 0.78**

Trip Gen Manual, 11th Edition • Institute of Transportation Engineers

Public Park
(411)

Vehicle Trip Ends vs: **Acres**
On a: **Weekday**

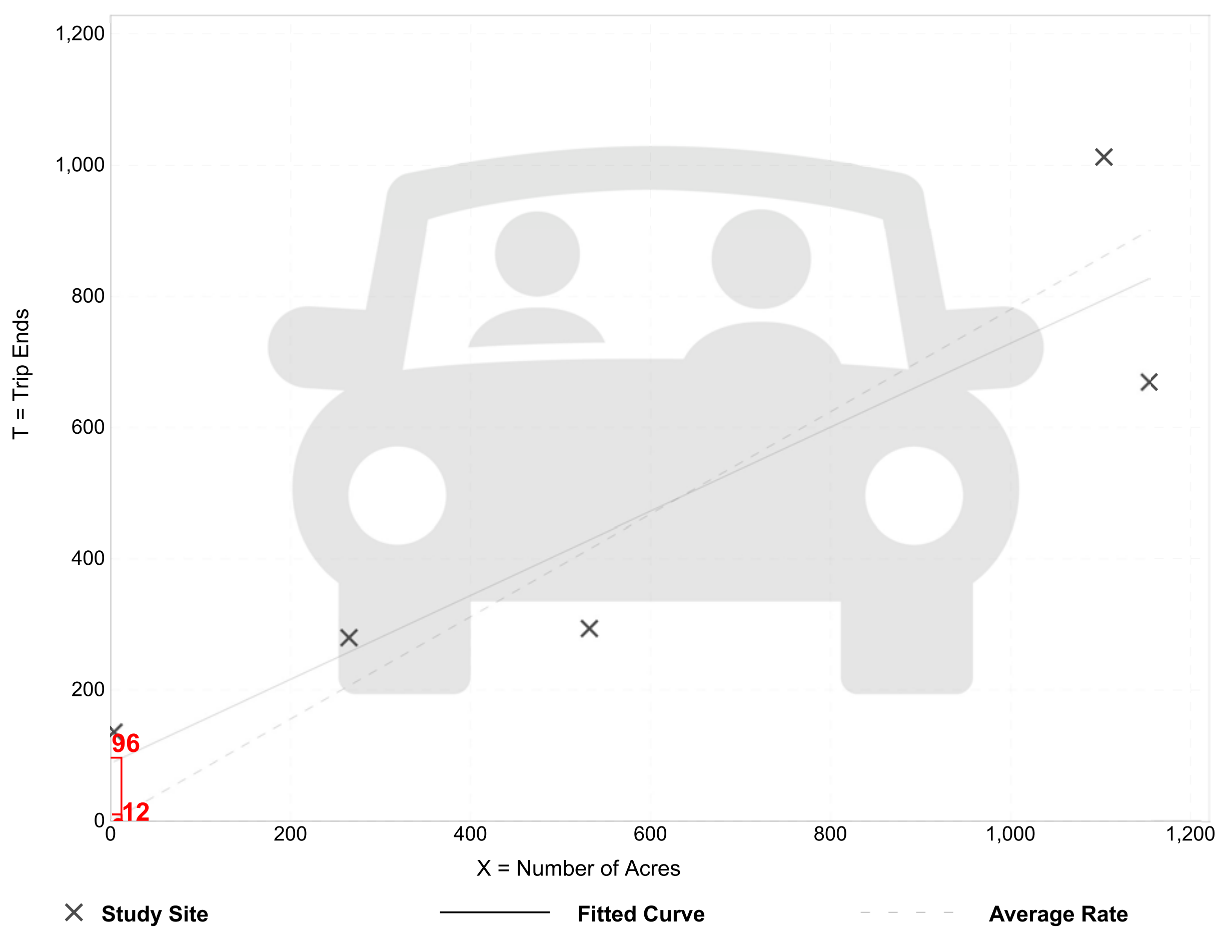
Setting/Location: **General Urban/Suburban**
Number of Studies: 5
Avg. Num. of Acres: 612
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per Acre

Average Rate	Range of Rates	Standard Deviation
0.78	0.55 - 34.00	1.36

Data Plot and Equation

Caution – Small Sample Size



Fitted Curve Equation: T = 0.64(X) + 88.46 **R^2= 0.82**

Trip Gen Manual, 11th Edition • Institute of Transportation Engineers

ATTACHMENT 3

Project Trip Generation Data Sheets – Residential Only
1,331 Dwelling Units (25 Percent Inclusionary Income-Restricted)

(Source: Institute of Transportation Engineers,
Trip Generation Manual*, Eleventh Edition, 2021.*)

Single-Family Detached Housing
(210)

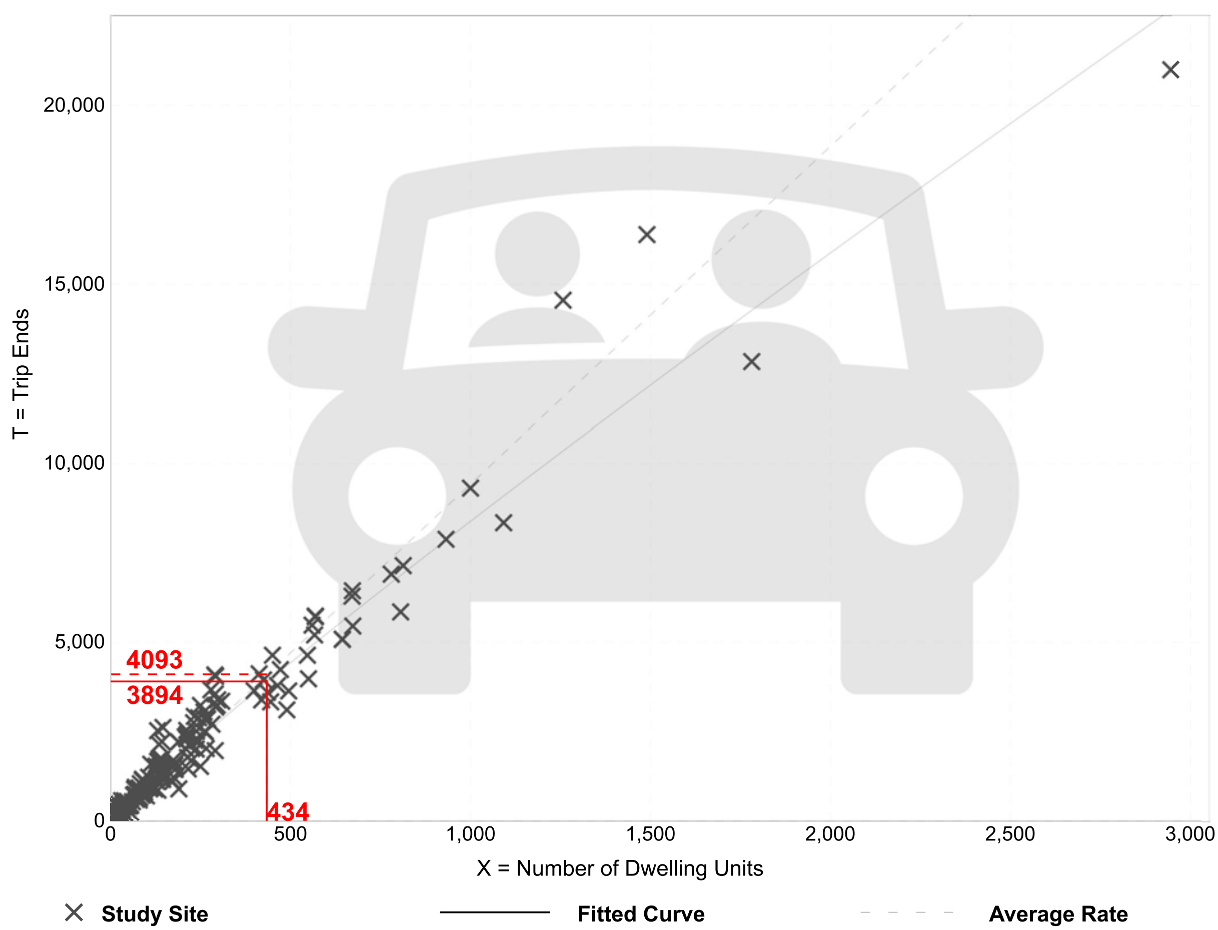
Vehicle Trip Ends vs: **Dwelling Units**
On a: **Weekday**

Setting/Location: **General Urban/Suburban**
Number of Studies: 174
Avg. Num. of Dwelling Units: 246
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
9.43	4.45 - 22.61	2.13

Data Plot and Equation



Fitted Curve Equation: Ln(T) = 0.92 Ln(X) + 2.68 **R^2= 0.95**

Trip Gen Manual, 11th Edition • Institute of Transportation Engineers

Affordable Housing - Income Limits
(223)

Vehicle Trip Ends vs: **Dwelling Units**
On a: **Weekday**

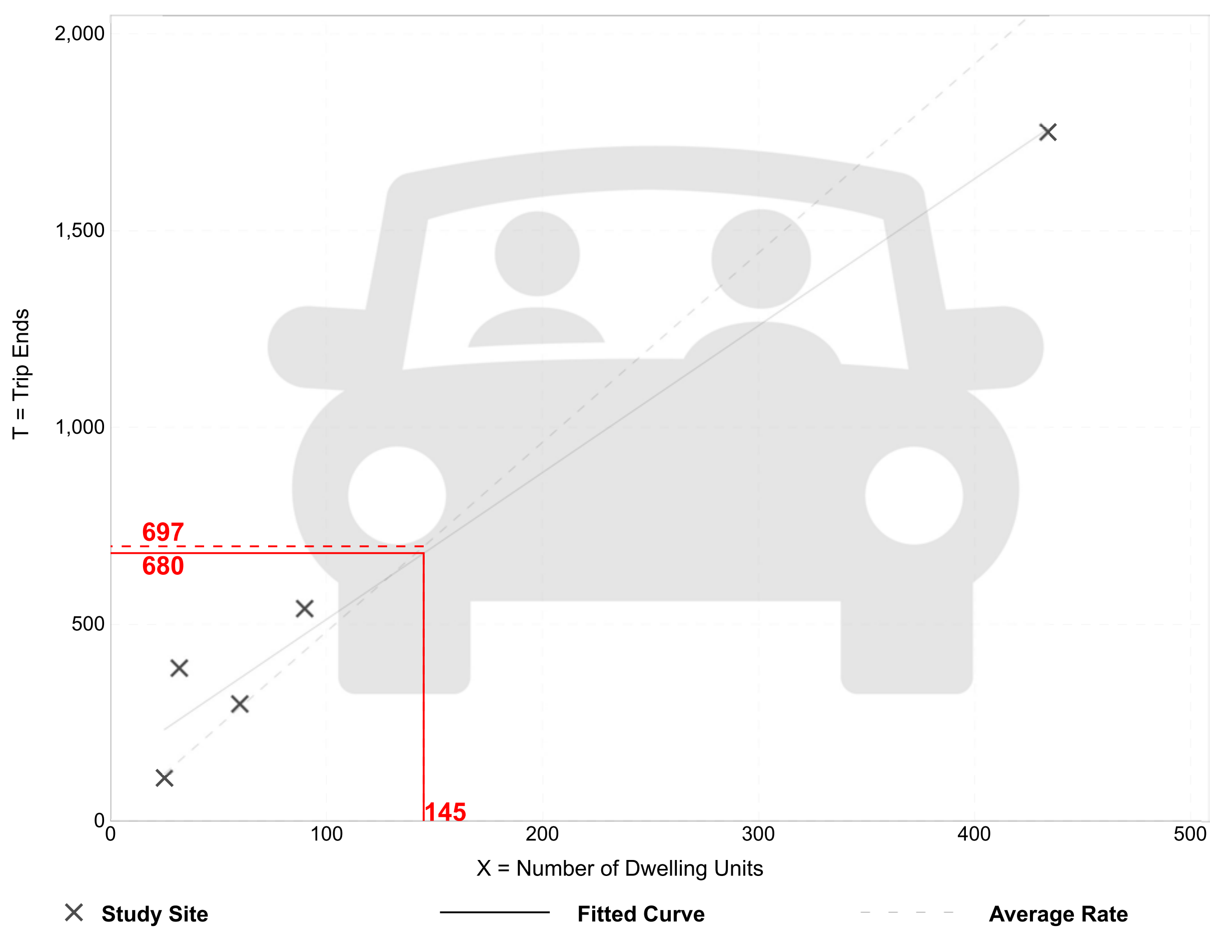
Setting/Location: **General Urban/Suburban**
Number of Studies: 5
Avg. Num. of Dwelling Units: 128
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
4.81	4.03 - 12.16	2.03

Data Plot and Equation

Caution – Small Sample Size



Fitted Curve Equation: T = 3.73(X) + 139.35 **R^2= 0.98**

Trip Gen Manual, 11th Edition • Institute of Transportation Engineers

Multifamily Housing (Low-Rise)
Not Close to Rail Transit (220)

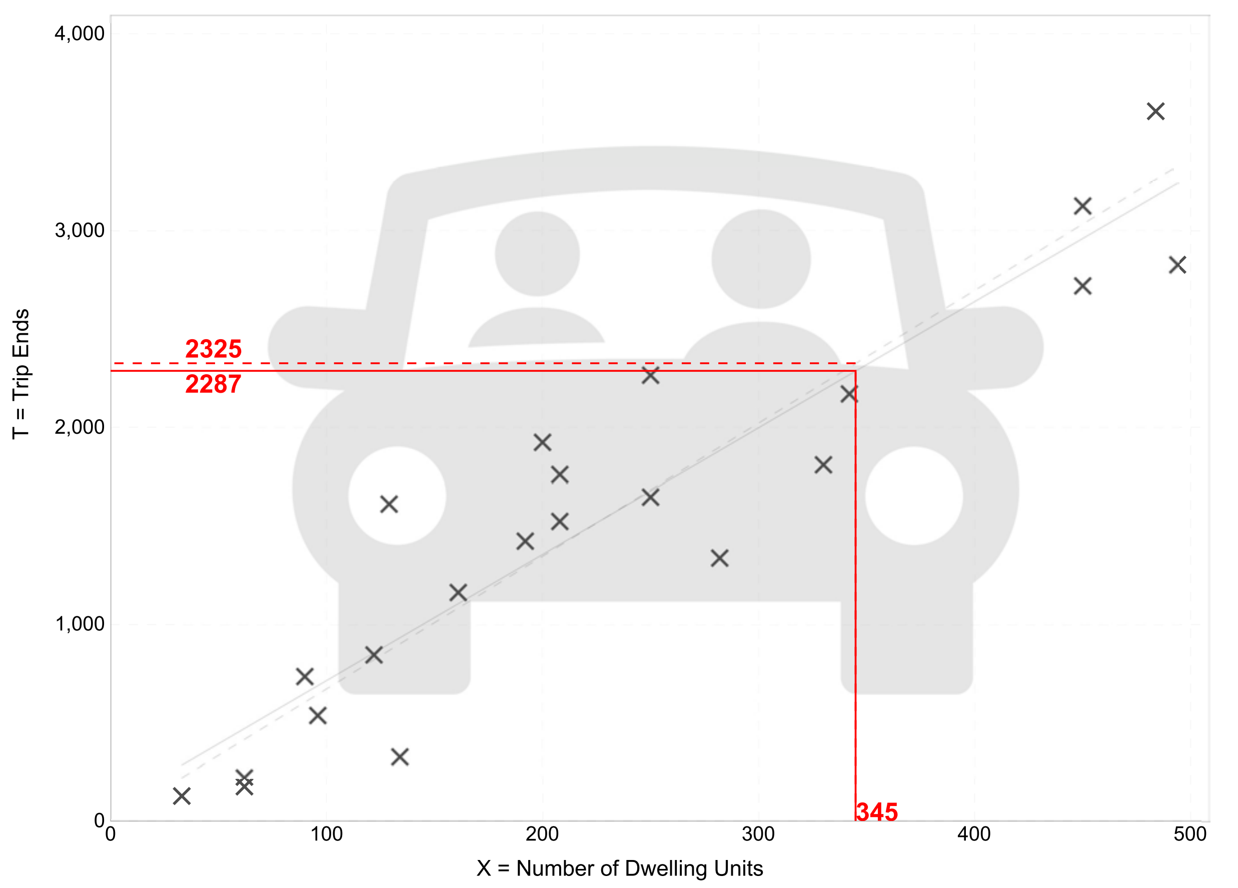
Vehicle Trip Ends vs: **Dwelling Units**
On a: **Weekday**

Setting/Location: **General Urban/Suburban**
Number of Studies: 22
Avg. Num. of Dwelling Units: 229
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
6.74	2.46 - 12.50	1.79

Data Plot and Equation



Fitted Curve Equation: T = 6.41(X) + 75.31 **R^2= 0.86**

Trip Gen Manual, 11th Edition • Institute of Transportation Engineers

Affordable Housing - Income Limits
(223)

Vehicle Trip Ends vs:	**Dwelling Units**
On a:	**Weekday**

Setting/Location:	**General Urban/Suburban**
Number of Studies:	5
Avg. Num. of Dwelling Units:	128
Directional Distribution:	50% entering, 50% exiting

Vehicle Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
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Data Plot and Equation

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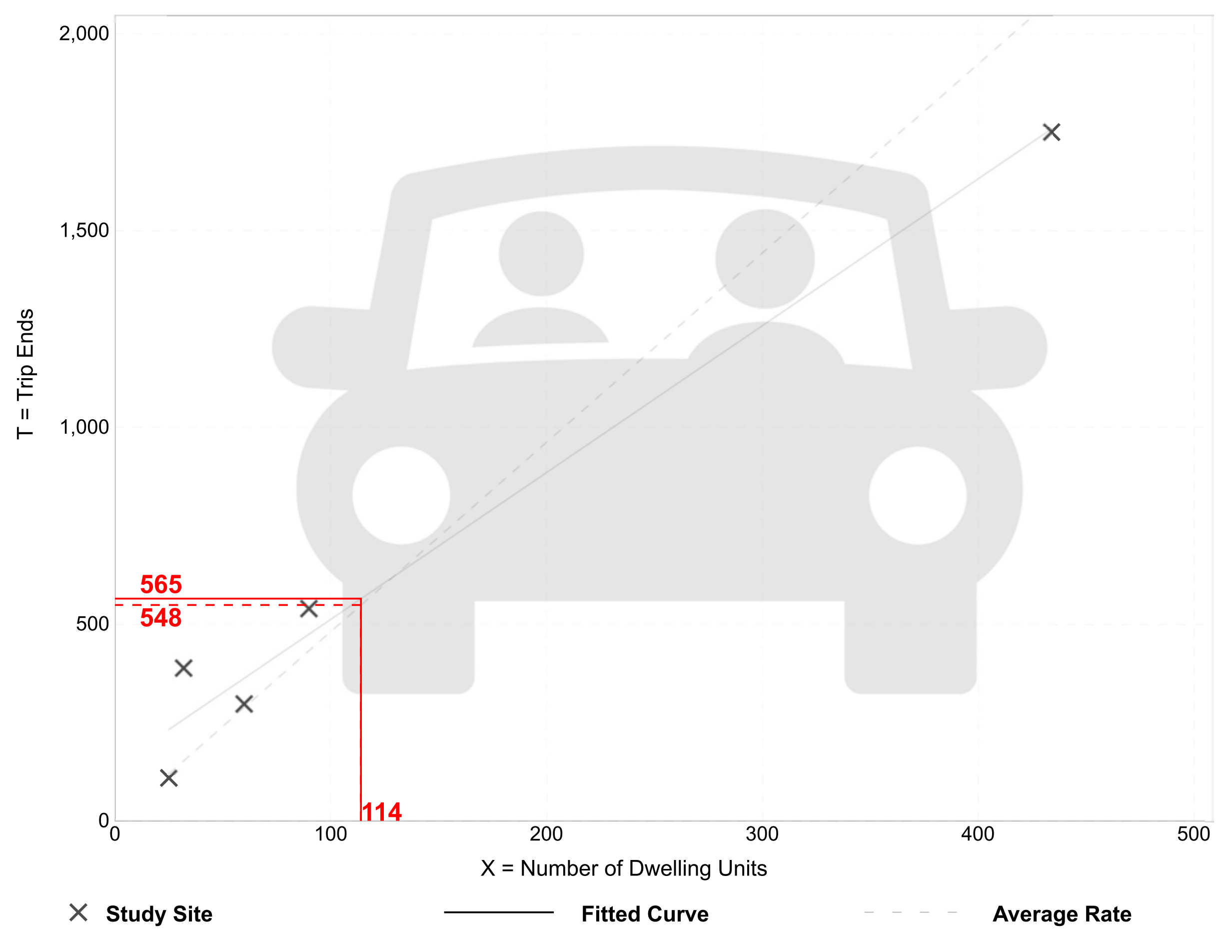


Fitted Curve Equation: $T = 3.73(X) + 139.35$ **$R^2 = 0.98$**

Trip Gen Manual, 11th Edition • Institute of Transportation Engineers

Senior Adult Housing - Single-Family
(251)

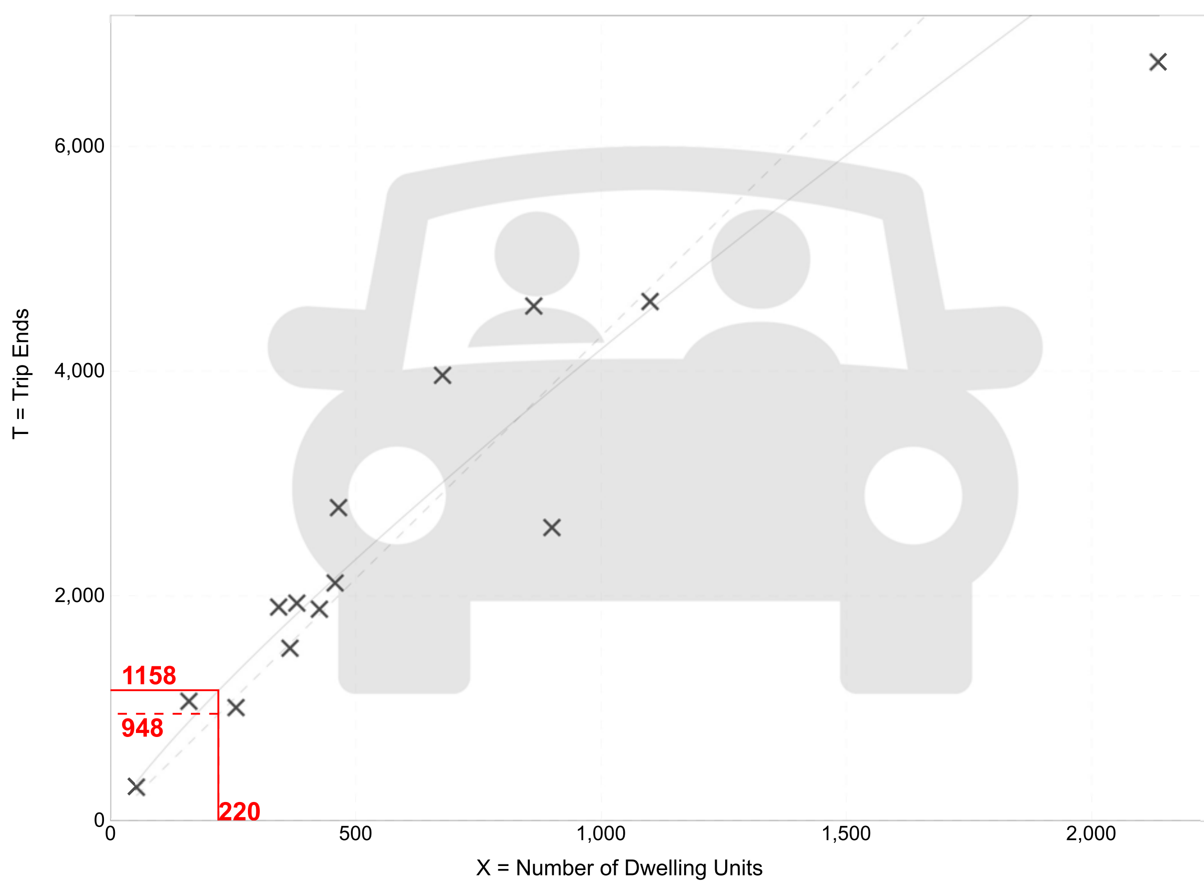
Vehicle Trip Ends vs: **Dwelling Units**
On a: **Weekday**

Setting/Location: **General Urban/Suburban**
Number of Studies: 15
Avg. Num. of Dwelling Units: 646
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
4.31	2.90 - 6.66	1.07

Data Plot and Equation



Fitted Curve Equation: Ln(T) = 0.85 Ln(X) + 2.47 **R^2= 0.94**

Trip Gen Manual, 11th Edition • Institute of Transportation Engineers

Senior Adult Housing - Multifamily
(252)

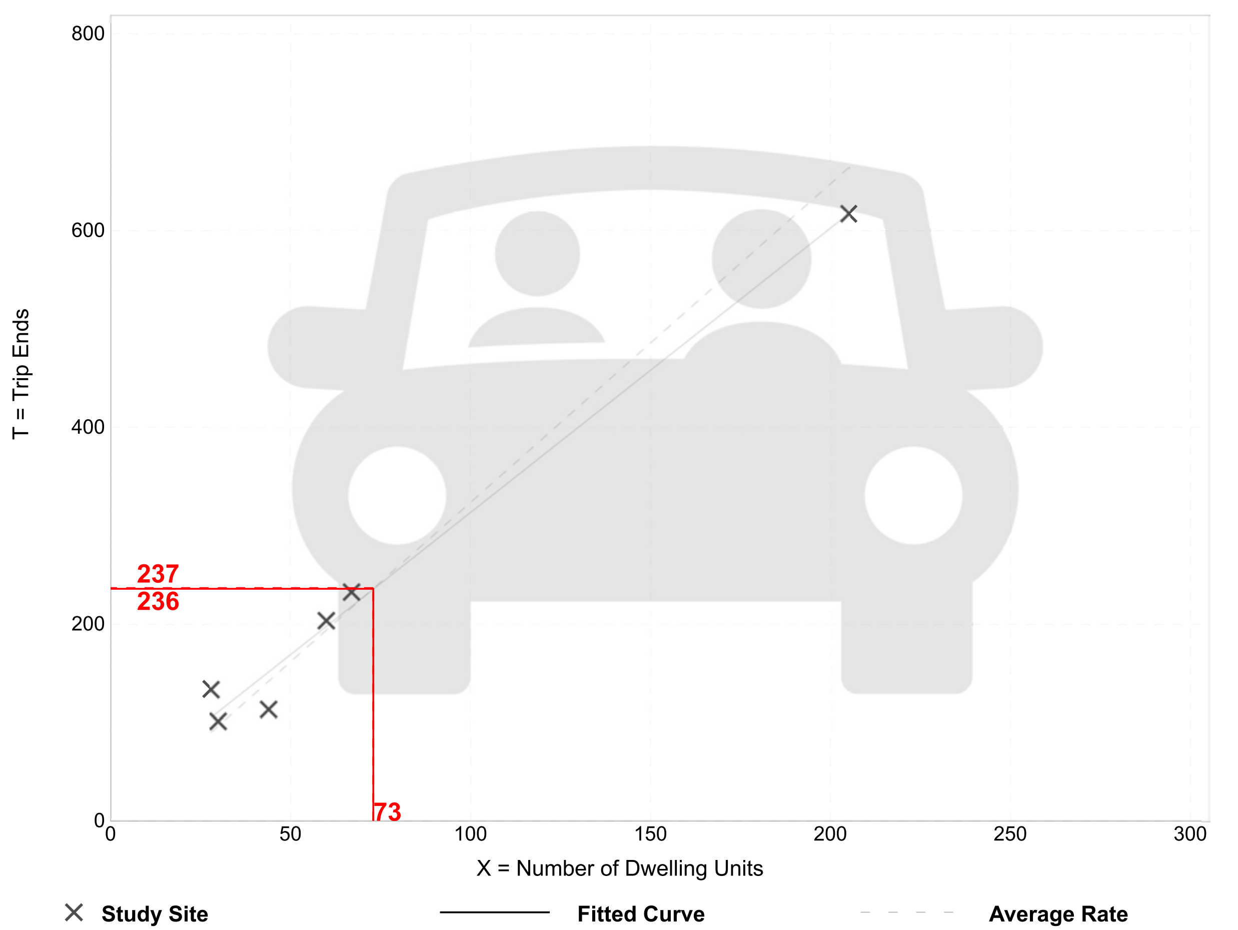
Vehicle Trip Ends vs: **Dwelling Units**
On a: **Weekday**

Setting/Location: **General Urban/Suburban**
Number of Studies: 6
Avg. Num. of Dwelling Units: 72
Directional Distribution: 50% entering, 50% exiting

Vehicle Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
3.24	2.59 - 4.79	0.53

Data Plot and Equation



Fitted Curve Equation: T = 2.89(X) + 24.82 **R^2= 0.99**

Trip Gen Manual, 11th Edition • Institute of Transportation Engineers

ATTACHMENT 4

Institute of Transportation Engineers/NCHRP 684
Internal Trip Capture Estimation Tool

NCHRP 684 Internal Trip Capture Estimation Tool

Project Name:	Sonoma Developmental Center		**Organization:**	Griffin Cove Transportation Consulting
Project Location:	Sonoma County, CA		**Performed By:**	NKL
Scenario Description:	Project w/ 1,000 DU		**Date:**	16-Sep-22
Analysis Year:			**Checked By:**	
Analysis Period:	**Daily**		**Date:**	

Table 1-A: Base Vehicle-Trip Generation Estimates (Single-Use Site Estimate)

Land Use	Development Data (***For Information Only***)				Estimated Vehicle-Trips[3]		
	ITE LUCs[1]	Quantity	Units		Total	Entering	Exiting
Office					2,028	1,014	1,014
Retail					2,702	1,351	1,351
Restaurant					0		
Cinema/Entertainment					0		
Residential					6,556	3,278	3,278
Hotel					960	480	480
All Other Land Uses[2]					10	5	5
					12,256	6,128	6,128

Table 2-A: Mode Split and Vehicle Occupancy Estimates

Land Use	Entering Trips				Exiting Trips		
	Veh. Occ.[4]	% Transit	% Non-Motorized		Veh. Occ.[4]	% Transit	% Non-Motorized
Office							
Retail							
Restaurant							
Cinema/Entertainment							
Residential							
Hotel							
All Other Land Uses[2]							

Table 3-A: Average Land Use Interchange Distances (Feet Walking Distance)

Origin (From)	Destination (To)					
	Office	Retail	Restaurant	Cinema/Entertainment	Residential	Hotel
Office						
Retail						
Restaurant						
Cinema/Entertainment						
Residential						
Hotel						

Table 4-A: Internal Person-Trip Origin-Destination Matrix*

Origin (From)	Destination (To)					
	Office	Retail	Restaurant	Cinema/Entertainment	Residential	Hotel
Office		284	0	0	0	0
Retail	41		0	0	66	0
Restaurant	0	0		0	0	0
Cinema/Entertainment	0	0	0		0	0
Residential	30	33	0	0		0
Hotel	30	54	0	0	0	

Table 5-A: Computations Summary

	Total	Entering	Exiting
All Person-Trips	12,256	6,128	6,128
Internal Capture Percentage	9%	9%	9%
External Vehicle-Trips[5]	11,180	5,590	5,590
External Transit-Trips[6]	0	0	0
External Non-Motorized Trips[6]	0	0	0

Table 6-A: Internal Trip Capture Percentages by Land Use

Land Use	Entering Trips	Exiting Trips
Office	10%	28%
Retail	27%	8%
Restaurant	N/A	N/A
Cinema/Entertainment	N/A	N/A
Residential	2%	2%
Hotel	0%	18%

[1]Land Use Codes (LUCs) from ***Trip Generation Manual***, published by the Institute of Transportation Engineers.

[2]Total estimate for all other land uses at mixed-use development site is not subject to internal trip capture computations in this estimator.

[3]Enter trips assuming no transit or non-motorized trips (as assumed in ITE ***Trip Generation Manual***).

[4]Enter vehicle occupancy assumed in Table 1-A vehicle trips. If vehicle occupancy changes for proposed mixed-use project, manual adjustments must be made to Tables 5-A, 9-A (O and D). Enter transit, non-motorized percentages that will result with proposed mixed-use project complete.

[5]Vehicle-trips computed using the mode split and vehicle occupancy values provided in Table 2-A.

[6]Person-Trips

*Indicates computation that has been rounded to the nearest whole number.

Estimation Tool Developed by the Texas A&M Transportation Institute - Version 2013.1

ATTACHMENT 5

U.S. Environmental Protection Agency (EPA) Mixed Use Trip Generation Model

EPA MIXED USE TRIP GENERATION MODEL - RESULTS

MODEL APPLICATION - ALL TRIPS

	Daily			
	HBW	HBO	NHB	Total
Baseline # of External Trips (ITE Model)	2804	6976	2474	12253
% External Trip Reduction (predicted by MXD Model)				
Internal Capture	3.71%	7.46%	6.93%	6.49%
Walking External	0.93%	1.24%	0.37%	0.99%
Transit External	0.23%	0.42%	0.86%	0.46%
# of Trips Reduced (predicted by MXD Model)				
Internal Capture	104	520	172	796
Walking External	25	80	8	114
Transit External	6	27	20	53
MXD Model # of Vehicle Trips	**2668**	**6349**	**2274**	**11291**

Results	**External Vehicle Trips**		
	Baseline	Adjusted	Reduction %
Daily	12,253	11,291	8%
AM Peak Hour	760	708	7%
PM Peak Hour	1,147	1,060	8%

MODEL APPLICATION - TRIP ENDS ASSOCIATED WITH HOUSES IN THE PROJECT ONLY

	Daily			
	HBW	HBO	NHB	Total
Baseline # of External Trips (ITE Model)	1282	4054	900	6235
% External Trip Reduction (predicted by MXD Model)				
Internal Capture	3.71%	7.46%	6.93%	6.61%
Walking External	0.93%	1.24%	0.37%	1.05%
Transit External	0.23%	0.42%	0.86%	0.44%
# of Trips Reduced (predicted by MXD Model)				
Internal Capture	48	302	62	412
Walking External	12	46	3	61
Transit External	3	16	7	26
Adjusted # (MXD Model) of Vehicle Trips generated by Project Residences	**1220**	**3689**	**827**	**5736**

	External Vehicle Trips		
Results	Baseline	Adjusted	Reduction %
Daily	6,235	5,736	8%
AM Peak Hour	487	452	7%
PM Peak Hour	602	556	8%

ATTACHMENT 6

San Diego Association of Governments (SANDAG)
Smart Growth Trip Generation Spreadsheet Tool

MIXED USE TRIP GENERATION MODEL V4 - RESULTS

MODEL APPLICATION - ALL TRIPS

	Daily			
	HBW	HBO	NHB	Total
Number of "Raw" SANDAG Rate Trips Subject to Model	3395	6453	2405	12253
Predicted Probabilities:				
Internal Capture	3.89%	7.66%	8.10%	6.70%
Walking External	1.00%	1.33%	0.39%	1.05%
Transit External	0.30%	0.44%	0.87%	0.48%
Number of Trips:				
Internal Capture	132	494	195	821
Walking External	33	79	9	120
Transit External	10	26	19	55
Net Number of IXXI Vehicle Trips	**3221**	**5854**	**2183**	**11257**

	External Vehicle Trips		
Results	Raw	Net	Reduction %
Daily	12,253	11,257	8%
AM Peak Hour	906	842	7%
PM Peak Hour	1,129	1,039	8%

MODEL APPLICATION - TRIP ENDS TO/FROM RESIDENCES IN THE PROJECT ONLY

	Daily			
	HBW	HBO	NHB	Total
Number of "Raw" ITE Trips Subject to Model	1320	4174	927	6420
Predicted Probabilities:				
Internal Capture	3.89%	7.66%	8.10%	6.95%
Walking External	1.00%	1.33%	0.39%	1.12%
Transit External	0.30%	0.44%	0.87%	0.47%
Number of Trips:				
Internal Capture	51	320	75	446
Walking External	13	51	3	67
Transit External	4	17	7	28
Net Number of IXXI Vehicle Trips generated by Project Residences	**1252**	**3786**	**841**	**5879**

	External Vehicle Trips		
Results	Raw	Net	Reduction %
Daily	6,420	5,879	8%
AM Peak Hour	514	475	7%
PM Peak Hour	621	571	8%

ATTACHMENT E

September 26, 2022

Via Email Only

Mr. Brian Oh, Comprehensive Planning Manager
Permit Sonoma County of Sonoma
2550 Ventura Avenue
Santa Rosa, CA 95403

Brian.Oh@sonoma-county.org

Dear Mr. Oh:

I have been asked to review and comment on the Sonoma Developmental Center (SDC) Specific Plan and associated Draft Environmental Impact Report (DEIR). I write this as a research scientist who has spent more than two decades studying wildfire science and fire ecology, global change, and conservation biology. From this perspective, I appreciate the intention to balance human welfare and economic development with plans for preservation of historical and natural resources in the area. Nevertheless, my review of the plan and DEIR have led me to conclude that many issues relative to wildfire risk have been overlooked.

The discussion of fire risk in the DEIR reflects several misconceptions concerning fire ecology, fire history, and the consequences and effectiveness of different fire mitigation strategies. The SDC property is situated within a highly fire-prone landscape, and based on evidence from the scientific literature, the Proposed Plan has high potential to significantly increase fire risk even further to new and existing structures at the SDC property as well as to the surrounding communities. A rise in human-caused ignitions due to increased population growth and expansion of human infrastructure could increase fire frequency to the point that wildfire would significantly affects public health, ecological functioning, and provision of ecological services (e.g., erosion and flood control). Unfortunately, research on recent destructive fires shows that the proposed mitigation strategies to reduce fire risk are unlikely to eliminate these significant impacts.

Below please find an explanation for my conclusions summarized in three main points.

RELIANCE UPON FIRE HAZARD SEVERITY ZONES IS INAPPROPRIATE FOR CONCLUDING THERE IS NO FIRE RISK.

The reliance upon existing Fire Hazard Severity Zones as the basis of the findings reflects a misunderstanding of the purpose of the maps, their scale of accuracy, and their potential for uncertainty at specific locations. They are also out of date. The Cal Fire maps were not designed with the intention of indicating precisely where structures are most at risk for wildfire. Instead, the objective for these maps is for use in *general* planning and policy guidance. For example, defensible space practices are only enforceable within high hazard zones; homeowners are required to disclose upon sale whether the property is in a in high hazard zone; and county governments can use the zones to enforce building codes or other fire safety measures. The maps were developed in 2007 using a simple set of variables, map overlays, and general assumptions to delineate the relative degree of fire hazard across the landscape – that is, areas where fire behavior is likely to become extreme given a fire occurs.

In other words, the hazard areas shown on Fire Hazard Severity Zones are delineated in very broad classes and have limited precision. Given the uncertainty and coarse scale of these maps, they are not appropriate for predicting where buildings are likely to be destroyed. This is something that Cal Fire has been transparent about (Sapsis 2018), as the appropriate use of these maps has been misinterpreted elsewhere.

Part of the reason they are inappropriate to predict structure loss is that the location and behavior of fire is stochastic and unpredictable at any given time or location. Fire occurrence, behavior, spread, and eventual destruction of a house depends upon a large suite of random factors, such as where and when an ignition occurs; what the fire weather at the time of ignition is; what direction the wind is blowing; what the fuel and topography conditions are at the point of ignition; what kind of housing density and arrangement are in the surrounding area; whether any other fires are burning and the availability of firefighters, etc. This does not mean that the maps of fire hazard are useless. It means that they need to be interpreted with an understanding of what they can or cannot do; and that they are not completely accurate.

This is true of fire mapping in general. For example, a map delineating probability of ignition will look completely different than a map delineating probability of a large fire (e.g., Syphard et al. 2019). Unlike the Cal Fire maps, some maps are designed with the specific objective of delineating fire risk to structures (e.g. Syphard et al. 2012), but even these maps have substantial uncertainty given the random nature of wildfire. A study comparing maps of fire risk to structures in southern California with the Cal Fire maps in the same regions found significant differences in the areas mapped as high risk, and the Cal Fire maps performed poorly compared to the other maps (Syphard et al. 2012).

Another source of uncertainty in the Cal Fire maps is the assumption that hazard is likely to be governed by the same factors in the same way across the state. Science shows that the relative weighting and direction of variables that influence the locations of fire occurrence, size, and risk vary from region to region (e.g., Syphard et al. 2019). Therefore, accuracy of the Cal Fire maps is likely to vary from place to place, and there is no guarantee that the maps near the SDC are accurate, even in a general sense or for their intended purpose. There are examples of recent highly destructive fires where substantial structure loss occurred in areas not mapped as high risk in the Cal Fire maps (e.g., Coffee Park in the Tubbs Fire, Malibu City in the Woolsey Fire). This should serve as an important illustration of why the maps should not be the final word in a conclusion about fire risk to structures.

An important point is that the current maps - the ones used for the DEIR - were developed in 2007. The current landscape reflects very different environmental and housing conditions than those that were there 15 years ago. The factors used to create the 2007 the maps, such as fuel type, fire history, and housing, have all changed substantially. Cal Fire has been putting significant effort into updating their maps with new variables and assumptions, and these may be more appropriate for future decisions. However, those maps are not available yet - and maps developed in 2007 should not be trusted to assess the fire risk for a development to be constructed after 2022.

The Proposed Plan Is Likely To Increase Regional Fire Risk

Although the DEIR acknowledges that the location of the proposed development is in a fire-prone part of the landscape, it does not thoroughly establish the baseline conditions that this is an area with a long history of wildfires that have already resulted in serious impacts. It was only a few years ago that structures were destroyed by wildfire at this very site and many more structures were destroyed nearby. Even without the new residents and visitors proposed for the site, the evacuation situation has apparently been extremely problematical in recent fires - and evacuation is often the time when people lose their lives to wildfires. These baseline conditions have not been adequately described in the DEIR despite the need to establish them before assessing the impact of the project.

Based on data regarding repeat fires in the same locations, there is reason to believe that the area proposed for development on the SDC site is susceptible to more wildfires in the future. There is also reason to believe that the SDC development will lead to an increase in the number of wildfires in the region, not only due to the potential for climate change to exacerbate fire risk, but also because of the probable increase in human-caused ignitions. In addition, the DEIR lacks a description of how the Proposed Project will not only be impacted by fire, but also how it will impact fire in the vicinity in the future.

As evidenced by the almost perfect overlap of the nearby 2017 Tubbs fire with the 1964 Hanley Fire (Keeley and Syphard 2020), fires often recur in the same locations. This is because certain locations are more fire-prone than others given their topography, location within a wind corridor, climate, and vegetation. Research on structure loss in California has demonstrated that structures located in areas with a history of recurring fire are among those that are most likely to be destroyed by fire (Syphard et al. 2012). Although the 1964 Hanley Fire occurred in nearly the same location as the 2017 Tubbs Fire, there were only about 100 structures lost, and there were no fatalities. However, in 2017, more than 5500 structures were destroyed and 22 people lost their lives. The difference is the rapid growth of human population and housing in the footprint of the fire during the interim.

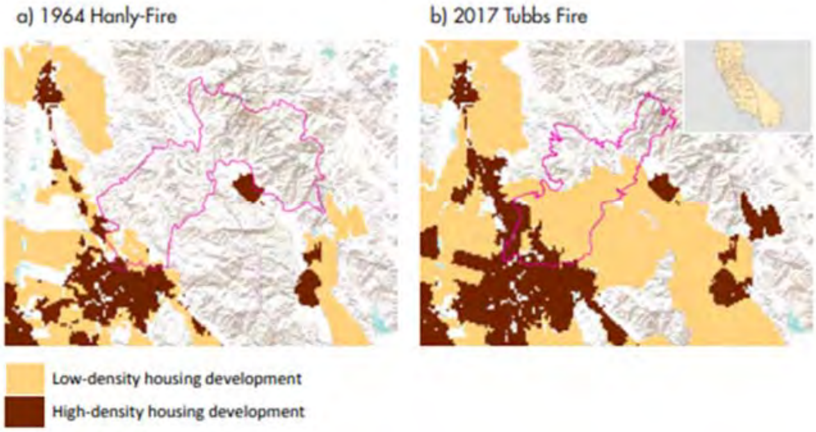


Figure 10. a) 1964 Hanly Fire perimeter in pink, and b) 2017 Tubbs Fire perimeter in pink, with changes in low density and high density housing *(from Keeley and Syphard 2019)*.

The placement of new housing in fire-prone locations, like the proposed Project, not only increases the exposure of those structures to wildfire, but it also increases the likelihood of more fire occurring in the surrounding region due to human-caused ignitions. As recognized in the DEIR, humans cause more than 95% of the fire ignitions in Sonoma County, and studies repeatedly show that fire frequency is highest in low-intermediate-density development patterns, particularly when surrounded by wildland vegetation (i.e., the Wildland Urban Interface) (Syphard et al. 2007, Syphard et al. 2019, Radeloff et al. 2018). This is because, as low-medium density housing development expands (the kind proposed for this development), there is an increase in the number of people and opportunities for fires to ignite; and there is still ample continuous vegetation in the surrounding landscape for wildfires to spread. Larger numbers of people also increase the odds of fires starting during severe fire-weather conditions that lead to the most catastrophic outcomes. Recent research shows that human-caused ignitions are the top-ranking reason for area burned in Santa Ana wind-driven fires; and that human-caused fires have worse outcomes than lightning-caused fires.

Extensive research also shows that the location of human ignitions tends to occur closest to roads and human infrastructure (Syphard et al. 2008, Molina et al. 2019, Chen and Jin 2022). Therefore, the addition of people coming into and out of the region because of the new development increases the likelihood of more fires starting near the area. The lack of public transport is a concern not only in terms of greenhouse gas emissions, but also in terms of ignitions and increasing fire risk. Given that the most likely form of transportation to and from the development is via automobiles, many more people will be on the roadways, and thus, many more opportunities will arise for fire ignitions to occur. The increased access to open space areas also would provide more opportunities for humans to unintentionally start fires.

In turn, the type of low-medium density development proposed in the plan is not only where fire frequency tends to be highest, but this is also where structures are most likely to be destroyed by fire (Syphard et al. 2012, 2019, Kramer et al. 2018). Also, it is not just housing location and density that drives risk exposure; it is the overall location and pattern of development (Syphard et al. 2012). Isolated or remote clusters of development are particularly vulnerable (Syphard et al. 2013).

In other words, fire risk is a multi-scale issue (Syphard and Keeley 2021), and the landscape context is critical. Developments surrounded by large amounts of continuous wildland vegetation, such as is the case here, are particularly dangerous because they are exposed to potential fire on all sides. This scenario is similar to what happened in the town of Paradise in the 2018 Camp Fire. To that end, "community separation" of urban areas seems like a risky design strategy in the proposed plan - that adds edge between development and wildland. As acknowledged in the EIR, the potential for destructive wildfires is increasing in many parts of California due to climate change. Recent research also shows that proximity to the WUI is the top explanation for why fires have become destructive in the project region (Syphard et al. 2022).

Policies For Mitigation Do Not Eliminate Fire Risk

Although studies show that community planning and fire-safe design and landscaping can significantly enhance fire resilience, statistics from recent wildfires indicate that these actions are not guaranteed to reduce impacts to less than significant levels (Syphard and Keeley 2019, Baylis and Boomhower 2022). While having a strong and well-enforced community wildfire resilience plan is critically important for reducing fire risk to the largest extent possible, constructing a significant number of residences and businesses will add more frequent ignitions to an already highly fire-prone region. This will exacerbate fire risk in the region regardless of the mitigation policies put in place. Therefore, although the DEIR relies on policies and mitigation measures to conclude that the project would not exacerbate wildfire risk, the initiation and enforcement of these measures do not ensure that significant impacts would be sufficiently mitigated.

Vegetation Management

One of the measures that the DEIR relies upon to claim no significant wildfire impacts is vegetation management to reduce fire risk. Vegetation management includes mechanical fuel breaks surrounding the development, clearance of woody shrublands or understory woody trees, defensible space, and controlled burning of vegetation. There are several common misconceptions about, and overestimations of the relative effectiveness of, these measures for reducing structure loss, especially during severe fire weather when most structures are destroyed. Fuel reduction through vegetation management is often viewed as a means of stopping or slowing the spread of fire; however, treatments typically only do this under mild weather conditions. In severe fire weather, with strong winds, vegetation treatments generally do not prevent or stop fires on their own.

Policy 2-31 would require construction and maintenance of a managed landscape buffer along western and eastern edges of the Core Campus to aid in fire defense, consisting of a shaded fuel break in wooded areas and grazed or mown grassland. The construction of these types of fuel breaks can be helpful for protecting communities, when done strategically, by providing safe fire-fighter access. They may also slow fire spread enough to buy time for defensive activities

(Syphard et al. 2011). Despite these benefits, the big issue with placing too much trust in fuel breaks and other forms of vegetation management is that most structures are destroyed because they are exposed to the millions of wind-borne embers that are generated during severe fire-weather. Although woody vegetation is the primary source of firebrands, wind-borne embers are known to fly kilometers ahead of a fire front, crossing vegetation treatments, and landing on or near structures. In fact, wind-borne embers often jump California's widest freeways. Therefore, although fuel breaks can facilitate safe firefighter access in some circumstances, they cannot prevent embers from flying past them. Furthermore, despite the role of fuel breaks for providing safe firefighter access, it is often unsafe for firefighters to be present during the worst fire-weather conditions. In a historical survey of fires and fuel breaks in southern California national forests, 22- 47% of fires stopped at fuel breaks when they encountered them (Syphard et al. 2011).

The creation of defensible space around structures at the parcel level, as suggested in policies 2-34 and 2-36, is a mitigating policy proposed for the DEIR, and I concur that this should be implemented to increase community resilience. Studies show that properly created defensible space (https://www.fire.ca.gov/programs/communications/defensible-space-prc-4291/) can significantly reduce the probability of a structure being destroyed in a fire (although there is no additional benefit to extending the distance of defensible space beyond 100 feet (Syphard et al. 2014, Miner 2014)). Nevertheless, as with other vegetation treatments, defensible space should not be considered as something that can definitively prevent structure loss. Many embers directly penetrate a structure without vegetation playing a role, and many structures with well-designed defensible space have been destroyed in recent wildfires.

If embers land near the property, they may ignite new fires depending upon the flammability of the surroundings. While the recommended reduction of biomass near the property lowers flame lengths and enhances firefighter safety, the fuel moisture of the vegetation in the vicinity of structures is often more important than the amount of vegetation. Evergreen shrubs and trees are often referred to as "ember catchers" because of this – because the embers may be extinguished if they land on green vegetation. This argues for retaining some green vegetation near the structure and across the landscape.

Research in Australia also shows significant protective effects of irrigated land (Gibbons et al. 2018). Thus, a concern I have about the vegetation management approach described in the DEIR is the proposal to remove chaparral and other woody shrublands and to allow establishment and expansion of grass. Although fire in grass has lower flame lengths, grass is the most flammable and easily ignitable vegetation type in California (Syphard and Schwartz 2021, Syphard et al. 2022). Grass is dryer for a much longer period in the year than chaparral, and when it does ignite, it is the fastest spreading vegetation type. Most firefighters who lose their lives in fires have been killed in grass fires. Therefore, while the practice of mowing or grazing grass can enhance fire safety (if mowing does not occur during severe fire weather), removing shrublands and converting them to grass is likely to make the landscape more flammable.

Compliance With Fire-safe Building Codes

In addition to defensible space, the DEIR relies upon class A roof retrofits and the compliance with fire-safe building codes in the construction of new buildings to mitigate fire risk. Although fire-safe building practices, such as those required in new building codes, increase the possibility that structures will survive wildfires (Syphard and Keeley 2019), they also do not guarantee prevention of structure loss. The extent to which enforcement of building codes increases the rate of structure survival in wildfires is yet unknown. For example, one study shows that building codes that enforce fire-safe construction helped to decrease rates of structure loss compared to rates of loss before the codes were enforced (Baylis and Boomhower 2021). On the other hand, an analysis of the Camp Fire, where more than 18,000 structures were destroyed, showed that homes built before and after the enforcement of building codes were destroyed at roughly equal rates (Knapp et al. 2021). Therefore, as with defensible space, many new homes with fire-resilient construction have been destroyed in recent California wildfires.

Although fire-safe building practices improve the odds of survival for new homes, these codes do not protect the existing homes at the site and in the surrounding areas. The increase in population and human activity in the region at large increases the odds for more human-caused fires to start, as people will be moving in and out of the area, engaging in more activities that could generate sparks, and spending more time recreating in flammable open-space areas. Given that humans are mobile, ignitions are numerically more likely to occur anywhere in the surrounding area that experiences an increase in human presence and activity, and this exposes more existing structures to wildfires at a landscape scale.

In other words, because wildfires occur over large areas, with the most destructive wildfires becoming very large (Syphard et al. 2022), impacts can be expected to occur in areas much larger than the project footprint. Furthermore, new building codes will not benefit the older structures within the project footprint, some of which have significant historical and cultural value. Policy 2-38 suggests retrofits of new roofs, siding, and windows for existing structures, but this is not a complete list of needed retrofits for fire safety, and the details of this policy are vague. Would these retrofits be applied to all existing buildings, even the historical ones? They also would not apply to buildings outside of the SDC site.

Shelter in Place

The DEIR relies in part on proposed Policy 2-54, which requires the Project proponent to build or designate an on-site shelter-in-place facility. DEIR at pages 510 and 511. This alternative of sheltering in place is a dangerous proposition, as evidenced by the Black Saturday Fires in Australia in 2009. In those fires, 173 people lost their lives, and more than half of those people had been sheltering in place. (https://www.sciencedirect.com/science/article/abs/pii/S221242091730050X). As a result of these fires, the Australians have now shifted thinking away from their stay and defend policy and now have a system in which all residents are encouraged to evacuate when weather conditions meet a "catastrophic threat" level. In short, buildings are replaceable, but human lives are not. While having a shelter-in-place facility may benefit those who are simply unable to evacuate, this should be a last resort, and the SDC project should not rely on this method as mitigation for wildfire risk related impact.

Finally, I question the enforceability and endurability of many of the proposed policies. Who is ultimately responsible for ensuring that the policies are followed? Activities such as fire-safe education, defensible space maintenance, or maintenance of buildings require ongoing, permanent attention. Who will ensure that these activities will continue after the structures have been built? Will a permanent staff position be created to ensure ongoing compliance? In short, people will move in and move out over time, but the houses and the landscape will remain.

Conclusion

In conclusion, contrary to the assertions made in the DEIR, there is a strong likelihood that the proposed development, and its alternatives, will have significant impacts relative to wildfire. The potential for increased numbers of wildfires – and more wildfires during severe fire weather - are likely to significantly affect public health and ecological functioning. There are also likely to be increased economic costs for management and suppression, from damage/destruction to human infrastructure or agricultural lands, and from post-event hazards such as mudslides or debris flows. Sufficient homeowners insurance for wildfire, which is becoming increasingly expensive, will also be difficult to attain, particularly for the low-income residents that are supposed to be supported by this plan.

Public health may be threatened not only from direct injury and mortality during a fire, but from smoke. The evacuation plans described in the DEIR only account for fires coming in two directions and spreading through other towns before reaching the project site. These analyses should also incorporate scenarios in which fires are spreading directly from the roads east of or from Sonoma Mountain west of the project site. In these cases, if the fire weather is severe and the fires are burning toward the project site, there would likely be less time for residents to evacuate, and this puts human lives at risk. Another potential impact to public health and safety is that, if fire frequency increases regionally due to additional opportunities for human-caused ignitions, secondary hazards may occur post-fire, such as flooding, landslides, runoff, or debris flows. Not only may these secondary events be potentially harmful during the event, but there may be subsequent impacts to water quality.

While my letter is aimed at explaining the wildfire-related potential and costs associated with the project, there are also ecological impacts that may result from the increased fire risk in the area. For example, there are ecological costs associated with vegetation management and construction of fuel breaks. There are also potential ecological impacts that will result from the potential for increased fire frequency in the area. Many vegetation types in the western USA are experiencing fire-driven conversion, often from native vegetation to invasive species (Guiterman et al. 2022). Therefore, the DEIR's conclusion that the project would result in no potential loss of forest is inaccurate because it fails to account for the potential effects of increased wildfire.

While the policies to reduce fire risk at the site may work to lessen some of these impacts, the proposed policies are unlikely to offset the increase in fire risk to the property and surrounding area that results from the project. Fire hazards will nevertheless likely be significant.

Finally, in my reading of the DEIR, I was unable to understand some of the statements. Therefore, it would be helpful to have additional clarification on the following questions:

1) Why does the plan state that the Historic Preservation Alternative leads to higher fire risk? Based on its reduced population and housing, the Historic Preservation alternative appears to be more fire-safe than the proposed project or its other alternatives.
2) On what basis does the DEIR assume that low-lying creeks and riparian areas would increase fire safety? While these areas are less flammable in general, they do not appear to be close to the proposed housing. Also, when riparian areas dry out, they can burn rapidly at high intensity.
3) On what basis does the DEIR assume that the housing in low-elevation or flat areas would not be at high risk? While it is true that topographically complex areas can often have highly erratic fire behavior, many structures are lost in low-elevation, low-relief areas (Syphard et al. 2021).

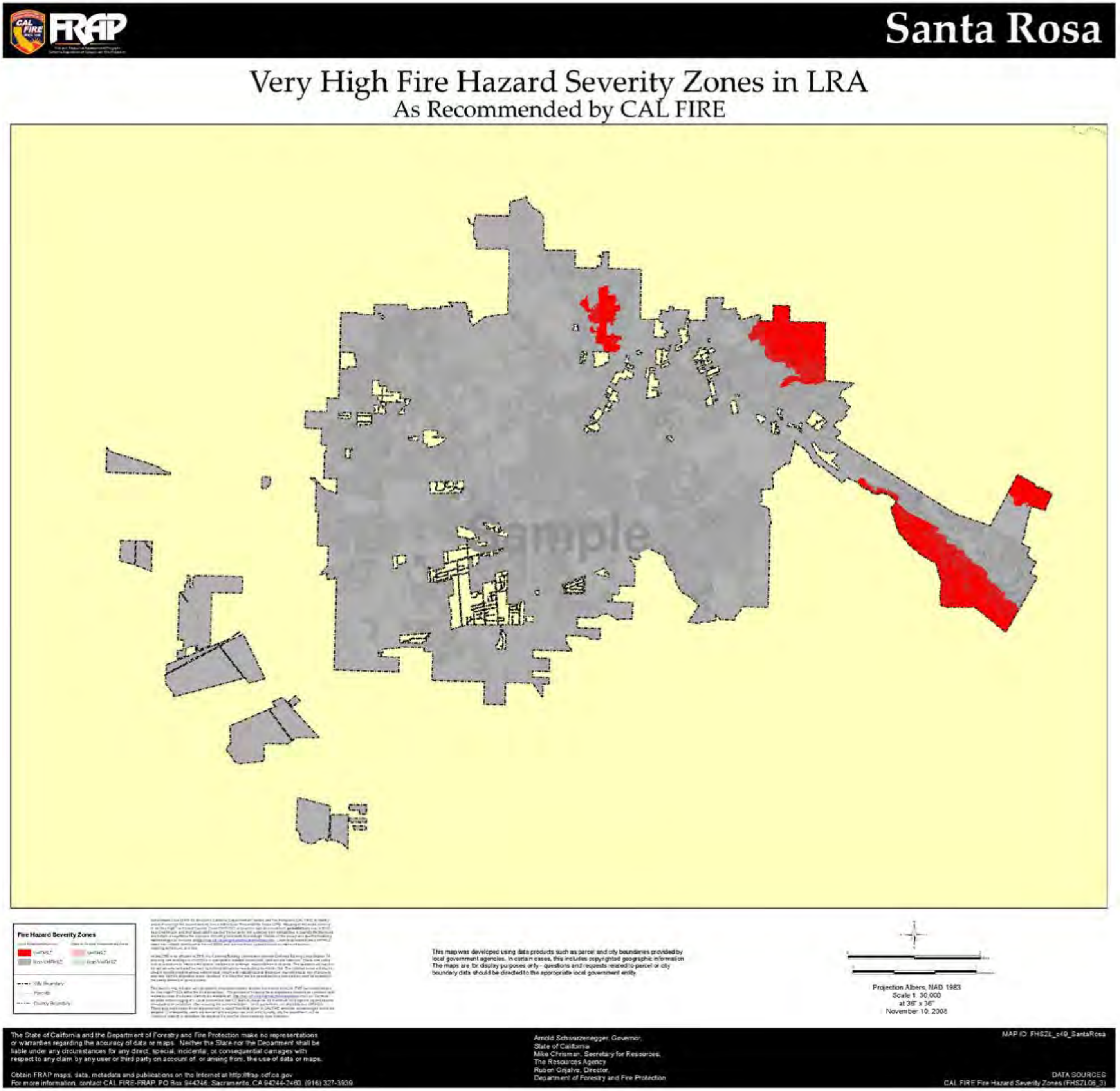
Thank you for your time in considering my review. Please let me know if you have any questions.

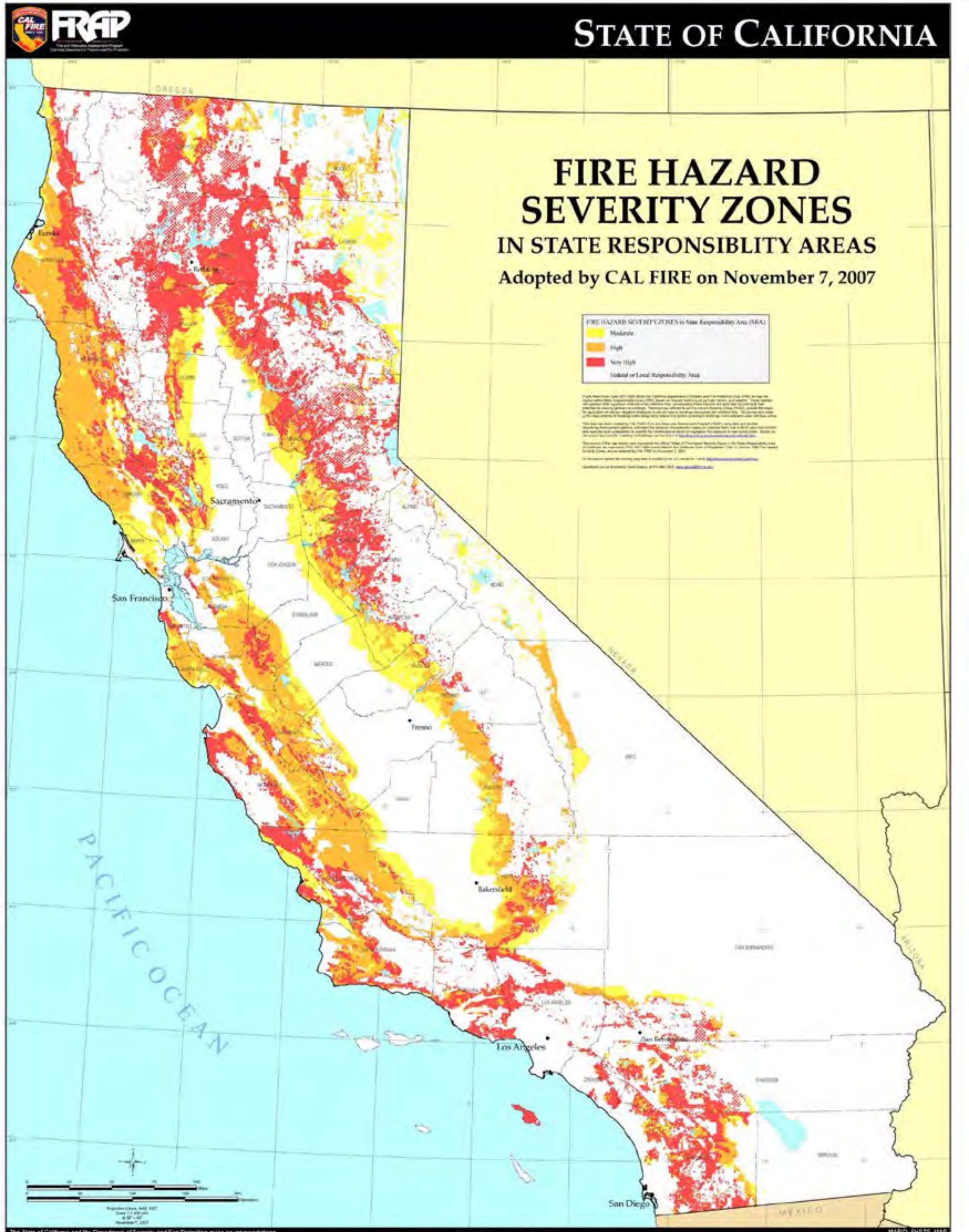
Sincerely,

Alexandra D. Syphard

Mapping Wildand Fire Threats to People and Property: Risk Communication for Regulators, Planners, and the Public

Dave Sapsis
May 8, 2018


FRAP
Santa Rosa
Very High Fire Hazard Severity Zones in LRA
As Recommended by CAL FIRE
Sample
Fire Hazard Severity Zones
This map was developed using data products such as parcel and city boundaries provided by local government agencies. In certain cases, this includes copyrighted geographic information. The maps are for display purposes only - questions and requests related to parcel or city boundary data should be directed to the appropriate local government entity.
Projection Albers, NAD 1983
Scale 1: 30,000
at 36" x 36"
November 10, 2008
The State of California and the Department of Forestry and Fire Protection make no representations or warranties regarding the accuracy of data or maps. Neither the State nor the Department shall be liable under any circumstances for any direct, special, incidental, or consequential damages with respect to any claim by any user or third party on account of, or arising from, the use of data or maps.
Obtain FRAP maps, data, metadata and publications on the Internet at http://frap.cdf.ca.gov
For more information, contact CAL FIRE-FRAP, PO Box 944246, Sacramento, CA 94244-2460, (916) 327-3939
Arnold Schwarzenegger, Governor
State of California
Mike Chrisman, Secretary for Resources
The Resources Agency
Ruben Grijalva, Director
Department of Forestry and Fire Protection
MAP ID: FHSZL_c49_SantaRosa
DATA SOURCES
CAL FIRE Fire Hazard Severity Zones (FHSZL06_3)


FRAP
STATE OF CALIFORNIA
FIRE HAZARD
SEVERITY ZONES
IN STATE RESPONSIBLITY AREAS
Adopted by CAL FIRE on November 7, 2007
Moderate
High
Very High
Federal or Local Responsibility Area
OREGON
Eureka
Redding
Sacramento
San Francisco
Fresno
Bakersfield
Los Angeles
San Bernardino
San Diego
PACIFIC OCEAN
NEVADA
ARIZONA
MEXICO

All these maps….

- Are designed to “help” people manage for fire
- Are somewhat unique, but still a “fire” map
- Have an element of “prediction”

“Making predictions is *hard*…

Especially about the future.”

--Yogi Bera

Why confess?

- Science and Models give everything anyone needs to make rational decisions
- Risk = probability x outcome

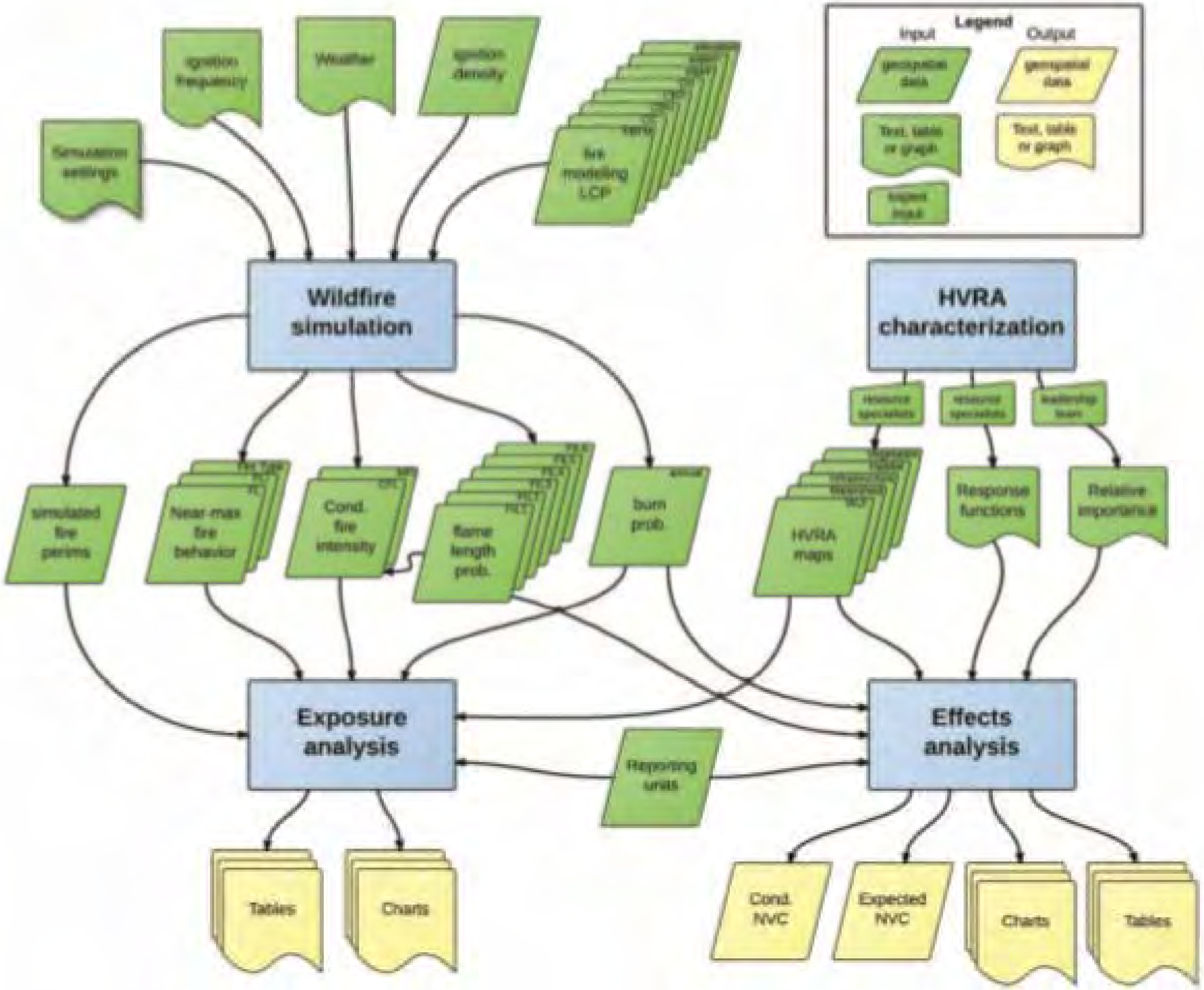
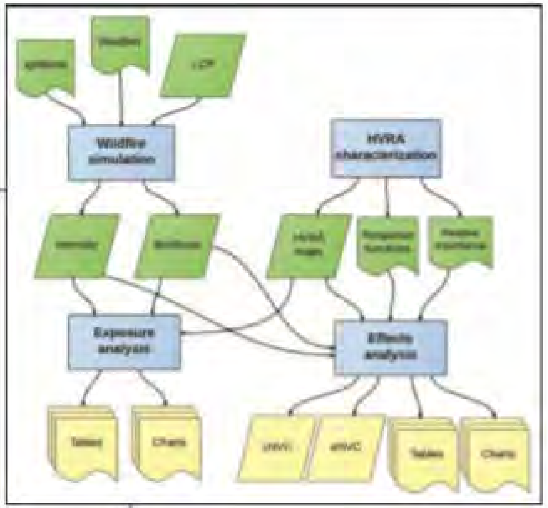
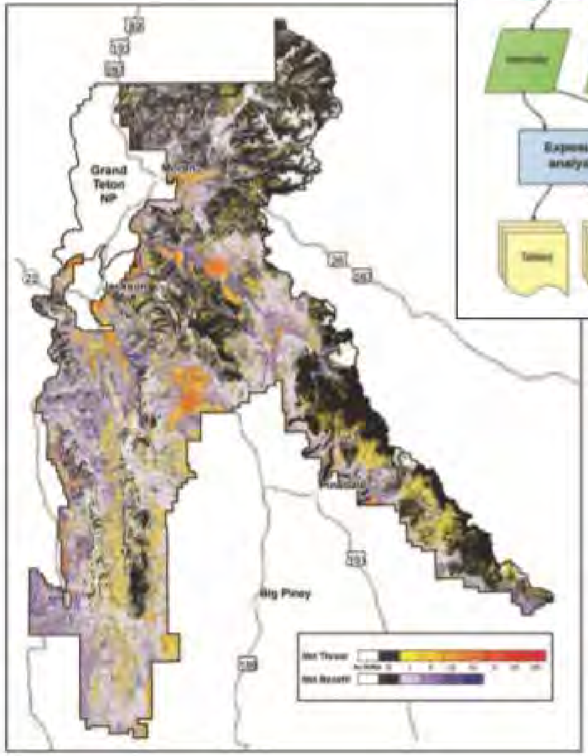


Figure 3—Process flowchart illustrating the relationships among the four components of the risk assessment process.

A Wildfire Risk Assessment Framework for Land and Resource Management

Joe H. Scott
Matthew P. Thompson
David E. Calkin





USDA
United States Department of Agriculture / Forest Service
Rocky Mountain Research Station
General Technical Report RMRS-GTR-315
October 2013

Models are really only so good…

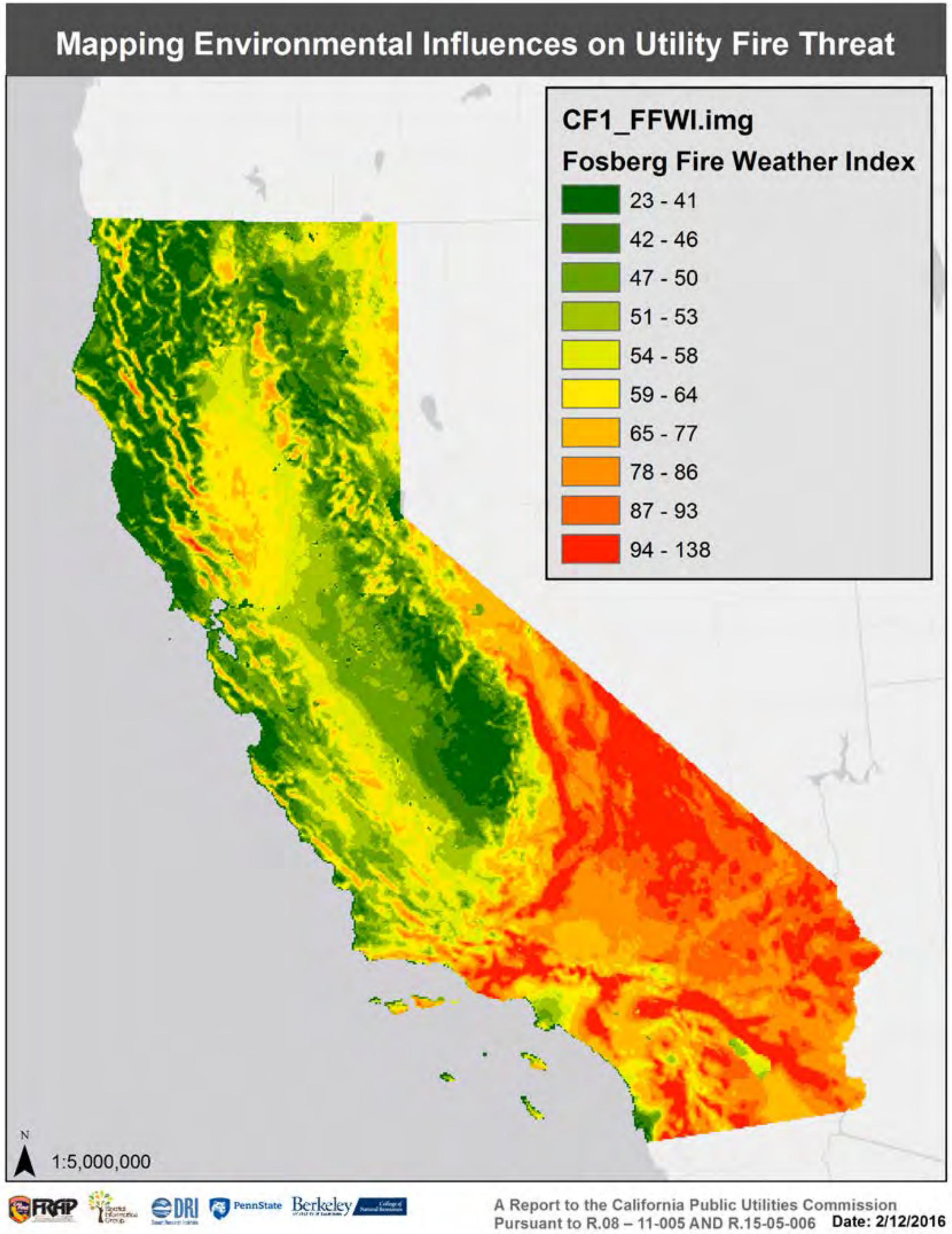
- Remember – they are predicting future outcomes:
  - UNCERTAINTY
  - STOCHASTICITY
  - PROBABILITY
- PEOPLE (how can you forget about people?)

People

- Have unique histories and experiences
- Are (usually) not experts in fire, but are very, very interested in it and want to know more
- Interpret predictions/expectations/forecasts/probabilities different
  - 1/10 of 1% ; one in one thousandths chance
- Varying opinions about the government's abilities to do the right thing*

Improve Models/Improve Communication: Technology alone will not solve the problem

- Fire Hazard Severity Zones –REFRESH
- 2018-19 (?)
- Improved Fire Allocation (probabilities, fire behavior, embers)
- Downscaled fire climatology
  - SB1241 Requires local wind information to be included

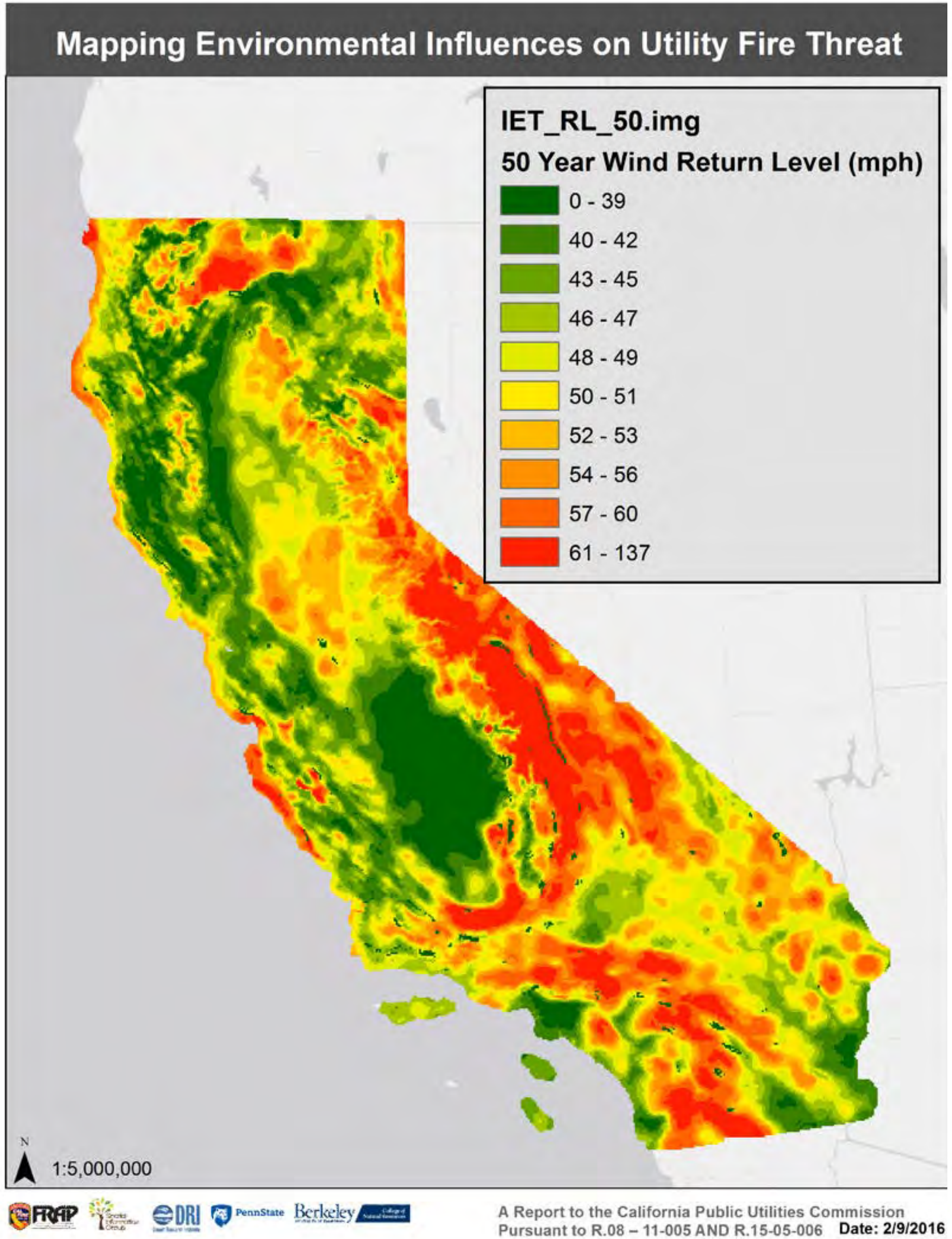


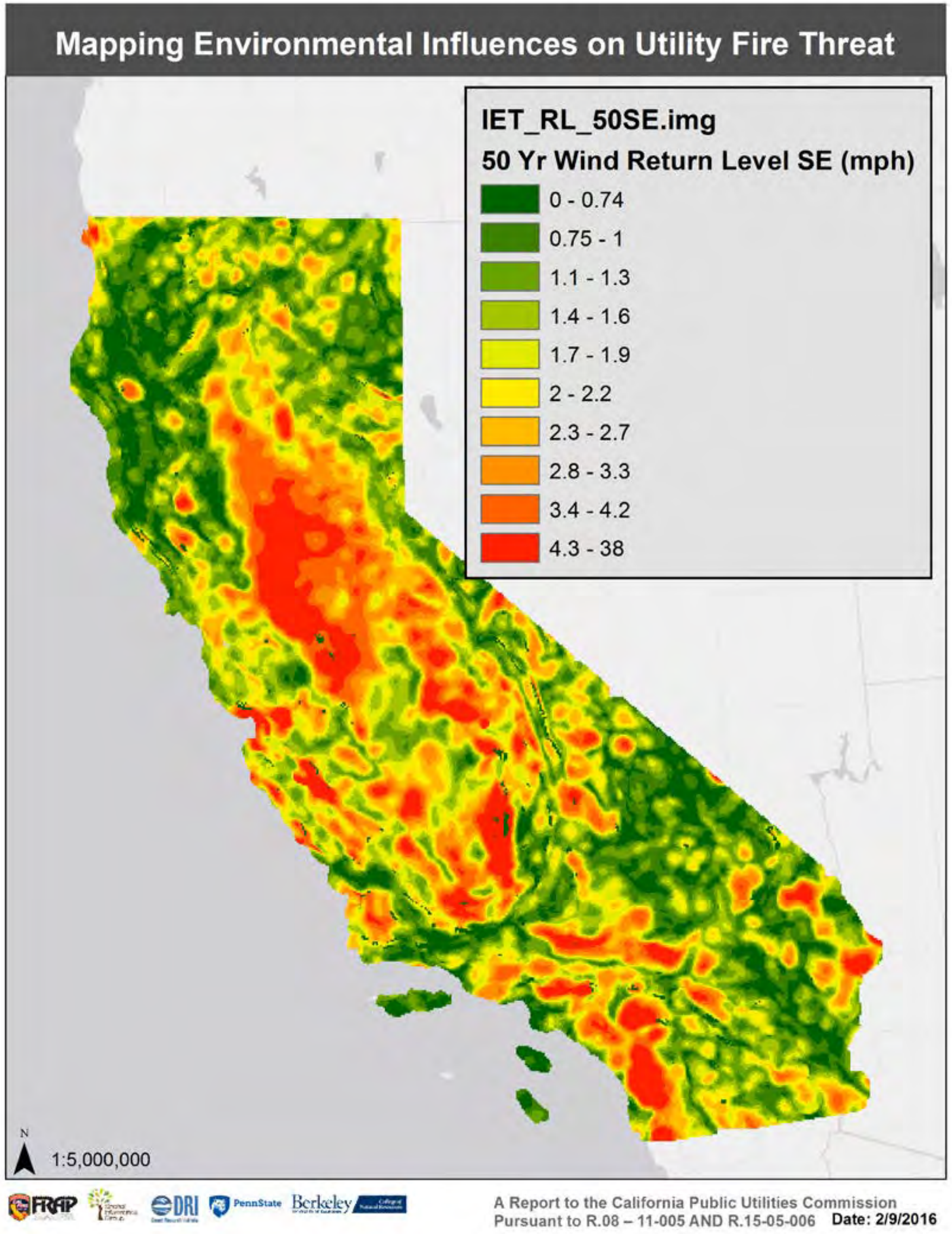
Fosberg Fire Weather Index 98thtile

10 year reconstruction
2 km grids
Hourly, 24x365 data stack

Actively working on extension and improvement: 15 years, NFDRS, H-D-W, etc.

WINDS!


Mapping Environmental Influences on Utility Fire Threat
IET_RL_50.img
50 Year Wind Return Level (mph)
0 - 39
40 - 42
43 - 45
46 - 47
48 - 49
50 - 51
52 - 53
54 - 56
57 - 60
61 - 137
N
1:5,000,000
FRAP
DRI
PennState
Berkeley
A Report to the California Public Utilities Commission
Pursuant to R.08 – 11-005 AND R.15-05-006
Date: 2/9/2016


Mapping Environmental Influences on Utility Fire Threat
IET_RL_50SE.img
50 Yr Wind Return Level SE (mph)
0 - 0.74
0.75 - 1
1.1 - 1.3
1.4 - 1.6
1.7 - 1.9
2 - 2.2
2.3 - 2.7
2.8 - 3.3
3.4 - 4.2
4.3 - 38
N
1:5,000,000
FRAP
DRI
PennState
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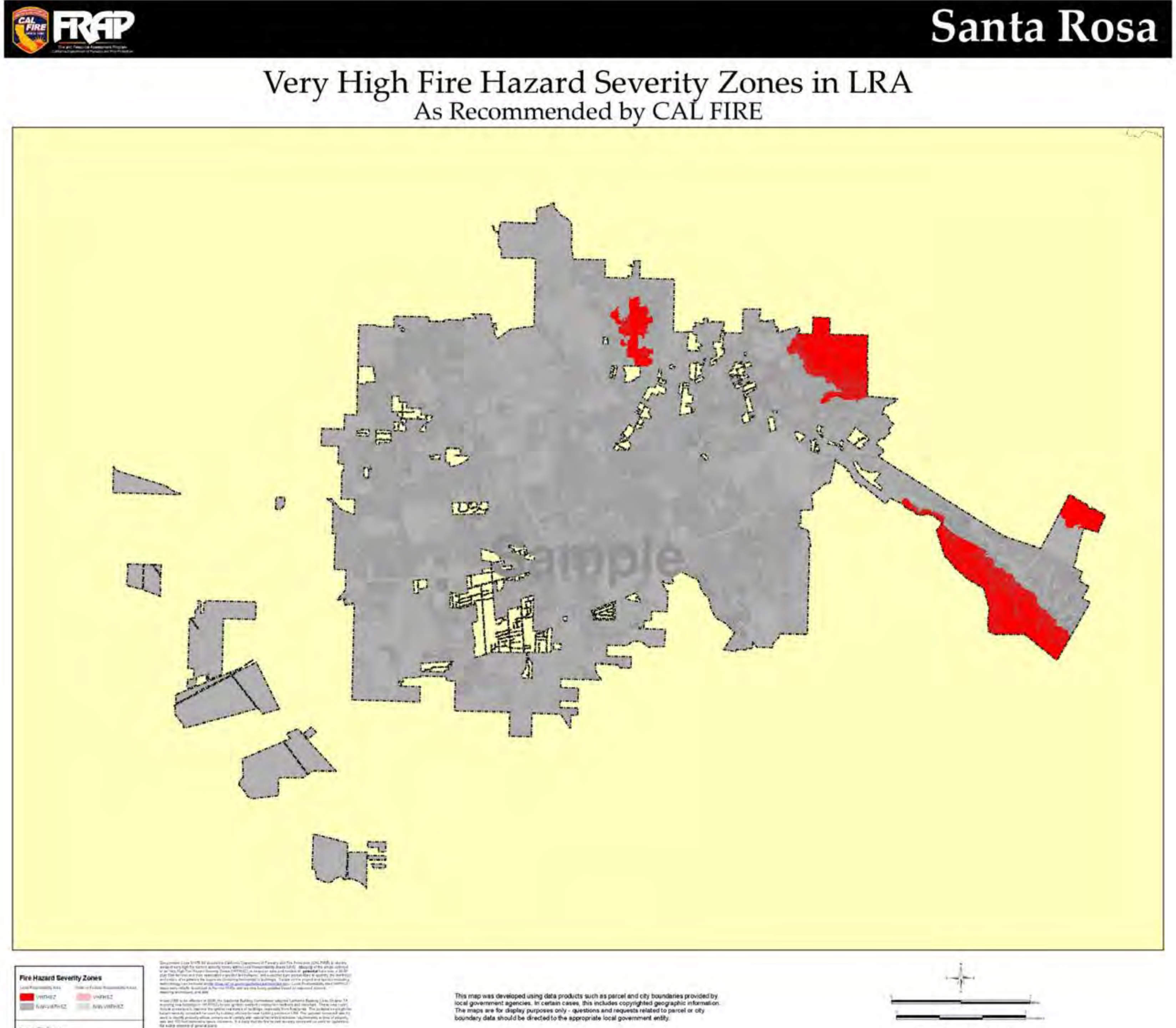
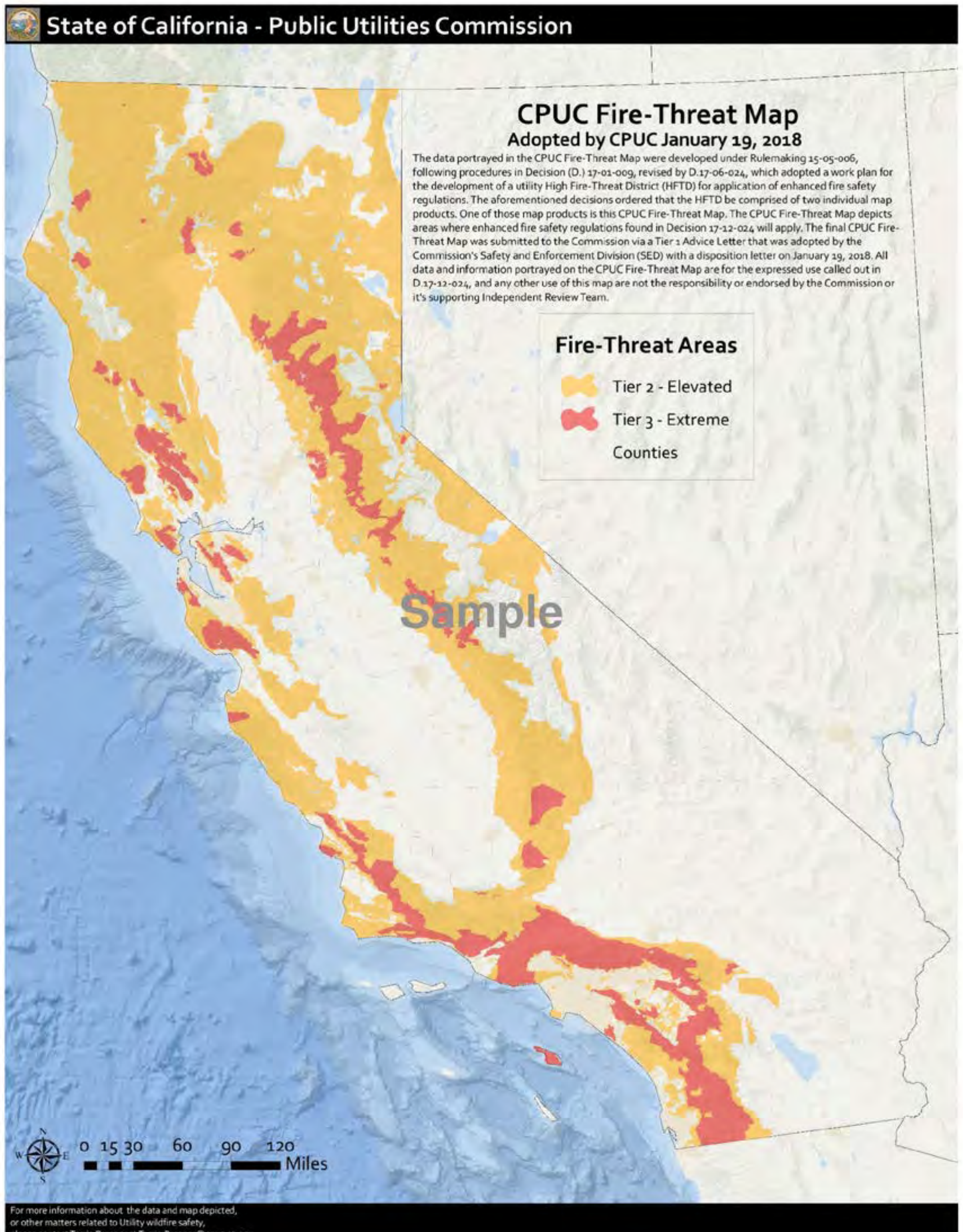
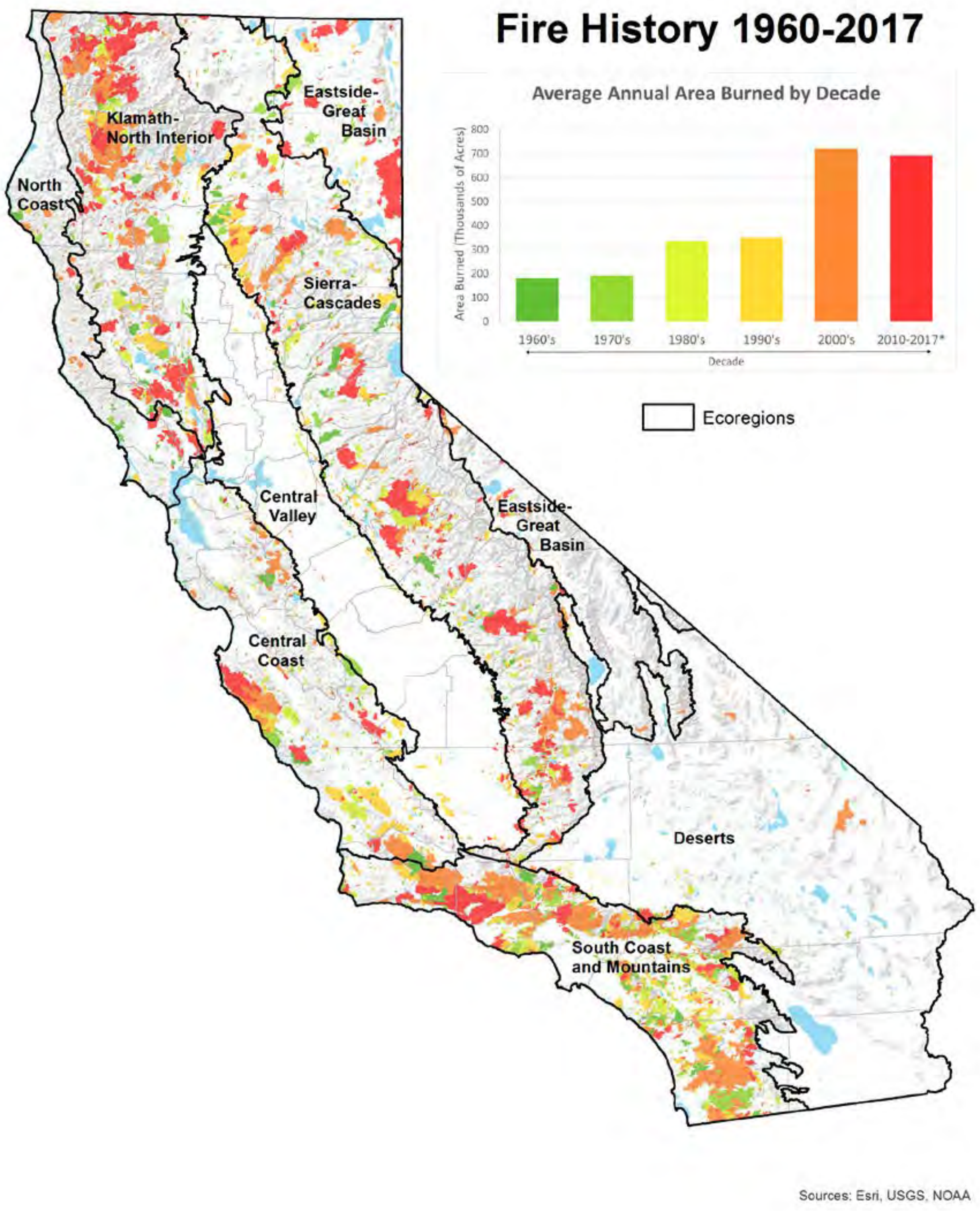

FRAP
Santa Rosa
Very High Fire Hazard Severity Zones in LRA
As Recommended by CAL FIRE
Sample
Fire Hazard Severity Zones
VHFHSZ
This map was developed using data products such as parcel and city boundaries provided by local government agencies. In certain cases, this includes copyrighted geographic information. The maps are for display purposes only - questions and requests related to parcel or city boundary data should be directed to the appropriate local government entity.

New Stuff: Ignition Reduction under extreme fire potential



Questions


Fire History 1960-2017
Average Annual Area Burned by Decade
Area Burned (Thousands of Acres)
800
700
600
500
400
300
200
100
0
1960's
1970's
1980's
1990's
2000's
2010-2017*
Decade
Ecoregions
Klamath-North Interior
North Coast
Eastside-Great Basin
Sierra-Cascades
Central Valley
Eastside-Great Basin
Central Coast
Deserts
South Coast and Mountains
Sources: Esri, USGS, NOAA

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Research Paper

Options for reducing house-losses during wildfires without clearing trees and shrubs

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GRAPHICAL ABSTRACT

Two houses impacted by a wildfire in southeastern Australia. Our study indicates that the "greenness", spatial arrangement and proximity (relative to the wind direction) of trees and shrubs close to houses (within red circle) can be manipulated to reduce the risk of house losses during wildfires without necessarily clearing trees and shrubs. (Imagery supplied by South Australian Government.)

ARTICLE INFO

Keywords:
Bushfire
Wildfire
House loss
Fuel reduction
Hazard reduction
Wildland-urban interface

ABSTRACT

Removing vegetation close to houses is at the forefront of advice provided to home owners by fire management agencies. However, widespread clearing of trees and shrubs near houses impacts aesthetics, privacy, biodiversity, energy consumption and property values. Thus, stakeholders may oppose this practice. Regulators and property owners therefore require options for vegetation management that reduce risk to houses during wildfires without complete removal of trees and shrubs. Using data from 499 houses impacted by wildfires, we tested three hypotheses: (1) maintaining 'green' vegetation affords houses additional protection during wildfires; (2) risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches; and (3) trees and shrubs retained in the upwind direction from which wildfires arrive represent greater risk to houses than trees and shrubs retained in the downwind direction. We found empirical support for each hypothesis. Increasing the mean Normalised Vegetation Difference Index (NDVI) (a measure of "greenness") of vegetation near houses had the same effect on reducing house losses as removing some trees and shrubs. Trees and shrubs within 40 m of houses arranged as many discrete patches posed less risk than the same cover of trees and shrubs arranged as few discrete patches. Trees and shrubs retained downwind from houses represented less risk than

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trees and shrubs retained upwind. Our findings represent options for regulators or home owners seeking to balance risk posed by wildfires with benefits associated with retaining trees and shrubs near houses.

1. Introduction

House losses during wildfires are increasing in fire-prone regions of the world because of growing housing density at the wildland-urban interface (Crompton, McAneney, Chen, Pielke, & Haynes, 2010; Hughes & Mercer, 2009; McAneney, Chen, & Pitman, 2009). Houses are destroyed during wildfires when exposed to flame contact, radiant heat and/or burning embers. Because the likelihood or severity of flame contact, radiant heat and embers increase closer to burning vegetation (Cohen, 2000; Koo, Pagni, Weise, & Woycheese, 2010; Maranghides & Mell, 2011), it follows that the characteristics of vegetation close to houses is strongly associated with house loss during wildfires (Abt, Kelly, & Kuypers, 1987; Barrow, 1944; Gibbons et al., 2012; Ramsay, Macarthur, & Dowling, 1996; Syphard, Brennan, & Keeley, 2014; Wilson & Ferguson, 1986). Intensive management of vegetation (e.g., removal of trees and shrubs) close to houses is therefore at the forefront of advice provided to home owners by fire management agencies around the world (Gill & Stephens, 2009; Massada, Radeloff, & Stewart, 2011; Nelson, Monroe, & Johnson, 2005).

This advice results in widespread removal of trees and shrubs within, and adjacent to, the wildland-urban interface (Radeloff et al., 2005). The removal of this vegetation can have negative impacts on aesthetics and privacy (Nelson et al., 2005), biodiversity (Driscoll et al., 2010) and energy consumption (Bowler, Buyung-Ali, Knight, & Pullin, 2010); it can be associated with health effects (Tzoulas et al., 2007), influence property values (Pandit, Polyakov, Tapsuwan, & Moran, 2013) and be expensive for residents (Penman, Eriksen, Horsey, & Bradstock, 2016). Thus, there are different attitudes to vegetation clearing among stakeholders across the wildland-urban interface (Nelson et al., 2005). This limits the ability to achieve effective fuel reduction across those parts of the wildland-urban interface where there is considerable tree and shrub cover around houses, thereby placing some communities or individuals within them at increased risk from wildfire. Policy-makers and residents therefore require options for fuel management that can achieve a balance between the protection of houses from wildfire and the services provided by retaining trees and shrubs.

Our understanding of fire behaviour and the mechanisms that cause damage to houses during wildfires invite the following hypotheses:

(1) Maintaining 'green' vegetation affords houses additional protection during wildfires. Vegetation with a high moisture content requires more energy to ignite than cured vegetation. Fuel moisture plays an important role in the self-extinction of fires (Wilson & Ralph, 1985) and therefore fuel moisture influences the rate of spread of fires (Rothermel, 1972). Thus, maintaining "greener" landscaping is likely to result in a reduced probability of house loss during wildfires than drier gardens supporting equivalent cover of trees and shrubs.
(2) Risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches. The propagation of fire depends on the properties of the flame and the properties of the fuel ahead of the flame (Catchpole, Hatton, & Catchpole, 1989) and so the spatial heterogeneity of fuels affect the rate at which fires spread (Burrows, Ward, & Robinson, 1991). This suggests that trees and shrubs arranged in a patchy distribution around houses will represent less hazard than an equivalent cover of trees and shrubs arranged in a more continuous distribution.
(3) Trees and shrubs in the upwind direction from which wildfires arrive represent greater risk to houses than trees and shrubs in the downwind direction. The effect of wind on the direction of flames, radiant heat and embers (Rothermel, 1972) suggests that trees and shrubs in the downwind direction from which wildfires arrive will have less effect on the likelihood of house loss than trees and shrubs close to houses in the upwind direction from which wildfires arrive.

We tested these hypotheses using data from three wildfires in south-eastern Australia.

2. Methods

2.1. Study area and sampling strategy

We sampled 499 houses from three wildfires that ignited on 7 February 2009 in south-eastern Australia (145°0′–146°50′E, 37°10′S–38°30′S). These wildfires, known as the East Kilmore, Murrindindi and Churchill fires, collectively burnt 194,403 ha and destroyed 1925 houses (Teague, McLeod, & Pascoe, 2010). The landscapes affected by these wildfires included rural areas where most native tree cover had been cleared, plantations dominated by introduced radiata pine (*Pinus radiata*), *Eucalyptus* forests managed for wood production and *Eucalyptus* forests managed as conservation estate. Housing occurred as a mix of rural, semi-rural and urban areas. Prior to sampling we stratified the study area by the three principal drivers of wildfire behaviour: weather, terrain and fuel (Countryman, 1972). Weather (measured using the Forest Fire Danger Index or FFDI) (McArthur, 1967), ranged from 5 to 189 (mean = 47.6). Slope ranged from 0.3° to 22.6° (mean = 8.5°). Fuel, measured as the % of land upwind from houses that had been burnt within ≤5 years and as the % of trees and shrubs cleared upwind from houses, ranged from 0% to 36% (mean = 2.8%) and 0% to 100% (mean = 32.3%) respectively. Houses were sampled using random points allocated in approximate proportion to the area of each stratum within a Geographical Information System (GIS). We sampled the nearest house to each random point using fine-scale (35 cm–50 cm pixel resolution) aerial imagery taken 1–37 months prior to the wildfires. We recorded damage to each sampled house as a binary variable (intact or destroyed) based on a visual inspection of fine scale (8–15 cm pixel resolution) aerial imagery in the visible spectrum taken 17–23 days after the wildfires. At each house we recorded a set of potential explanatory variables representing terrain; weather; and the amount, configuration, distance and direction to fuels from houses (Appendix A).

2.2. Statistical analysis

We used an information-theoretic approach (Burnham & Anderson, 1998) and Generalised Linear Modelling (GLM) to test our hypotheses. We commenced with a base model containing variables representing weather and fuel (measured at different scales) that are significantly ($p < 0.05$) associated with house loss during these wildfires as reported in a previous study (Gibbons et al., 2012). These variables were: weather (measured with FFDI), upwind distance to forest burnt within five years, the % cover of trees and shrubs and type of vegetation within 40 m of houses, total buildings within 40 m of houses, upwind distance to patches of trees and shrubs, upwind amount of private land and an 'autocovariate' to account for spatial autocorrelation between adjacent houses (Appendix A). We then compared this base model reported in Gibbons et al. (2012) with the following alternative models representing our hypotheses.

Hypothesis 1. Maintaining 'green' vegetation affords houses additional protection during wildfires.

To test this hypothesis we added to the base model a variable representing the average NDVI within 40 m from the centroid of each house. We measured NDVI to a distance of 40 m from each house because this is the maximum distance at which the three key mechanisms that destroy houses during wildfires—flame contact, radiant heat and embers—overlap and it is within this distance that the effects of vegetation on house loss are at their greatest (Gibbons et al., 2012; Syphard et al., 2014). Average NDVI was fitted as a polynomial term, as exploratory data analysis (using Generalised Additive Models) suggested there was a curvilinear relationship between the probability of house loss and average NDVI.

NDVI is strongly associated with active photosynthesis and water use in plants, distinguishes green vegetation from non-photosynthetic land classes (e.g., impervious surfaces and water) and has been used to predict the rate of irrigation in suburban gardens (Johnson & Belitz, 2012). We calculated NDVI in ArcMap using Landsat TM imagery sourced from the United States Geological Survey (USGS) Earth Explorer for the Kilmore-Murrundindi fire (dated 31 January 2009) and the Churchill fire (dated 24 January 2009). NDVI was calculated as

$$\frac{NIR-RED}{NIR+RED}$$

where *NIR* is the near infrared part of the electromagnetic spectrum that is reflected by leaves and *RED* is part of the electromagnetic spectrum that actively photosynthesising leaves absorb. NDVI values range from -1 (water) to $+1$ (green vegetation). Landsat TM multispectral imagery has a 30 m × 30 m spatial resolution. If half or more of the area of a pixel fell within 40 m of the centroid of each house then the value of that pixel was included in the calculation of average NDVI.

Hypothesis 2. Risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches.

To test this hypothesis we added to the base model a variable representing the number of discrete patches of trees and shrubs within 40 m of each house, and a variable representing an interaction between the number of patches and % cover of trees and shrubs within 40 m of each house. We added the interaction term to test whether the arrangement of trees and shrubs within 40 m of houses as more discrete patches, compared with larger continuous patches, reduced the probability of house loss at all levels for tree and shrub cover within 40 m of houses. We counted patches of trees and shrubs manually around each of the 499 sampled houses using fine-scale (35 cm–50 cm pixel resolution) aerial imagery taken 1–37 months prior to the wildfires. A discrete patch of trees and shrubs was defined as visible tree and shrub canopies of any size that were at least 2 m from other trees and shrubs within 40 m from the centroid of each house.

Hypothesis 3. Trees and shrubs in the upwind direction from which wildfires arrive represent greater risk to houses than trees and shrubs in the downwind direction.

To test this hypothesis we added to the base model variables representing: the distance to the nearest large patch of trees and shrubs, the direction to that patch relative to the wind direction when the wildfire impacted each house and an interaction term between these variables. The distance from houses to the nearest large patch of trees and shrubs (> 10 m width) and the direction from the house to the patch (degrees) were measured in ArcMap using fine-scale (35 cm–50 cm pixel resolution) aerial imagery taken 1–37 months prior to the wildfires. The direction to the nearest large patch of trees and shrubs was converted to one of eight cardinal or inter-cardinal directions and then compared with the wind direction recorded when wildfire impacted each house. The estimated time that wildfire impacted each house was estimated from fire progression maps (isochrones) for the Kilmore East and Murrindindi fires provided by the Victorian Department of Sustainability and Environment (now Department of Environment and Primary Industries) and for the Churchill fire provided by the Victorian Country Fire Authority; and wind direction to the nearest 30 min was taken from the nearest permanent automated weather station managed by the Bureau of Meteorology. Observed wind direction was converted to one of four inter-cardinal directions (i.e., north-east, south-east, south-west and north-west). The direction from each house to the nearest large patch of trees and shrubs relative to the wind direction when the wildfire impacted was recorded as: (i) upwind (0° difference); (ii) adjacent (45° to < 135° difference); and (iii) downwind (≥135° difference). For example, where the direction of wind was recorded as NW at the time the wildfire reached a house of interest, vegetation patches in a NW direction from the house were classified 'upwind', patches in a N, W, NE or SW direction were classified 'adjacent', and all other patches (E, S and SE) were classified 'downwind.'

We included a further two alternative "global" models in the candidate set. The first included all of the variables representing each of the three hypotheses (the average NDVI of vegetation within 40 m of houses, the number of discrete patches of trees and shrubs within 40 m of houses, the distance to the nearest patch of trees and shrubs and the direction of that patch) to examine whether there was an additive effect of these variables. The second alternative model included each of these variables plus all of the interaction terms we tested.

Alternative models were judged to have strong empirical support where Akaike's Information Criterion (AIC) values were within ≤2 of the model with the lowest AIC value, were judged to have some

Table 1
Candidate models used to test our hypotheses, the variables included in those models, the log-likelihood of each model, AIC_c differences (ΔAIC_c) relative to the 'best' model and AIC_c weights for each model, which can be interpreted as the probability that the candidate model is the best of the set. Average NDVI was fitted as a polynomial term in all models in which it is included.

Model	Variables	Log-likelihood	ΔAIC_c	AIC_c weight
1	Base model	−252.621	3.53	0.07
2	Base model + average NDVI	−251.239	7.04	0.01
3	Base model + average NDVI + (average NDVI × % cover of trees and shrubs within 40 m)	−246.049	3.01	0.09
4	Base model + number of patches	−252.018	4.41	0.05
5	Base model + number of patches + (number of patches × % cover of trees and shrubs within 40 m)	−251.306	5.08	0.03
6	Base model + distance to nearest large patch of trees and shrubs + the direction of this large patch relative to the wind direction	−248.387	1.34	0.21
7	Base model + distance to nearest large patch of trees and shrubs + the direction of this large patch relative to the wind direction + (distance to nearest large patch of trees and shrubs × the direction of this large patch relative to the wind direction)	−247.251	3.29	0.08
8	Base model + average NDVI + number of patches + distance to nearest large patch of trees and shrubs + the direction of this large patch relative to the wind direction	−245.481	4.01	0.06
9	Base model + average NDVI + (average NDVI × % cover of trees and shrubs within 40 m) + (average NDVI × vegetation type) + number of patches + (number of patches × % cover of trees and shrubs within 40 m) + distance to nearest large patch of trees and shrubs + the direction of this large patch relative to the wind direction + (distance to nearest large patch of trees and shrubs × the direction of this large patch relative to the wind direction)	−236.976	0	0.41

empirical support where AIC differences were between > 2 and < 6 and were rejected where AIC differences were ≥6 (Symonds & Moussalli, 2011). We also calculated AIC weights for each model, which can be interpreted as the probability that the candidate model is the best of the set (Burnham & Anderson, 1998). All calculations of AIC were for small samples (AIC_c). All predictions from selected models were made with covariates held at their median (or for categorical variables the level with the highest sample size), except for FFDI, which was held at 100 (Catastrophic). Most houses destroyed during wildfires in Australia (64%) occurred on days when FFDI exceeded 100 (Blanchi, Lucas, Leonard, & Finkele, 2010) suggesting that it is at more severe weather conditions when the effect of these variables is most important. Errors around all means are 95% confidence limits. We also calculated Pearson correlation coefficients for all pairs of continuous variables. All statistical analyses were undertaken using R (R Development Core Team, 2010).

3. Results

The list of candidate models, the variables included in those models, AIC_c differences (ΔAIC_c) and AIC weights are provided in Table 1. The model with strongest empirical support was the global model that contained all terms representing our hypotheses plus the interaction terms (Model 9 in Table 1), suggesting an additive effect of each of the variables representing our hypotheses. The only model with no empirical support (i.e., $\Delta AIC_c > 6$) was Model 2 which was the base model with average NDVI added as a polynomial term.

3.1 Hypothesis 1: Maintaining 'green' vegetation affords houses additional protection during wildfires

Average NDVI values recorded within 40 m of houses ranged from 0.03 to 0.57 (median = 0.24) and the % cover of trees and shrubs within 40 m of houses ranged from 0% to 90% (median = 25%). Average NDVI was not highly correlated with the % cover of trees and shrubs within 40 m of houses (r = 0.41) so both of these variables were included in alternative models. There was some empirical support ($\Delta AIC_c = 3.01$) for the candidate model in which an interaction between average NDVI within 40 m of houses and the cover of trees and shrubs within 40 m of houses were added to the base model (Model 3 in Table 1). However, there was stronger empirical support for the full model that including this interaction and all of the other variables (Model 9 in Table 1). Predictions from this full model indicated that, for houses surrounded by a given percentage of trees and shrubs, the mean probability of house loss was less where vegetation surrounding the house had higher values for average NDVI, although there is considerable uncertainty around these predictions (Fig. 1). For example, if the cover of trees and shrubs around houses was 20% and the average NDVI was 0.20 then the mean probability of house loss is 0.53 ± 0.15. If the cover of trees and shrubs was doubled to 40% then the mean probability of house loss increases to 0.65 ± 0.15. However, if the NDVI can be concomitantly increased to 0.30, then the mean probability of house loss remains similar at 0.52 ± 0.15 despite doubling the cover of trees and shrubs.

3.2 Hypothesis 2: Risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches

The number of discrete patches of trees and shrubs within 40 m of the sampled houses ranged from 0 to 46 (median = 10). The number of discrete patches of trees and shrubs within 40 m of houses was not highly correlated with the % cover of trees and shrubs within 40 m of houses (r = 0.33). Although there was some empirical support for the model including the number of patches of trees and shrubs within 40 m of houses (Model 4 in Table 1) and an interaction between this variable and the cover of trees and shrubs within 40 m of houses (Model 5 in Table 1), there was strongest empirical support for the full model that contained these terms plus all of the others examined here (Model 9 in

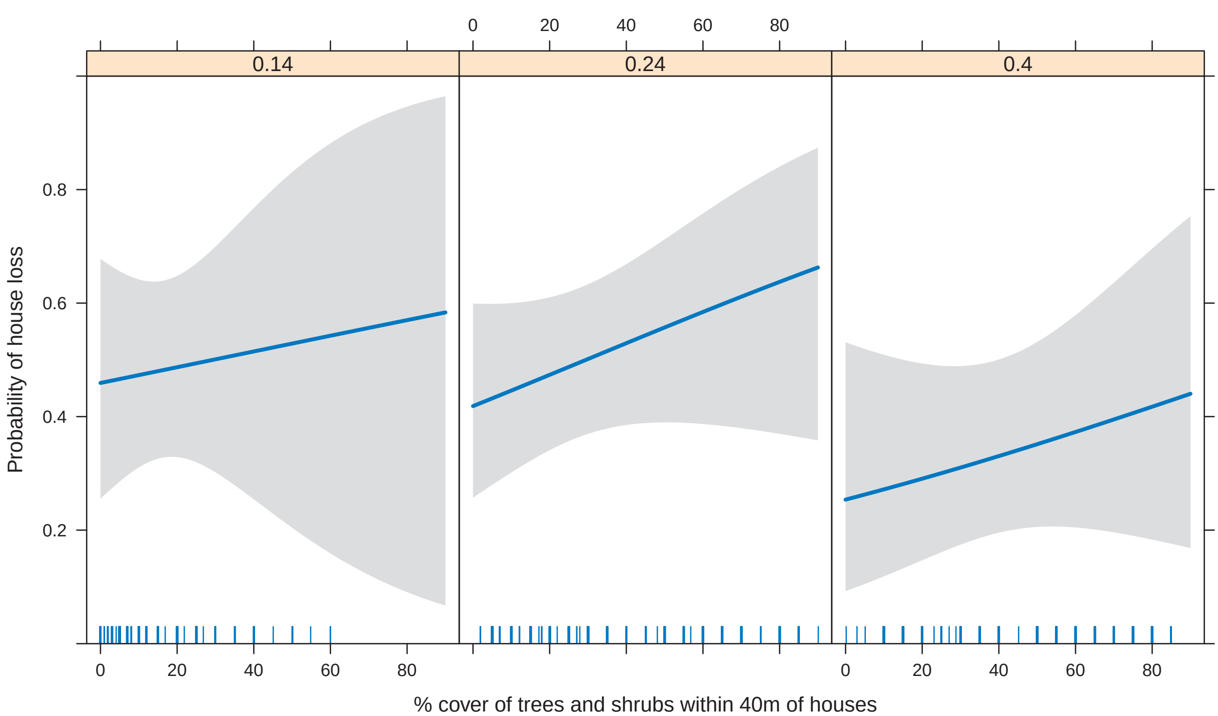

Fig. 1. The mean (± 95% confidence interval) predicted probability of house loss with changes to the % cover of trees and shrubs within 40 m of houses when the average NDVI of this vegetation is 0.14, 0.24 and 0.40 (i.e., the 10th, 50th and 90th percentiles). Predictions were made from Model 9 in Table 1 with all other continuous covariates held at their median except for FFDI which was fixed at 100.

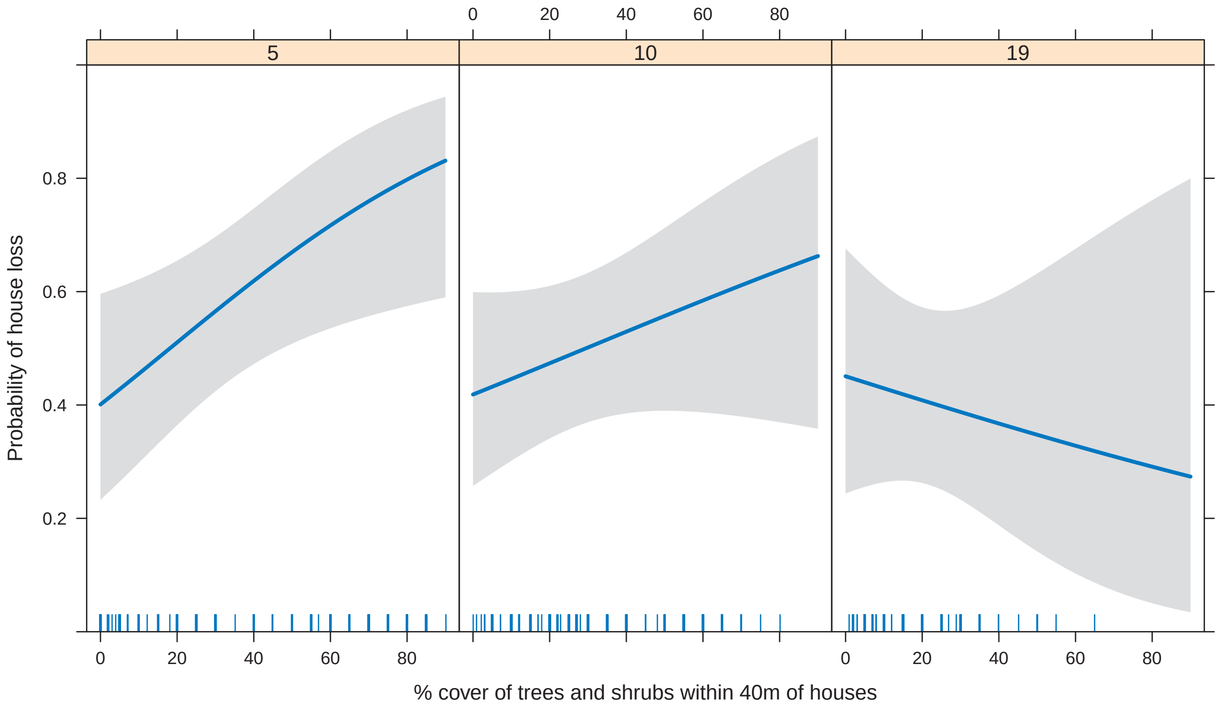

Fig. 2. The mean (± 95% confidence interval) predicted probability of house loss with changes to the total % cover of trees and shrubs within 40 m of houses when this vegetation was configured as 5, 10 or 19 discrete patches (i.e., the 10th, 50th and 90th percentiles). Predictions were made from Model 9 in Table 1 with all other continuous covariates held at their median except for FFDI which was fixed at 100.

Table 1). Predictions from this full model indicated that, other things being equal, the risk posed to houses from trees and shrubs within 40 m is reduced where that vegetation is configured as many discrete patches, particularly a higher levels of tree and shrub cover (Fig. 2). For example, houses surrounded by 50% cover of trees and shrubs configured as five discrete patches had a higher mean probability of house loss (0.67 ± 0.15) than houses surrounded by the same cover of trees and shrubs configured as 10 discrete patches (0.56 ± 0.17). However, predictions from this model should be disregarded at higher amounts of tree cover and a larger number of patches due to a high amount of uncertainty (i.e., wide confidence bands) (Fig. 2).

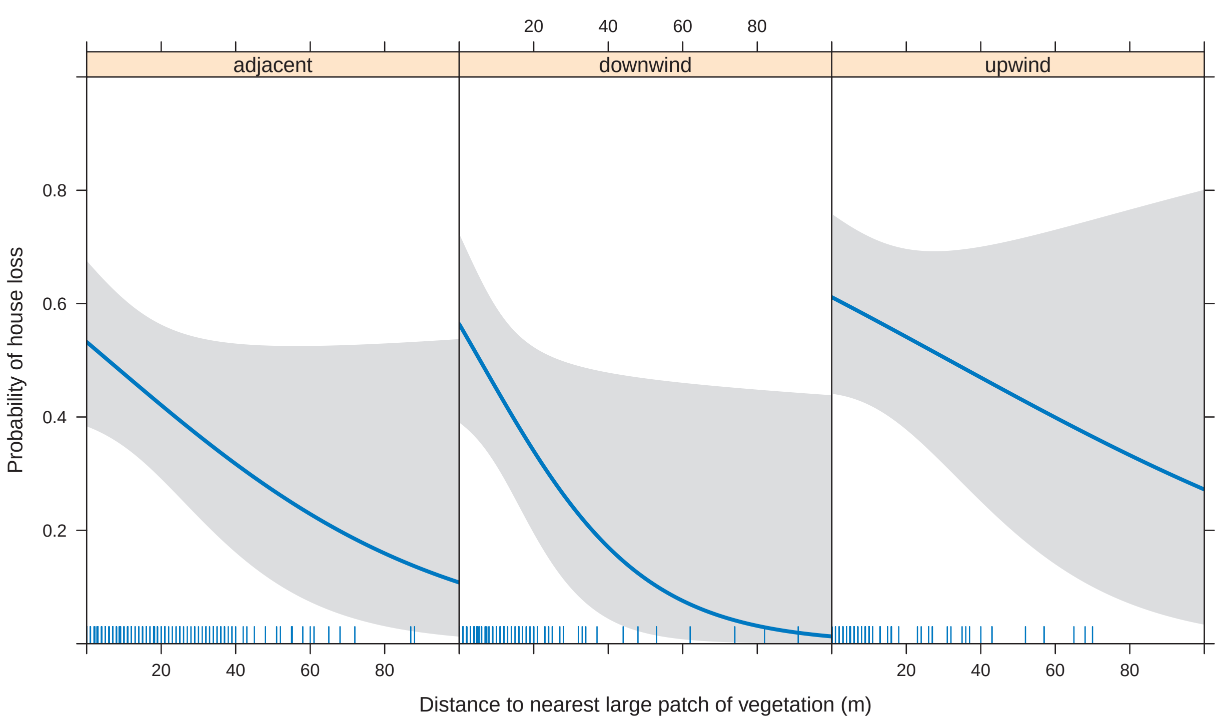

Fig. 3. The mean (± 95% confidence interval) predicted probability of house loss with distance to the nearest large patch of trees and shrubs (> 10 m across) when this patch is adjacent, downwind or upwind relative to wind direction when the wildfire impacted the house. Predictions were made from Model 9 in Table 1 with all other continuous covariates held at their median except for FFDI which was fixed at 100.

3.3 Hypothesis 3: Trees and shrubs in the upwind direction from which wildfires arrive represent greater risk to houses than trees and shrubs in the downwind direction

The distance from houses to the nearest large patch of trees and shrubs (> 10 m wide in its narrowest dimension) ranged from 0 to 433 m (median = 8 m). The % of the nearest large patches of vegetation that were upwind, adjacent and downwind from houses was 23%, 45% and 32% respectively. There was empirical support for models that included variables representing distance to the nearest large patch of trees and shrubs, the direction of large patches relative to the wind direction (Model 6 in Table 1) and/or an interaction term between these variables (Model 7 in Table 1). However, there was strongest support for the model that included these and all other terms (Model 9 in Table 1). Predictions from this latter model suggested that, for any given distance between houses and a large patch of trees and shrubs, there was a greatest risk to houses when this vegetation was upwind from houses, except when patches are very close to houses (Fig. 3). For example, other things being equal, predictions from this model indicated that the mean probability of house loss when the nearest large patch of trees and shrubs is located 10 m in the upwind direction was 0.58 ± 0.16, while this estimate was 0.45 ± 0.14 when the nearest large patch of trees and shrubs was 10 m in the downwind direction from houses.

4. Discussion

We sought to identify landscaping options that afford some protection to houses during wildfire, but represent an alternative to widespread removal of trees and shrubs, and thus provide options for home owners and regulators seeking to balance the protection of built assets and natural assets at the wildland-urban interface. Drawing on current understanding of wildfire behaviour and the mechanisms by which houses are destroyed during wildfires, we posed three hypotheses: (1) maintaining 'green' vegetation affords houses additional protection during wildfires; (2) risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches; and (3) trees and shrubs in the upwind direction from which wildfires arrive represent greater risk to houses than trees and shrubs in the downwind direction. We found evidence to support each our hypotheses.

4.1. Maintaining 'green' vegetation affords houses additional protection during wildfires

For any amount of tree and shrub cover within 40 m of houses, there were slightly lower predicted house losses where this area had higher average values for NDVI. NDVI is positively associated with the density of vegetation, vegetation "greeness" (the degree to which vegetation is photosynthesising) and the moisture content of vegetation (Ceccato, Flasse, Tarantola, Jacquemoud, & Grégoire, 2001; Gamon et al., 1995). Further, NDVI is indicative of reflectance in the upper vegetation stratum at a site rather than vegetation in lower strata. Thus, it is not clear which of the variables correlated with NDVI is critical with respect to house loss. However, given average NDVI within 40 m of houses was only weakly positively correlated with the % cover of trees and shrubs within 40 m of houses and NDVI had an additional effect to the % cover of trees and shrubs around houses (Table 1), our results suggest that 'greenness' of the upper stratum of vegetation is a factor associated with house loss during wildfire. Some plants have naturally higher moisture content and this is, in turn, associated with lower flammability (Gill & Moore, 1996). Thus, the negative association between average NDVI and house loss may indicate that the selection of plants with lower flammability affords houses some protection during wildfire—a strategy recommended in some wildfire-prone areas (Detweiler & Fitzgerald, 2006). The level of irrigation used in gardens is also positively associated with NDVI (Johnson & Belitz, 2012) and therefore our results could also suggest that irrigating vegetation around houses could reduce risk to houses as an alternative, or adjunct to, removing trees and shrubs. However, this strategy is likely only to be effective where there is capacity to increase "greeness" among the plant species around houses, which may not be feasible among plant species adapted to relatively low available water, which is the case for many native plant species in our study area. Therefore, advantages from irrigation may only be realised with the concomitant replacement of some plant species with others. However, notwithstanding any of these issues, there was considerable scope to substantially increase the average NDVI of vegetation around houses: 34% of houses were surrounded by vegetation with an average NDVI ≤ 50% of the 90th percentile (0.40).

4.2. Risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches

Trees and shrubs within 40 m of houses arranged as many discrete patches posed less risk to houses than the same cover of trees and shrubs arranged as few discrete patches—particularly at higher levels of cover for trees and shrubs (Fig. 2). As fuels become less continuous, the heat transfer between burning fuel and adjacent fuel becomes less efficient and the intensity and spread of a fire will decline (Rothermel, 1972). Effects of fuel patchiness on fire behaviour have been confirmed in the field by several authors (e.g., Bradstock & Gill, 1993; Burrows et al., 1991). On the other hand, a wider spacing between trees and shrubs can result in less sheltering of wind during fire (Zylstra et al., 2016), although we are unaware of any empirical studies where this has been linked to reduced house losses. The effect of patchiness among trees and shrubs on house loss during wildfires is likely to have greatest effect where fuel between patches of trees and shrubs (e.g., grass) is insufficient to maintain the intensity or rate of spread of the fire. However, benefits from increasing the number of patches of trees and shrubs became increasingly uncertain where the total number of patches and the cover of trees and shrubs were close to maximum observed values (Fig. 2), possibly reflecting few observations in the field where a high cover of trees and shrubs could be configured as many discrete patches.

4.3 Trees and shrubs in the upwind direction from which wildfires arrive represents a greater risk to houses than trees and shrubs in the downwind direction

Our results indicated that patches of trees and shrubs represented greatest risk when they occurred in the upwind direction from which the wildfire arrived, except where this vegetation was very close to houses (Fig. 3). Fire is more likely to propagate rapidly downwind because fuels are exposed to relatively greater convective and radiant heat (Rothermel, 1972), and direct ignition by flames. Further, embers are a key factor in the ignition of houses during wildfires (Barrow et al., 1944; Chen & McAneney, 2004; Cohen, 2000) and will predominantly travel downwind from a fire. However, fuels downwind or adjacent to houses during a wildfire can represent a hazard where they are close enough to direct radiant heat to the structure, where convective winds caused by the fire are drawn towards the structure from multiple directions, or on lee slopes where fires can spread laterally relative to wind direction (Sharples, McRae, & Wilkes, 2012). This may explain why fuels adjacent to, or downwind, from the prevailing wind direction still pose a risk to houses, albeit a relatively lower risk than fuels upwind from houses. Our results therefore suggested that, on average, less intensive fuel management downwind from houses can be tolerated without increasing the probability of house loss. However, this is only a useful strategy where the directions from which wildfires arrive at houses are consistent.

4.4. Implications for policy

In wildfire-prone regions management agencies may permit, or demand, home-owners to remove some vegetation near houses. These regulations are often generic. For example, in two of the most wildfire-prone states of Australia, regulations focus on the removal of trees and shrubs to set distances from houses (New South Wales Rural Fire Service, 2015; Victorian Department of Planning & Community Development, 2011). However, trees and shrubs provide many services such as aesthetics, privacy, shade and biodiversity (Driscoll et al., 2010; Nelson et al., 2005) and many people are attracted to the wildland-urban interface because of these (Nelson et al., 2005). Thus, individuals may be reluctant to clear vegetation around their houses (Nelson et al., 2005) placing some of the community at greater risk than others. Our results suggest that reducing the risk that trees and shrubs pose to houses during wildfires can be achieved without necessarily removing all trees and shrubs. Each of the three strategies examined here—-maintaining a green garden, retaining vegetation in discrete clumps and retaining more vegetation downwind from houses (with less vegetation retained upwind)—are options for fuel management that reduce risk to houses during wildfires without blanket removal of trees and shrubs and thus may be more acceptable fuel management options to some stakeholders. Accommodating diverse interests at the wildland-urban interface is likely to result in more uniform hazard reduction than imposing blanket approaches that are not supported by all stakeholders.

However, it is important to note that the management of vegetation close to houses alone will not eliminate risks to houses and occupants from wildfire. Other variables not considered in this study such as building design and the ability to actively defend a house can also affect house losses during wildfire (Penman et al., 2013). Further, the efficacy of strategies such as vegetation management decline with the severity of fire weather conditions (Gibbons et al., 2012). Thus, other strategies such as evacuation well before wildfires impact houses combined with adequate house insurance, building codes that reduce risk of house loss during wildfires and planning controls that limit house construction in areas with high risk must always be considered alongside vegetation management when managing risks to communities from wildfires.

5. Conclusions

We identified three landscaping options around houses—increasing the 'greenness' of vegetation, configuring trees and shrubs as many discrete patches, and focusing tree and shrub removal in the upwind direction from houses—that individually or together reduce the risk of house loss during wildfires without requiring the total removal of trees and shrubs. These findings represent options for regulators or home owners seeking to balance risk posed by wildfires with benefits associated with retaining trees and shrubs at the wildland-urban interface (e.g., privacy, aesthetics, biodiversity, shade). We encourage policy-makers to consider our findings as information that can be made available to residents and other actors at the wildland-urban interface to use in light of their individual circumstances rather than imposing uniform standards or regulations.

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Appendix A

Explanatory variables included in the base model used to predict house loss.

Variable	Definition
Buildings	The number of buildings (excluding circular water tanks) visible on the imagery intersecting a circle with a radius of 40 m from the centroid of each house
% cover of trees and shrubs	Visual estimate of % woody vegetation within a circle with a radius of 40 m from the centroid of each house using the pre-fire imagery. This estimate was verified against digitised data
Vegetation type (planted and remnant)	A visual assessment of whether woody vegetation within a circle with a radius of 40 m from the centroid of each house was predominantly planted or remnant using the pre-fire imagery. The features of trees and shrubs that were indicative of their origin were: crown texture, size, shape and arrangement relative to trees in nearby remnant vegetation
Distance upwind to nearest of trees or shrubs	Distance from each house to nearest group of ≥2 trees or shrubs (or one tree if its canopy was ≥10 m wide) from the edge of the house in the upwind direction measured manually in a GIS using the pre-fire imagery
Distance upwind to nearest block of trees	Distance from each house to nearest block of trees ≥50 m wide at the narrowest point from the edge of the house in the upwind direction measured manually in a GIS using the pre-fire imagery
Distance upwind to mapped cleared land	Distance from each house to nearest area without woody vegetation as mapped in the NV2005_EXTENT GIS raster provided by the then Victorian Department of Sustainability and Environment (DSE) in the upwind direction
% cleared upwind	% mapped woody vegetation calculated along a transect in the upwind direction from each house to the 2009 wildfire boundary using the NV2005_EXTENT GIS raster provided by DSE
Amount of land not burnt for ≤5 years upwind	Amount (m) of land from each house that was not burnt for ≤5 years prior to 2009 (as mapped in the PROD_FIRE_LASTBURNT100 layer provided by DSE) measured in the upwind direction
Upwind amount of private land	Amount (m) of land from each house that is not a public land tenure (as mapped in the PLM100 GIS shape file provided by DSE) in the upwind direction
Forest Fire Danger Index (FFDI)	Calculated using the formula $FFDI = 2.0 \times \exp(-0.450 + 0.987\ln(DF) - 0.0345RH + 0.338T + 0.0234V)$ where, DF is drought factor, RH is relative humidity (%), T is air temperature (°C) and V is wind speed ($km\,h^{-1}$). Weather variables used to calculate FFDI were derived from half-hourly data recorded at the closest weather station to each house

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Fire Ecology

ORIGINAL RESEARCH

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Housing arrangement and vegetation factors associated with single-family home survival in the 2018 Camp Fire, California

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Abstract

Background: The 2018 Camp Fire, which destroyed 18,804 structures in northern California, including most of the town of Paradise, provided an opportunity to investigate housing arrangement and vegetation-related factors associated with home loss and determine whether California's 2008 adoption of exterior building codes for homes located in the wildland-urban-interface (WUI) improved survival. We randomly sampled single-family homes constructed: before 1997, 1997 to 2007, and 2008 to 2018, the latter two time periods being before and after changes to the building code. We then quantified the nearby pre-fire overstory canopy cover and the distance to the nearest destroyed home and structure from aerial imagery. Using post-fire photographs, we also assessed fire damage and assigned a cause for damaged but not destroyed homes.

Results: Homes built prior to 1997 fared poorly, with only 11.5% surviving, compared with 38.5% survival for homes built in 1997 and after. The difference in survival percentage for homes built immediately before and after the adoption of Chapter 7A in the California Building Code (37% and 44%, respectively) was not statistically significant. Distance to nearest destroyed structure, number of structures destroyed within 100 m, and pre-fire overstory canopy cover within 100 m of the home were the strongest predictors of survival, but significant interactions with the construction time period suggested that factors contributing to survival differed for homes of different ages. Homes >18 m from a destroyed structure and in areas with pre-fire overstory canopy cover within 30–100 m of the home of <53% survived at a substantially higher rate than homes in closer proximity to a destroyed structure or in areas with higher pre-fire overstory canopy cover. Most fire damage to surviving homes appeared to result from radiant heat from nearby burning structures or flame impingement from the ignition of near-home combustible materials.

Conclusions: Strong associations between both distance to nearest destroyed structure and vegetation within 100 m and home survival in the Camp Fire indicate building and vegetation modifications are possible that would substantially improve outcomes. Among those include improvements to windows and siding in closest proximity to neighboring structures, treatment of wildland fuels, and eliminating near-home combustibles, especially in areas closest to the home (0–1.5 m).

Keywords: Building codes, Defensible space, Flame impingement, Fuels, Radiant heat, Structure loss, Wildfire, Wildland-urban interface

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Resumen

Antecedentes: El incendio de Camp Fire, el cual destruyó 18.804 estructuras en el norte de California, incluido la mayor parte del pueblo de Paradise, proveyó una oportunidad de investigar la ubicación de las casas y factores vegetales asociados con la pérdida de hogares, y determinar si la adopción de los códigos de construcción de California de 2008 para el exterior de las viviendas ubicadas en las áreas de interfaz urbano rural, mejoraban su supervivencia. Muestreamos al azar casas individuales construidas antes de 1997, de 1997 a 2007, y de 2008 a 2018, las últimas por dos períodos, anterior y posterior a los cambios en los códigos de construcción. Luego cuantificamos los doseles de la vegetación aledaña y la distancia a la vivienda y estructura más cercana destruidas por el fuego usando imágenes satelitales. Usando fotografías post-fuego, también determinamos el daño por fuego y asignamos una causa de daño, pero no casas destruidas.

Resultados: Las casas construidas antes de 1997 se desempeñaron pobremente, con solo un 11,5% de supervivencia, comparado con un 38,5% de supervivencia de aquellas construidas en 1997 y a posteriori. La diferencia en el porcentaje de supervivencia para las casas construidas antes y después de la adopción del Capítulo 7A del código de Construcción de California (37% y 44%, respectivamente), no fue estadísticamente significativa. La distancia a la estructura más cercana destruida por el fuego, el número de estructuras destruidas dentro de los 100 m, y la cobertura del dosel vegetal previo al fuego fueron los predictores de supervivencia más importantes, aunque las interacciones más significativas con el período de construcción sugieren que los factores que contribuyeron a la supervivencia difirieron para casas de diferentes edades. Las casas distantes > 18 m de una estructura destruida y en áreas con cobertura de vegetación previa dentro de los 20-100 m de esa casa < 53% sobrevivió a tasas superiores que aquellas en proximidad de una estructura destruida o en áreas con mayor cobertura vegetal pre-fuego. La mayoría de los daños a las casas supervivientes parece resultar del calor radiante de las estructuras quemadas próximas o por el impacto de las llamas de igniciones de materiales combustibles cercanos a las casas.

Conclusiones: Las fuertes asociaciones entre la distancia de la estructura destruida más cercana y la vegetación dentro de los 100 m y la supervivencia de las casas en el incendio de Camp Fire indican que es posible que las modificaciones en las construcciones y en la estructura de la vegetación mejoren los resultados en relación a su supervivencia. Entre ellos se incluye el mejoramiento de las ventanas y paredes en la proximidad de estructuras vecinas, el tratamiento de los combustibles vegetales, y la eliminación de combustibles cercanos, especialmente en áreas muy cercanas a las casas (entre 0 y 1,5 m).

Background

California, like many other regions having a Mediterranean climate, is set up to burn. Cool, wet winters, which promote vegetation growth, are followed by long, hot, nearly rain-free summers during which these wildland fuels are primed for combustion (Sugihara et al. 2018). In forested areas such as the northern Sierra Nevada, where the town of Paradise is located, wildfires ignited by indigenous peoples and lightning were historically frequent (mean fire return interval of mostly <15 years) (Van de Water and Safford 2011) and integral to shaping vegetation composition and structure (Leiberg 1902; Sugihara et al. 2018). The historical fire return interval in shrub-dominated chaparral vegetation was somewhat longer—15 to 90 years (Van de Water and Safford 2011). While overall acres burned in wildfires today is still substantially less than what burned historically (Stephens et al. 2007), both acres burned and associated losses to infrastructure have been increasing in recent times with 15 of the 20 most destructive events in modern California history, based on the number of structures destroyed, occurring since 2014 *(see California Fire Statistics:* https://www.fire.ca.gov/media/t1rdhizr/top20_destruction.pdf*)*.

The increase in destructive wildfire events has been linked to changes in fire frequency, development patterns, and climate. Loss of indigenous burning and active fire suppression over the past 150 or more years following Euro-American expansion into California reduced the incidence of fire in many forested areas. Where fire historically burned most frequently, surface and vegetative fuels have increased, often leading to more severe fire when it does burn (Steel et al. 2015). Such fires are also frequently more intense because fire suppression has effectively eliminated much of the lower intensity burning under more benign weather conditions. When landscapes now experience fire, most often it is when wildfire escapes initial attack under worst-case scenario weather conditions (Calkin et al. 2014). In addition, over the last several decades, warmer temperatures and longer fire seasons (Westerling et al. 2006) have increased fuel volatility and the probability of ignitions coinciding with extreme weather conditions. In other areas such as chaparral ecosystems in southern California, fire suppression has had less influence on the fire regime—fire frequency has increased in some areas on account of numerous human ignitions, but stand-replacing fire was and still is the norm (Conard and Weise 1998). Further complicating the wildfire challenges, human populations have increased nearly ten-fold over the last 150 years, with a substantial proportion of houses built within or among wildland vegetation (Radeloff et al. 2018). Partly due to the effectiveness of fire suppression, most of these homes were not built or maintained with the goal of being able to withstand wildfire in the absence of fire suppression resources. In addition, home design or construction codes and standards to enhance a building's exterior resistance to wildfire are relatively recent (International Code Council 2003), with substantial development having occurred prior.

Post-wildfire analyses provide an opportunity to investigate why some houses survive and learn how to better co-exist with wildfire in fire-prone environments. During wildfire, buildings can be subjected to three different wildfire exposures—wind-blown embers, radiant heat, and direct flame contact (Caton et al. 2017). Embers are produced when vegetation ignites and burns (Koo et al. 2010). In large, fast-moving wildfires burning under extreme conditions, embers can be transported several kilometers or more (Koo et al. 2010) and ignite buildings directly or indirectly (Caton et al. 2017). A direct ember ignition includes embers igniting decking or siding by accumulating on or next to the material or penetrating vents or open windows and entering the building (Quarles et al. 2010; Hakes et al. 2017). In contrast, indirect ignitions occur when embers ignite combustible materials such as vegetation, bark mulch, leaf litter, neighboring buildings, or near-home objects such as stored materials, decks, or wood fences (Quarles et al. 2010; Hakes et al. 2017). Indirect ignition scenarios ultimately result in radiant heat and/or flame contact to the home or building. Direct flame contact and extended radiant heat exposures can ignite siding and other exterior-use construction materials or break glass in windows. Radiant heat exposure often occurs when a neighboring structure ignites. The dominant mechanism of home loss in numerous particularly destructive wildfires has been described as initial direct or indirect ember ignitions, with burning homes then leading to house-to-house fire spread (Murphy et al. 2007; Cohen and Stratton 2008). However, the potential influence of housing density on structure losses in wildfires has varied, with some studies finding a greater probability of loss at higher housing densities (Price and Bradstock 2013; Penman et al. 2019), while other studies have reported a greater risk at lower housing densities (Syphard et al. 2012, 2014, 2017). Amount of near-home combustible vegetation has also been linked to the probability of home loss in wildfires (Price and Bradstock 2013; Syphard et al. 2014; Penman et al. 2019).

California leads the USA in having a building code with the objective of limiting the impact of wildfires on the built environment. In the 1960s, the state began requiring homeowners to implement defensible space fuel modifications, initially within the first 9 m (30 ft) of a building, but since expanded to 30 m (100 ft) (https://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?sectionNum=4291.&lawCode=PRC). Work on standardized test methods to evaluate exterior-use construction materials for fire performance began in the late 1990s and later incorporated into Chapter 7A, an addition to the California Building Code which was adopted in 2008. Chapter 7A provides prescriptive and performance-based options for exterior construction materials used for roof coverings, vents, exterior walls, and decks (https://codes.iccsafe.org/content/CBC2019P4/chapter-7a-sfm-materials-and-construction-methods-for-exterior-wildfire-exposure) and applies to new construction of residential and commercial buildings in designated fire hazard severity zones. In some jurisdictions, provisions of Chapter 7A also apply to "significant remodels" of existing buildings. The 2018 Camp Fire, which destroyed much of Paradise, California, provided an opportunity to evaluate the performance of buildings constructed after the adoption of Chapter 7A and explore factors associated with home survival.

The Camp Fire started on the morning of November 8, 2018, with the failure of an electrical transmission line and spread rapidly through wildland fuels comprised of mixed conifer forest, brush, grass, and dead and down surface fuels (Maranghides et al. 2021). Surface fuels were unusually dry due to persistently low relative humidity throughout the summer and fall and the late onset of fall rains (Brewer and Clements 2019). Driven by strong NE winds, the fast-moving fire quickly reached the towns of Concow, Paradise, and Magalia and became the most destructive wildfire in California history. At least 85 people were killed and 18,804 structures were destroyed. A high proportion of the home and business losses occurred in Paradise—the largest town within the fire footprint. The fire passed from one side of Paradise to the other during one burn period over less than 12 h (Maranghides et al. 2021). With the focus on saving people's lives, very few homes were subject to firefighting efforts, and survival was therefore largely a function of characteristics of the home and surrounding environment. Previous similar analyses have typically combined data across multiple fires and years, with an unknown extent of defensive intervention.

While conditions as the Camp Fire burned through Paradise were still highly variable, the massive home loss in a single burn period presents an opportunity to investigate factors with potentially lesser confounding by differences in geography, weather, and defensive action by firefighters or civilians.

The objective of this research was to answer three questions as follows: (1) did proximity to nearby burning structures factor into the probability of home survival, (2) did fuels associated with nearby vegetation factor into the probability of home survival, and (3) was the full adoption in 2008 of Chapter 7A into the California Building Code associated with improved odds of home survival?

Methods

The Butte County Assessor's database, dated June 1, 2018, was used to extract 11,515 parcels within the Paradise city limits (Fig. 1). Parcels were sorted by use code and 7949 single-family dwellings were selected, after discarding 89 without a listed build year. Mobile homes, businesses, and other non-single-family structures were excluded. We then linked Damage Inspection (DINS) data, obtained from CAL FIRE, to parcel number to ascertain damage sustained in the Camp Fire and whether the building was destroyed, partially damaged, or had no impact from the Camp Fire. We lumped homes classified as "damaged" into the "survived" category, because in most instances, the damage, based on photos included with the DINS data, was minor—e.g., cracked windows, bubbled exterior paint, or melted vinyl gutters and window frames, with the structure itself intact.

Sample population

For our analyses, we randomly selected 400 single-family dwellings in Paradise, stratified by three time periods (Fig. 1): time 1 = homes built before 1997, while time 2 (homes built from 1997 to 2007) and time 3 (homes built from 2008 to 2018) represented the two 11-year periods on either side of the 2008 adoption of Chapter 7A in the California Building Code. If the changes to the building code improved home survival, survival percentage in time 3 should be significantly higher than survival in time 2, especially after adjusting for any potentially confounding variables. The stratification was done to ensure a large enough sample size in time period 3. Two hundred homes (out of 7288) were randomly selected in time 1, one hundred homes (out of 519) were selected in time 2, and 100 homes (out of 142) were selected in time 3 (Fig. 1). More homes were selected during time 1 because such a low percentage (13%) of older (pre-1997) homes survived. Of the population of homes that were randomly selected by the construction period, 24 of the surviving homes were noted as damaged in the DINS report, the rest undamaged. Damage was listed as "affected (1–9%)" for 23 of the damaged homes and "minor (10–25%)" for one.

Variables

For each randomly selected home, we used Google Earth to measure the distance from the edge of the home (as defined by edge of the roof, using pre-fire images when destroyed) to the closest edge of the nearest home and nearest structure, as well as the nearest home and nearest structure that burned. "Nearest structure" was in most cases another single-family home, but also

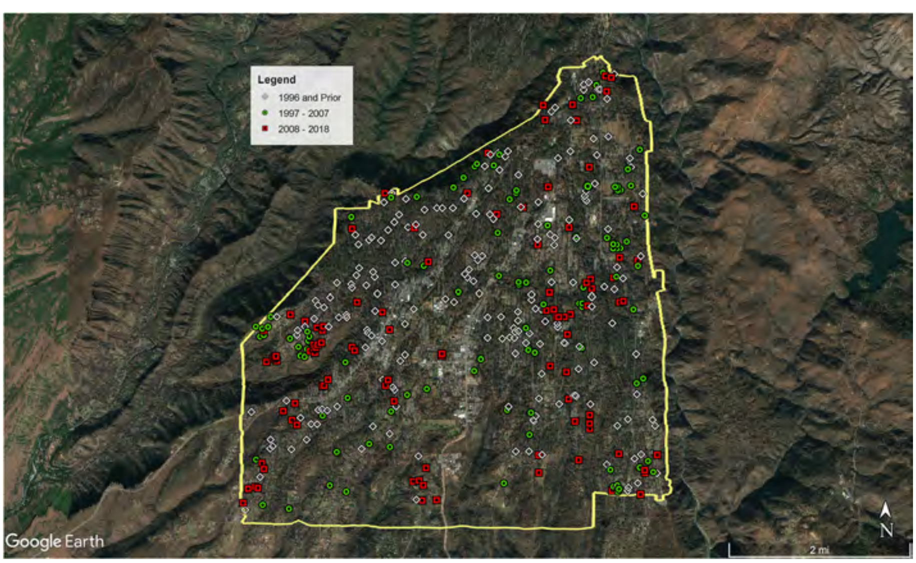

Fig. 1 Map showing the perimeter of Paradise, California, with the location of 400 randomly selected homes built during three time periods (pre-1997, 1997–2007, and 2008–2018)

included mobile homes, businesses, detached garages, or outbuildings such as larger sheds. Small sheds—those <120 ft^2, where a building permit is not required—were excluded. Such smaller sheds may have posed a threat to the home as well but were more challenging to consistently quantify, especially if under a tree canopy. We determined the density of structures in the surrounding area by counting the number of single-family homes, partially-built homes, mobile homes, and businesses (excluding small sheds) with midpoints (based on a visual estimate) included within a 100-m radius centered on the target home. We then counted how many of those structures were destroyed. We visually estimated the percentage cover of overstory vegetation from Google Earth images taken prior to the fire in 2018 and/or 2017 within a 30-m radius circle centered on the selected home and between 30 m and 100 m from the selected home. Cover of the understory of grass and/or shrubs or landscape plantings was not estimated, as pre-fire overstory canopy cover was relatively high, and this often obscured the understory. Some larger mid-story shrubs might have been included with the tree overstory due to the difficulty in distinguishing them from trees. The lot size was provided in the Butte County Assessor's data. Whether the house was located in the Wildland Urban Interface (defined as developed areas that have sparse or no wildland vegetation but are near a large patch of wildland) or the Wildland Urban Intermix (defined as areas where houses and wildlands intermingle) was determined by overlaying a University of Wisconsin data layer on the city of Paradise (Radeloff et al. 2005). We used Radeloff et al. (2005) to define the interface as census blocks with at least 6.17 housing units km^{-2} that contained <50% wildland vegetation but were within 2.4 km of a heavily vegetated area (>75% wildland vegetation) larger than 5 km^2. Intermix was defined as an area with more than 6.17 housing units km^{-2} but dominated by wildland vegetation. Percent slope was calculated as the rise between the lowest and highest point along a 100-m radius circle centered on the home.

Analysis approach

Possible explanatory variables (S1 Table) were first analyzed individually using a generalized linear model in SAS PROC GENMOD and assuming a normal distribution to evaluate whether they differed by time period or by outcome (survived, destroyed). To account for the sampling scheme, in this and all subsequent analyses, each observation was weighted by the inverse of its probability of selection—i.e., homes from time period 1 had a weight of 7288/200, homes from time period 2 had a weight of 519/100, and homes from time period 3 had a weight of 142/100. Comparisons among main effects (outcome, time period) and interactions (outcome × time period) were determined using Tukey's HSD test for multiple comparisons, when significant.

To determine the relative strength of factors associated with home survival, we used a generalized linear model fit for binary response data, with a logit link function and weighting to account for the sampling scheme. Variables in the initial model were as follows:

1. Y-variable: Outcome (Survived/Destroyed); X-variables: construction time period, year built, Wildland Urban Interface/Intermix category, distance to nearest destroyed structure, total structures destroyed within 100 m, overstory canopy cover within 30 m, overstory canopy cover between 30 m and 100 m, slope, and the interaction of each with the construction time period.

When independent variables were highly correlated ($R > 0.6$), only the one most clearly mechanistically linked to outcome was included. For example, "distance to nearest structure" was highly correlated with "distance to the nearest destroyed structure," and "total structures–100 m" was highly correlated to "total structures destroyed—100 m" (Table 1), so only the latter were included. Lot size was not included as there was no clear mechanistic link with home survival, and we hypothesized that elements contributing to fire behavior would be captured by correlated variables. The Wildland Urban Interface/Intermix category was included to quantify differences in vegetation and housing arrangement at scales larger than 100 m. Non-significant interactions and non-significant main effects for variables that did not have a significant interaction with time were sequentially removed to produce the final model. To determine whether homes constructed after the Chapter 7A building code update survived at a significantly higher rate after factoring in all other possible confounding variables, the same analysis was conducted except without interactions with the construction time period.

We then designed models to first test the effect of variables that may have directly influenced home survival during the fire and second, to test the effect of just the variables available prior to the fire. The latter variables were ones that might be mitigated preemptively through planning, retrofitting, or vegetation management. For each of these models, we determined the effect size and performed a regression tree analysis. Variables included for each approach (accounting for the fire, pre-fire only):

1. Y-variable, accounting for the fire: Outcome (Survived/Destroyed); X-variables: year built, distance to nearest destroyed structure, total structures destroyed within 100 m, canopy cover within 30 m,

Table 1 Significance of individual factors by time period, outcome (destroyed, survived), and outcome × time period for a subset of single-family homes in Paradise, CA. Means for time period, outcome, and outcome × time period (when interaction was significant) are provided below (standard error in parentheses). Levels within variables followed by different letters were significantly different ($P<0.05$)

	N	**Lot size (ha)**	**Dist. nearest struct. (m)**	**Dist. nearest destr. struct. (m)**	**Total structures 100 m**	**Total structures destr. 100 m**	**% Canopy cover 0–30 m**	**% Canopy cover 30–100 m**	**Slope (%)**
		P							
Outcome		*0.946*	*0.971*	*<0.001*	*0.004*	*<0.001*	*0.154*	*0.001*	*0.532*
Time period		*0.153*	*0.010*	*<0.001*	*0.002*	*<0.001*	*<0.001*	*0.664*	*0.290*
Outcome × time period		-	-	*0.026*	-	-	-	-	-
		Average (standard error)							
Destroyed	296	0.42 (0.07)	15.4 (1.6)	-	10.3^{a} (0.8)	8.9^{a} (0.7)	40.5 (3.1)	49.1^{a} (2.8)	6.9 (0.6)
Survived	104	0.42 (0.08)	15.5 (1.9)	-	8.1^{b} (0.9)	5.5^{b} (0.9)	36.0 (3.7)	40.0^{b} (3.3)	7.2 (0.6)
Before 1997	200	0.30 (0.04)	10.9^{b} (0.8)	-	11.4^{a} (0.4)	9.4^{a} (0.4)	49.5^{a} (1.6)	46.7 (1.4)	6.4 (0.3)
1997-2007	100	0.45 (0.09)	16.1^{a} (2.1)	-	8.0^{b} (1.0)	5.9^{b} (1.0)	35.7^{b} (4.1)	43.7 (3.7)	7.5 (0.7)
2008-2018	100	0.51 (0.17)	19.3^{ab} (4.0)	-	8.1^{ab} (1.9)	6.3^{ab} (1.8)	29.5^{b} (7.9)	43.2 (7.0)	7.2 (1.4)
<1997 Dest.	177	-	-	12.3^{c} (0.8)	-	-	-	-	-
<1997 Surv.	23	-	-	22.3^{b} (2.1)	-	-	-	-	-
1997–2007 Dest.	63	-	-	20.0^{bc} (3.4)	-	-	-	-	-
1997–2007 Surv.	37	-	-	34.6^{ab} (4.4)	-	-	-	-	-
2008–2018 Dest.	56	-	-	16.1^{bc} (6.8)	-	-	-	-	-
2008–2018 Surv.	44	-	-	54.0^{a} (7.7)	-	-	-	-	-

canopy cover between 30 m and 100 m, wildland urban interface/intermix category, slope.

2. Y-variable, pre-fire only: Outcome (Survived/ Destroyed); X-variables: year built, distance to nearest structure, total structures within 100 m, canopy cover within 30 m, canopy cover between 30 m and 100 m, wildland urban interface/intermix category, slope.

To quantify the relative strength of continuous variables for explaining home survival, each of the dependent (x) variables were centered and scaled to have a mean of zero and standard deviation of one. Logistic regression (McCullagh and Nelder 1989) was then used to calculate coefficients and compare effect sizes. The logistic regression models were fit using the *svyglm* function from the *survey* package in R (Lumly 2020). A decision tree for predicting home survival was produced using the *rpart* function in the *rpart* package (Therneau and Atkinson 2019) in R, fit for binary response data with a logit link function (Breiman 1998). This approach is similar to logistic regression, where the linear predictor is a decision tree model. To determine the number of splits in the decision trees, we performed cross-validation 10,000 times to compute the optimal pruning parameters. We then used the average of the 10,000 optimal pruning parameters as the pruning parameter in the final decision tree. The latter group of statistical analyses was completed using R version 4.0.0 (R Core Team 2020). Figures were made in R using the *ggplot2* package (Wickham 2016).

Visual evaluation of damaged homes

To learn more about vulnerabilities of the Paradise home sample and gain insight into potential points of fire entry, we reviewed the CAL FIRE damage inspection (DINS) spreadsheet (obtained from CAL FIRE 12/18/ 2018) and obtained photographs of all damaged homes (N=310 homes with pictures).

Photographs typically keyed in on the damage, and we reviewed each, along with notes about damage in the DINS summary. Observed home damage was assigned to radiant heat, direct ember ignition, or flame impingement categories (S2 Table), based on the nature of the damage, location on the home, and visual as well as photographic (aerial imagery) evidence of other burned fuels, including homes, in the immediate vicinity. Homes where flame impingement was recorded were further split into three categories: (1) caused by fuel continuity with the broader landscape (which allowed fire to reach the home), (2) indirect ember ignition (e.g., gutter contents, near-home fuels) with flames then impacting the home, or (3) unknown/undetermined. [The DINS assessment gathered similar information, but the full suite of data was not collected for over a quarter of homes and ember ignition was not separated into direct and indirect categories.] Where DINS data were collected, our evaluation was often in agreement, but there were a few instances where we differed. For example, if the DINS assessment noted "direct flame impingement" but the photo showed no charring or near home fuels consumed, we listed the damage caused as "radiant heat." Gutter fires were variously categorized but we assigned them all to the "indirect ember ignition" category. The DINS assessment also only lists a single cause of fire damage when a considerable number of homes displayed multiple causes.

Results

Overall, most (86%) of the single-family homes in Paradise were built before 1990, and homes of this age fared poorly, with only 11.6% surviving the Camp Fire (Fig. 2). Survival increased to 20.6% for homes built between 1990 and 1996, 34.3% for homes built between 1997 and 2007, and 43.0% for homes built between 2008 and 2018. The 400 randomly selected homes in our sample had similar survival rates to the full population of single-family homes—11.5% vs. 13.3%, respectively, for the <1997 time period (time = 1), 37.0% vs. 34.3%, respectively, for the 1997–2007 time period (time = 2), and 44.0% vs. 43.0%, respectively, for the 2008 to 2018 time period (time = 3). Many of the potential explanatory variables differed over the three time periods as well and were therefore confounded with potential construction or building code differences (Table 1). Older homes (<1997) were on average in areas with higher housing density and had more homes burn within 100 m than homes built from 1997 to 2007 (Table 1). Homes built prior to 1997 had a higher average pre-fire overstory canopy cover in the first 0–30 m from the home than homes

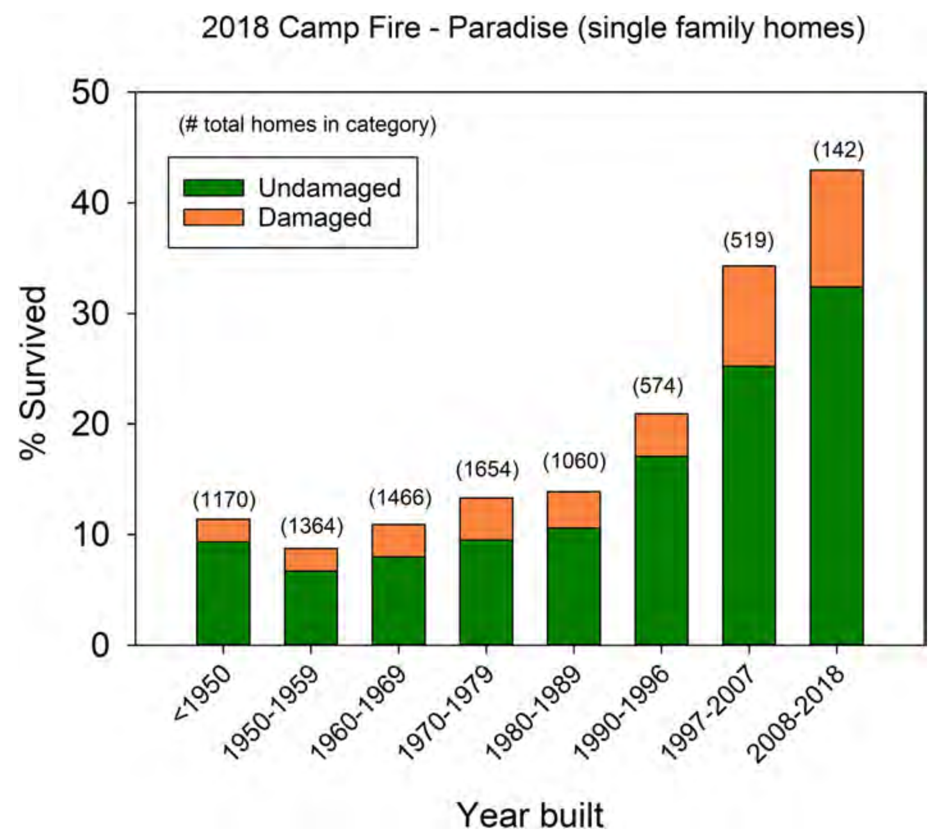

Fig. 2 Percentage of surviving single-family homes in Paradise by decade of construction

built afterwards (Table 1). The "distance to nearest destroyed structure" × time interaction was significant, with surviving homes a greater distance from the nearest destroyed structure in time periods one and three. This difference was especially pronounced for the newest homes (Table 1). While average lot size trended larger over time, the differences were not significant (Table 1). Pre-fire overstory canopy cover 30–100 m from the home was significantly lower for surviving homes (37.0%) than destroyed homes (50.4%) but did not differ between time periods (Table 1). With most houses situated on top of a plateau, the average percent slope was relatively low and did not differ significantly among outcomes or time periods (Table 1). None of the variables differed between time periods 2 and 3—immediately pre- and post-Chapter 7A adoption.

Many of the continuous variables we analyzed were significantly correlated with each other, with distance to nearest structure and distance to nearest destroyed structure (r = 0.625) and total structures within 100m and total structures destroyed within 100m (r = 0.926) being the most strongly correlated (Table 2).

Factors influencing home survival

Eliminating the two most highly correlated variables (distance to nearest structure and total structures per 100m) and analyzing the remaining variables together in the same model showed that both nearby destroyed structures and overstory canopy cover within 100 m were significantly associated with home survival. The "distance to nearest destroyed structure" × construction time period interaction was significant (Table 3), with a much higher survival probability when homes were a larger distance from a destroyed structure, especially for homes built 1997–2007 and 2008–2018 (Fig. 3a). Total structures destroyed within 100 m also was strongly linked to home survival (Table 3), with a much higher survival probability when fewer surrounding homes burned (Fig. 3b). For the vegetation variables, the "CanopyCover 0–30m" × construction time period interaction was significant (Table 3). Higher survival was noted with lower canopy cover for homes built since in 1997 and after but was not related to survival in older (<1997) homes (Fig. 3c). CanopyCover 30–100m also was highly significant, with a higher survival probability at lower canopy cover percentages across times (Table 3, Fig. 3d). Wildland urban interface/intermix category was significant, with a higher survival rate for homes in the wildland urban intermix (29.3%) than homes in the wildland urban interface (16.0%). Year built [within construction time period] and slope were not significant and did not make it into the final model (Table 3).

When the same analysis was conducted without interactions to test the effect of construction time period after correcting for covariates, homes built between 1997–2007 and 2008–2018 both survived at a significantly higher rate than homes built prior to 1997 ($P < 0.001$). Even though the survival rate was numerically higher for homes built after the 2008 building code update (44%) than homes built in an equivalent time period

Table 2 Correlation matrix of variables considered in the analyses of factors potentially contributing to home survival. The correlation coefficient (R) is above the diagonal, with statistical significance below. Distance to nearest destroyed home includes only single-family homes. Distance to nearest destroyed structure includes single-family homes, mobile homes, businesses, outbuildings, detached garages, and other large buildings

	Lot size	Year built	Dist. nearest structure	Dist. nearest dest. structure	Total struct. 100 m	Structures destroyed 100 m	Canopy Cover (%) 0–30 m	Canopy cover (%) 30–100 m	Slope (%)
Lot size		0.166	0.544	0.462	−0.499	−0.435	−0.111	−0.001	0.368
Year built	*<0.001*		0.262	0.283	−0.406	−0.424	−0.419	−0.146	0.156
Dist. nearest structure	*<0.001*	*<0.001*		0.625	−0.497	−0.432	−0.069	0.009	0.260
Dist. nearest dest. structure	*<0.001*	*<0.001*	*<0.001*		−0.471	−0.537	−0.263	−0.226	0.216
Total struct_ 100m	*<0.001*	*<0.001*	*<0.001*	*<0.001*		0.926	0.215	−0.007	−0.299
Struct. destroyed_ 100m	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*		0.300	0.134	−0.233
Canopy Cover 0-30m	*0.026*	*<0.001*	*0.171*	*<0.001*	*<0.001*	*<0.001*		0.571	−0.001
Canopy Cover 30-100m	*0.983*	*0.003*	*0.853*	*<0.001*	*0.890*	*0.007*	*<0.001*		0.135
Slope (%)	*<0.001*	*0.002*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*0.984*	*0.007*	

Table 3 Fixed effects in a generalized linear mixed model (PROC GENMOD) analysis of variance of the influence of nearby destroyed structures and pre-fire overstory canopy cover on Paradise single-family home loss in the Camp Fire, taking into account other potentially confounding variables. All variables plus their interactions with time period were put in the preliminary model with non-significant interactions and main effects sequentially dropped for the final model

Variable	DF	Chi-square	P
Construction time period	2	68.84	<0.001
Dist. nearest destroyed structure	1	57.10	<0.001
Tot. structures destroyed 100 m	1	179.77	<0.001
Canopy cover_0–30 m	1	1.61	0.205
Canopy cover_30–100 m	1	162.48	<0.001
Wildland urban intermix/interface category	1	4.54	0.033
Dist. nearest destroyed structure × time	2	16.45	<0.001
Canopy cover_0–30 m × time	2	25.35	<0.001

immediately before (37%), the difference was not statistically significant (adjusted $P = 0.309$).

For the next set of analyses, separate models (this time without specifying construction time period) were run on normalized data for (1) variables in play during the Camp Fire (including fire-related variables) and (2) variables present prior to the Camp Fire (i.e., variables that might factor into pre-fire planning). For the first model, distance to the nearest destroyed structure had the largest effect size, suggesting that the greater the distance to a burning structure, the higher the probability of survival (Fig. 4a). Also significant were canopy cover within 30–100 m and the number of destroyed structures within 100 m. Both the latter two variables had a negative relationship with survival, with higher survival where canopy cover within a 30–100 distance was lower, and number of destroyed structures within 100 m was fewer (Fig. 4a). Year built, slope, and canopy cover within 0–30 m all had confidence intervals that overlapped with zero. When only pre-fire variables were included, housing density had the largest effect size, with greater survival when the number of structures within 100 m was low (Fig. 4b). Canopy cover within 30–100 m had the second largest effect size, with greater survival at lower canopy cover levels (Fig. 4b). Distance to nearest structure, year built, slope, and canopy cover within 0–30 m all had confidence intervals that overlapped with zero (Fig. 4b).

Decision tree analysis using variables present during the fire indicated a threshold of 18 m from nearest destroyed structure best predicted whether a home survived or not. Survival probability for homes <18 m to the nearest destroyed structure was very low (0.058), compared with a 0.354 survival probability for homes ≥18 m from the nearest destroyed structure (Fig. 5a). Based on our sample, a majority (73.6%) of the homes in Paradise were <18 m from a destroyed structure. For the 26.3% of homes ≥18 m from a destroyed structure, if the pre-fire overstory canopy cover was also < 53% within 30–100 m, the survival probability improved to 0.481 (Fig. 5a). If the home was also built during or after 1973, the survival probability improved to 0.606 (Fig. 5a). The final split, involving just 10.2% of the homes in Paradise, suggested that for homes meeting these criteria (i.e., ≥18 m from the nearest destroyed structure, <53% canopy cover within 30–100 m, and built ≥1973), the survival probability improved to 0.733 if slope was less than 8.2%. For the decision tree including just pre-fire variables, year built was the first split, with a probability of survival of only 0.111 for homes built before 1996 (90.8% of homes in Paradise), compared with 0.396 for homes built during or after 1996 (9.2% of homes) (Fig. 5b). For homes in this latter category, survival probability improved to 0.766 if the pre-fire overstory canopy cover within 30–100 m was <33%. If pre-fire canopy cover within 30–100 was ≥33%, the survival probability fell to 0.239.

Damaged homes—nature of damage and cause

In our review of photographs of the 310 fire-damaged homes in Paradise, 63% had radiant heat damage (Fig. 6a), mostly to windows and exterior walls (Fig. 6b). Window damage consisted of cracked or broken glass and damaged window framing, but frequently included both. Blistered paint or melted/sagging vinyl siding were the most common wall (siding) damages. In most cases, the source of the radiant heat was difficult to assess, as the photos focused on the damage. However, a closer investigation of 20% of randomly sampled of homes where radiant heat damage was identified demonstrated that all had at least one neighboring structure that was destroyed during the fire, with an average distance to the destroyed structure of 12.1 m. Flame impingement was the next most common cause of damage (44% of damaged homes) (Fig. 6a). In most flame impingement cases (28% of the total damaged homes), the damage was interpreted to be the result of indirect ember ignition. For only 10% of damaged homes was the continuity of fuels from the broader surroundings (often needle or leaf litter) identified as the likely reason for flame impingement. For another 10% of damaged homes, whether needle or leaf litter was continuous with the surroundings or just localized next to the home could not be determined from the photograph. [Note—these three flame impingement categories do not add to 44% because some houses showed evidence of multiple flame impingement causes.] For the cases of flame impingement via indirect ember ignition, embers ignited near home flammable objects (e.g., fences, patio furniture, stored lumber), near home leaf litter, near home vegetation (or litter under that vegetation), leaf litter in gutters, or wood bark mulch, in order of frequency from most to least (S2 Table). Direct

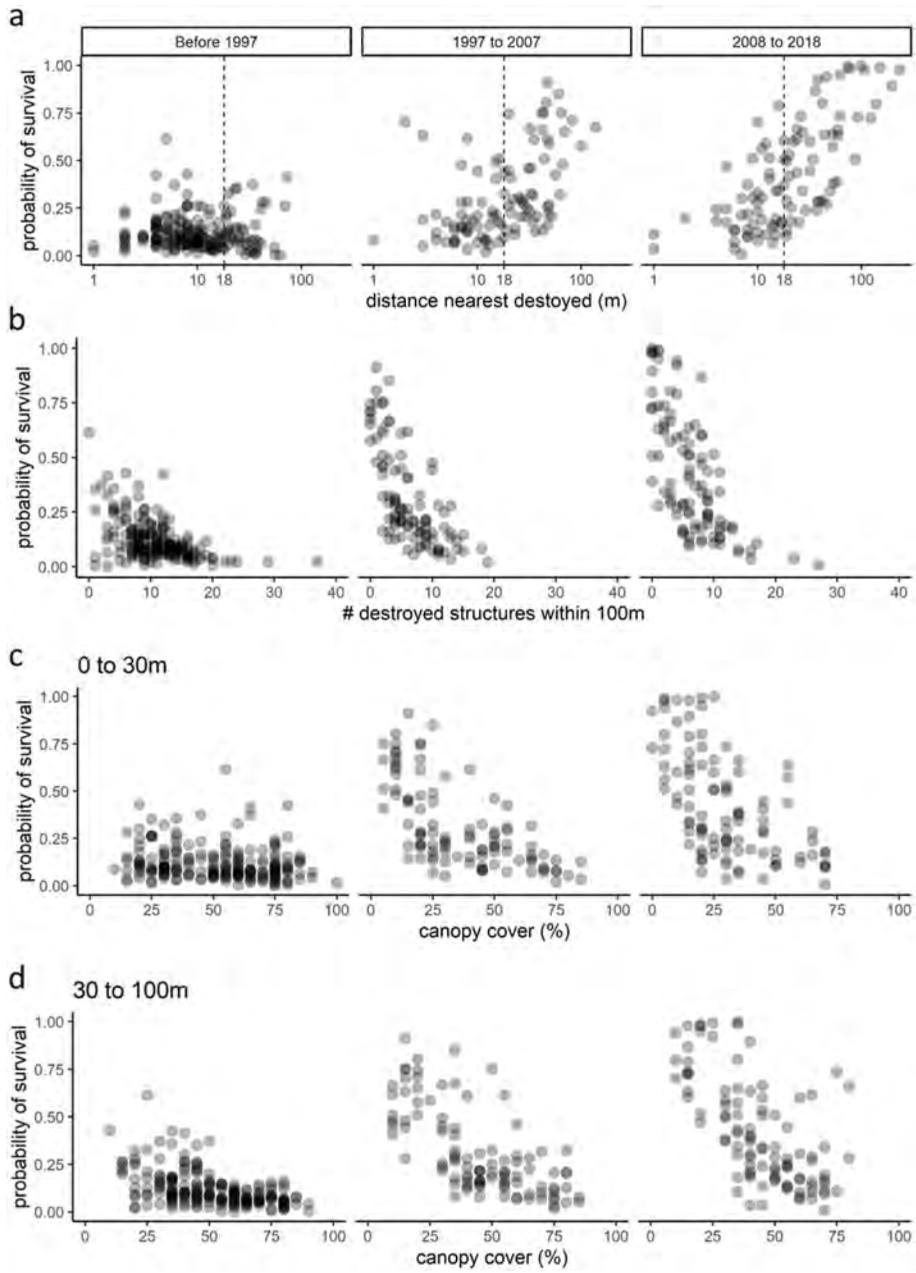

Fig. 3 Probability of home survival with **a** distance (m) to nearest destroyed structure, **b** the number of destroyed structures within a 100-m radius, **c** pre-fire overstory canopy cover within 0–30 m, and **d** pre-fire overstory canopy cover within 30–100 m, for homes built during three time periods (before 1997, 1997–2007, and 2008–2018). A vertical dotted line in **a** shows the 18-m threshold between survival and destruction identified by the regression tree analysis (Fig. 5a)

ember ignition was identified as the likely cause of damage for fewer than 6% of homes (Fig. 6a). The most common locations for embers to ignite were attached wood stairs, decking, and window trim. Counting either direct ember ignition or flame impingement due to indirect ember ignition, embers were implicated as a cause in 33% of damaged homes.

Discussion

Burning structures and wildland fuels both influence home survival

Our analysis of post-fire outcomes in the town of Paradise suggested that both the proximity to other burning structures and nearby wildland fuels factored in the probability of home survival, with several measures of

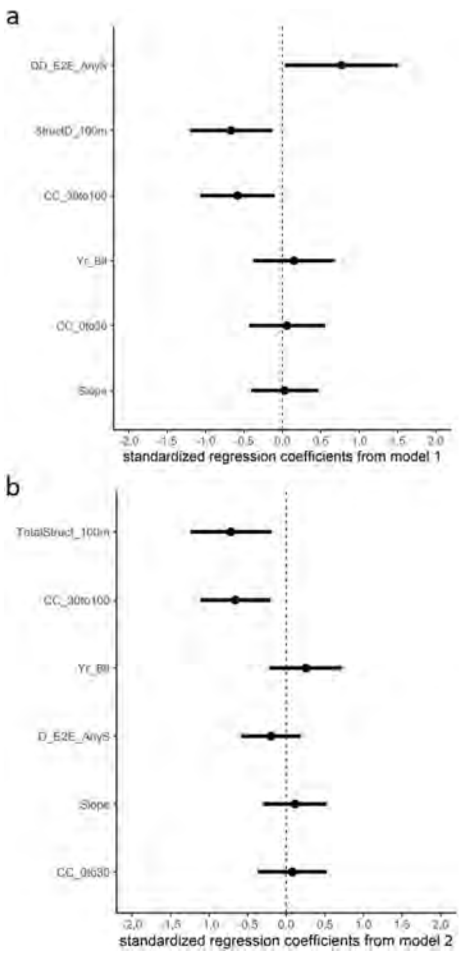

Fig. 4 Effect sizes for two logistic regression models of home survival in the town of Paradise during the 2018 Camp Fire, including continuous variables **a** present during the fire and **b** only variables present pre-fire. Regressions were based on a random sample of 400 homes

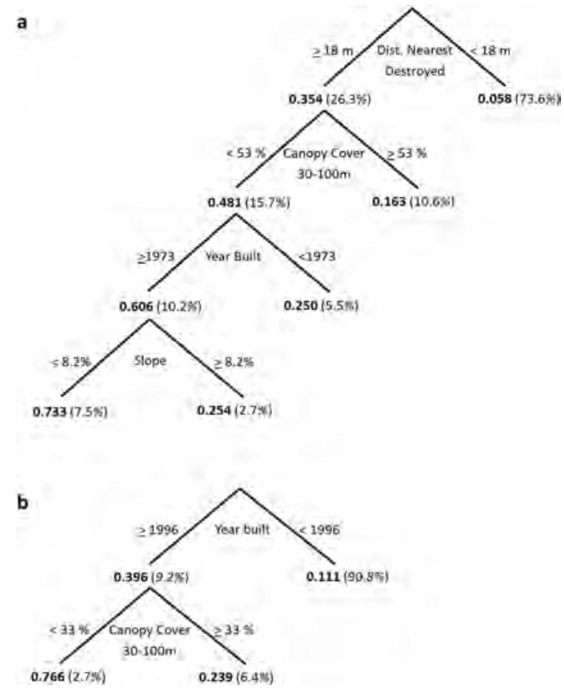

Fig. 5 Regression trees for predicting home survival in the town of Paradise in the 2018 Camp Fire, with models including continuous variables **a** present during the fire and **b** only variables present pre-fire, both based on a random sample of 400 homes. Survival proportion is listed in bold under each branch, along with the percentage of homes in Paradise that each branch applied to (in parenthesis)

distance and density of destroyed structures and nearby pre-fire overstory canopy cover emerging as significant explanatory variables. The relative importance of nearby burning home variables versus surrounding vegetation in explaining outcomes has varied among studies, with Gibbons et al. (2012) reporting canopy cover within 40m of the home to be the strongest predictor. Number of buildings within 40m was also a significant variable in their analysis. Even though nearby burning structure and vegetation variables were both included in the models in our study, interpretations about relative strength of these two sets of factors are tempered by limitations of the vegetation data, with overstory canopy cover an imperfect measure of wildland fuel hazard.

One possible clue to the relative importance of adjacent structures burning comes from the different outcomes for wildland urban intermix and interface homes. Houses built amongst wildland vegetation (intermix) survived at a higher rate (29%) than houses built in more of a subdivision arrangement with wildland fuels nearby (interface) (16%). Average pre-fire overstory canopy cover within 0–30 m was similar for intermix and interface homes (42% and 43%, respectively), but pre-fire overstory canopy cover within 30–100 m was higher for intermix than interface homes (49% vs. 42%, respectively). If proximity to wildland fuels had been the dominant driver, greater percentage losses in the wildland urban intermix would have been expected. The higher survival of intermix homes may therefore have been more a function of greater average distance to the nearest destroyed structure (24 m vs. 11 m in the intermix and interface, respectively) and lower average density (7.7 vs. 11.1 structures within 100 m in the intermix and interface, respectively). (Kramer et al. 2019) in an analysis of three-decade's worth of wildfires in California, also reported higher survival of homes in the wildland-urban intermix compared to the wildland-urban interface, and together with our results provide some additional evidence of the importance of nearby burning structures to home loss, relative to variables associated with wildland fuels. However, in our study, other factors

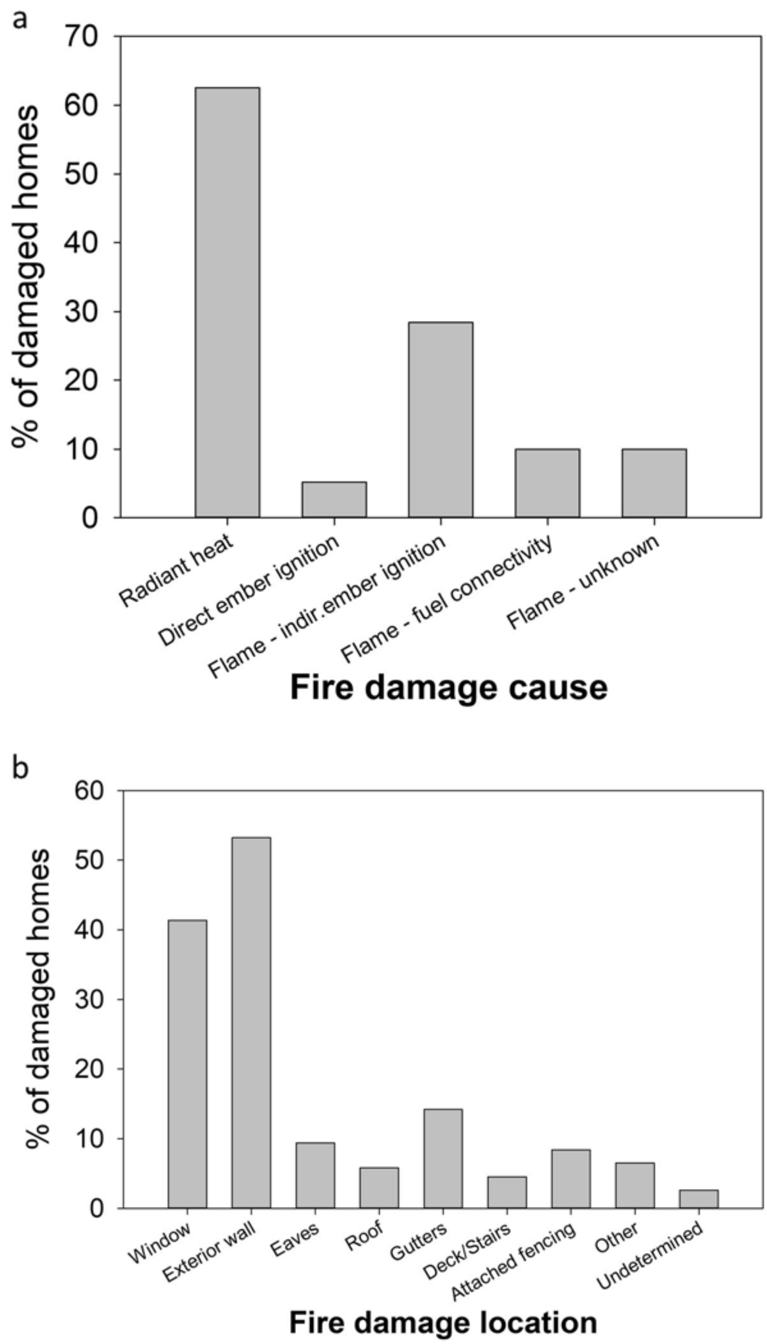

Fig. 6 Percentage of damaged but not destroyed homes in Paradise by **a** fire damage cause category and **b** fire damage location. Fire damage cause was either radiant heat, direct ember ignition, or flame impingement. Flame impingement was further subdivided into flame impingement due to indirect ember ignition, fuel continuity with the broader landscape, or unknown. Numbers were based on visual assessment of photos taken by the CAL FIRE inspectors and information in the CAL FIRE DINS (damage inspection) data. Totals exceed 100% because some homes had multiple sources of fire damage

were likely in play as well, with intermix homes being somewhat newer. In Paradise, an increasing percentage of homes were located in the intermix vs. the interface over time: 66% in time period 1, 80% in time period 2, and 88% in time period 3.

Homes as fuel

Distance to nearest destroyed structure and the total number of destroyed structures within 100 m were consistently the strongest predictors in our analyses. This makes intuitive sense because burning structures produce a substantial amount of radiant heat, which can ignite adjacent homes or break glass in windows, allowing embers to enter the home. Nearby burning structures are also a source of embers, which can result in direct or indirect ember ignitions of nearby structures. Our visual analysis of 310 damaged homes corroborated the results of the statistical analyses, with more homes showing evidence of damage from radiant heat exposure (often from adjacent structures burning) than from flame impingement. Our findings are consistent with other analyses of destructive wildfires showing housing density to be strongly associated with home loss (Price and Bradstock 2013; Penman et al. 2019), but in contrast to Syphard et al. (2012, 2014, 2017) and Syphard and Keeley (2020), who have reported reduced probability of home loss at higher housing densities. The difference between studies likely has to do with variation in density ranges evaluated, as well as variation in vegetation type and housing arrangement. Syphard et al. (2012) sampled large fire-prone regions with shrub-dominated vegetation in southern California, ranging from outlying WUI areas to denser cities that did not burn to answer the question of housing arrangements most prone to loss in a wildfire. Since the entire scope of our analysis was within the Camp Fire perimeter, our research question differs: when burned, what factors influenced survival? In any case, the interpretation of Syphard et al. (2012, 2014, 2017) of lower loss probability with higher density development may not apply to different development patterns, including those present in Paradise. Such intermediate to low density wildland urban intermix and interface development interspersed with native (and non-native) vegetation is prevalent in foothills and lower mountainous regions of central and northern California (Hammer et al. 2007). In chaparral dominated ecosystems of southern California, high-density housing might result in more of the proximate shrub vegetation being removed, but in Paradise, overstory canopy cover within 0–30 m of the home was actually positively correlated with housing density.

At what distance an adjacent burning structure presents a vulnerability is not well studied. Our analyses identified a threshold of 18 m from the nearest destroyed structure that best differentiated surviving and destroyed homes (Fig. 5a). Price and Bradstock (2013) found the presence of houses within 50 m to be predictive of loss. Radiant heat flux, which is inversely related to distance from the flaming source, can be a factor up to 40 m from a burning structure (Cohen 2000). Cohen (2004) reported that models predicted ignition of wood walls when less than 28 m from a crown fire in forested vegetation, with actual experimental crown fires finding ignition at a 10-m distance, but not 20 m or 30 m. The radiant heat flux adjacent to burning structures is different and likely more sustained than a similar heat flux adjacent to crowning wildland vegetation.

Between home spacing has been evaluated in post-fire assessments conducted after the Witch Fire in San Diego County, California (Insurance Institute for Business and Home Safety 2008), the Waldo Canyon Fire in Colorado Springs, Colorado (Quarles et al. 2013), and the Black Bear Cub Fire in Sevier County, Tennessee (Quarles and Konz 2016). During each of these fires, home-to-home spread was observed with spacing less than 10 m. The IBHS Witch Fire report (Insurance Institute for Business and Home Safety 2008) referred to home-to-home spread as "cluster burning," which was not observed when homes were located more than 14 m apart. Our finding of an 18-m threshold is similar to the IBHS Witch Fire results. Regardless of the actual ideal home separation level, many homes in fire-prone areas of the western USA are on lot sizes that do not permit more than 18 m of separation between buildings.

Wildland fuels and defensible space actions

Pre-fire overstory canopy cover was a significant predictor of home survival in the statistical models, with the canopy cover 30–100 m away having a larger effect size than canopy cover in the immediate vicinity of the home (0–30 m) (Fig. 4a, b). This result (and other evidence, below) suggests that overstory canopy cover may only be correlated to factors that contributed to fire spread and increased the threat to homes, rather than a direct contributor. The often indirect influence of tree canopies on home survival, mediated by the litter fuels produced rather than canopy combustion, has been noted by others (Keeley et al. 2013). Wildland fire spread is dependent on surface fuels—litter, duff, and dead and down woody material, which would be expected to be most abundant and continuous under or adjacent to overstory tree canopy. The link between overstory canopy cover and surface fuel abundance may have been weaker from 0 to 30 m than distances farther removed from the home because of the greater likelihood that such surface fuels were better managed near homes, perhaps as a result of defensible space activities. In addition, the continuity of vegetative fuels is more likely to be broken up by lawns, driveways, or irrigated landscaping near the home. While vegetation abundance within 30 m has been reported to be associated home loss in southern California fires burning in shrubland vegetation types (Syphard et al. 2014, 2017), Alexandre et al. (2016) found vegetation near a building not to be a strong factor in models of loss for fires in southern California and Colorado. They theorized that the connectivity of vegetation to the home was more critical than vegetative cover.

While burning trees and associated vegetation may generate substantial flame lengths and embers which can then threaten homes, the overstory tree canopies themselves did not appear to drive fire intensity in most cases. With the Camp Fire, many overstory trees located away from burning homes survived (Keeley and Syphard 2019; Cohen and Strohmaier 2020) (Fig. 7). Rather than tree torching directly impacting nearby structures, the torching of trees and other vegetation appeared from photographs and personal observation to frequently be caused by heat from nearby burning structures. Additionally, a substantial proportion of the canopy of native tree vegetation in Paradise at the time of the fire was comprised of California black oak (*Quercus kelloggii* Newb.), a native deciduous species that would have shed at least a portion of its leaves by the time of year when the Camp Fire burned through Paradise. Even when fully leafed out, the crowns of black oak trees are relatively open with low canopy bulk density. Deciduous oak litter breaks down faster than conifer litter, and the light fuel loads in pure black oak stands tend to promote low-intensity surface fire rather than crown fire (Skinner et al. 2006). Ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) was the other major native tree species. Leaf and needle litter can carry flames to the home or provide receptive fuels for ember ignitions and would likely have been positively correlated to pre-fire overstory tree canopy cover, especially in the fall. Embers can also ignite litter that has accumulated in gutters and roofs. High pre-fire overstory canopy cover may also indicate areas where associated vegetation and surface fuels had developed to the greatest extent in the absence of fire and active management, especially at a distance from homes. With the lands in the Paradise area having no record of fire in modern recorded history (Maranghides et al. 2021), considerable vegetative ingrowth and accumulation of dead and down surface fuels was likely, especially relative to historical amounts. Ingrowth could have included brush and smaller conifers that acted as ladder fuels, leading to torching and ember generation.

Even though our data showed a stronger association between pre-fire overstory tree cover and home survival for distances beyond which defensible space is typically mandated (100 ft or 30 m), this does not mean that vegetation modification within 30 m is any less important. For reasons described earlier, the fuel hazards contributing to outcome were likely not well captured by the overstory canopy cover variable, especially in this near-home zone. In addition, once structures become involved, defensible space vegetation modification to 30 m (100 ft) may be insufficient to mitigate ember and radiant heat exposures contributing to home loss. In an analysis of CAL FIRE DINS data over multiple fires, including the Camp Fire, Syphard and Keeley (2019) reported that defensible space was a poor predictor of outcome, with structural variables (e.g., eave construction details, numbers of windowpanes (double vs. single), vent screen size) more highly correlated with home survival. The low predictive power of defensible space may be partially due to the coarseness with which defensible space is classified in the DINS data, with broad distance categories not fully capturing spacing, composition, or flammability of the vegetation. In addition, in many destructive wildfires, a large portion of homes are lost through direct or indirect ember ignition and not flame impingement associated with the continuity with

Fig. 7 Aerial image showing a portion of Magalia just NW of Paradise, illustrating a gradient of fire damage to overstory vegetation with distance from destroyed homes. At least in some areas, burning homes may have influenced the effects to overstory vegetation more so than burning overstory vegetation influenced the outcome to homes. Photo: Owen Bettis, Deer Creek Resources

wildland fuels (Murphy et al. 2007; Cohen and Stratton 2008). With embers capable of igniting fuels over 1–2 km away, the protective effect of vegetation modification within 30 m of the house does not guarantee survival when fire-fighting resources are not present. Vegetation modifications in this zone, however, do provide access and a safer means of protecting a home when firefighting resources are available.

Our analysis relied upon aerial photo interpretation, and we could not assess surface fuels under dense tree canopies. As a result, and because of the likely indirect effect of leaf litter coming from the canopy, we caution against using cover percentages in the decision trees as forest thinning targets. Furthermore, surface and near-ground live fuels are considered the priority for altering fire behavior and influencing fire hazard (Agee and Skinner 2005). Higher canopy cover may be correlated to the rate of surface litter and woody fuel accumulation but does not necessarily directly translate to high fire hazard if these surface fuels are managed and maintained at low levels. In other words, higher overstory canopy cover can provide important amenities (e.g., shade, habitat—Gibbons et al. 2018) without undue fire hazard as long as the resulting litter and surface fuels are maintained and gutters are cleaned. Gibbons et al. 2018 also noted that patchiness and arrangement relative to prevailing winds can also reduce threat posed by near-home vegetation.

Did the adoption of Chapter 7A into the California Building Code influence survival?

While the survival rate for homes built in the 11 years after the adoption of Chapter 7A to the California Building Code in 2008 was numerically slightly higher than the survival rate of homes built in the 11 years immediately before, the difference was not statistically significant. It is possible that significance might have been found with a larger sample size, but even so, any influence of the building code update was likely overwhelmed by other factors. This was not a surprise because of the many interacting variables that affect building performance, in addition to building products rated to resist exterior fire exposures. The 2008 Chapter 7A building code update institutionalized several important and worthwhile changes to construction in high fire hazard zones, including the use of ember and flame-resistant vents. These changes may improve the probability of survival for some types of wildfire (e.g., vegetation and wind-driven fires); however, the changes were apparently not sufficient to fully protect buildings from radiant heat exposures from nearby burning structures. One of the primary mechanisms for radiant heat impact is the breaking of window glass, which can allow embers to enter the building (Penman et al. 2019). A common method for complying with Chapter 7A is through the use of tempered glass in one pane of a double-paned window. However, the magnitude of radiant heat exposure was likely still too much in many cases, or other vulnerabilities remained.

Variation in factors contributing to home loss across construction time periods

In models for predicting survival, the significant interaction of several of the potential explanatory variables with construction time period suggested that factors most strongly influencing home vulnerability differed for homes of different ages. Homes built in the most recent two 11-year periods (1997–2007 and 2008–2018) survived at a significantly higher rate than homes built prior to 1997. Factors potentially contributing to this increase include trends towards a longer average distance to the nearest structure and nearest destroyed structure, and a larger average lot size. Newer homes had lower pre-fire overstory canopy cover in the immediate vicinity (0–30m), whereas the older homes tended to be concentrated near the center of Paradise, where pre-fire overstory tree cover was higher. The two most recent construction time periods also saw changes in building construction including roofing materials having longer periods of robust performance (i.e., 30–50 years of service life), double-pane windows (as a result of changes to the energy code), and increased use of noncombustible fiber-cement siding. Many of these improvements, which potentially make newer homes less vulnerable to wildfire exposures, occurred well before the 2008 Chapter 7A update to the building code. Older homes may also have developed vulnerabilities resulting from overdue home maintenance. We speculate that with a higher proportion of newer homes surviving the ember onslaught, outcome then depended to a greater extent on degree of radiant heat exposure from nearby burned structures. This hypothesis is supported by the much stronger influence of distance to nearest burned structure and the number of structures burned within 100 m for newer (1997 and after) than older <1997) homes. A substantially lower proportion of older homes survived regardless of the distance to or density of nearby burned structures, suggesting other vulnerabilities (such as maintenance issues). Another factor that may have increased the survival probability of newer homes was simply less time for occupants to accumulate combustible items on their properties (e.g., sheds, stored objects, wood piles, play structures). The difference between distance to nearest home and distance to nearest structure was much greater for older than newer homes (data not shown), indicative of structures such as sheds, detached garages, or other outbuildings being added to properties over time. Our summary of damage location and cause for damaged homes as well as first-hand accounts (Maranghides et al. (2021); N. Wallingford, personal communication) indicated such non-vegetative items were frequently ignited by embers and the reason for a flame impingement exposure.

Difficulties in post-wildfire interpretation

A primary challenge in determining the potential causes for building survival after wildfire can be the variation in fire behavior experienced. The Camp Fire was no exception, with considerable observed differences in fire spread rates driven by ember-ignited spot fires, along with complex topography and local variation in wind speed (Maranghides et al. 2021). However, the Camp Fire burning through Paradise in 1 day may still have provided a more homogenous burn environment than present in many other post-fire evaluations of home survival, most of which combined data across multiple fires in different geographic locations and years (e.g., Syphard et al. 2012, 2017; Alexandre et al. 2016; Penman et al. 2019; Syphard and Keeley 2019)). Another factor that can often complicate interpretation is variation in the extent of firefighter intervention (McNamara et al. 2019). In the case of the Camp Fire, with the focus of first responders initially on evacuation, relatively few homes experienced defensive action by firefighters or civilians (according to the DINS assessment, defensive action was noted for only seven of the 400 randomly selected homes (1.7%), six of which survived). More broadly, while similar factors as those analyzed in this study may be pertinent in other wildfires, it is important to recognize that the variables identified here were specific to the housing, vegetation, and topographic conditions found in Paradise and may not apply elsewhere.

Determining pre-fire structural characteristics post-fire is difficult and availability of such data is generally limited (Syphard and Keeley 2019). Details about near-home vegetation, especially within the first 1.5 m of the structure, which has been shown to be an especially vulnerable location for ember ignition, were not available. We were also not able to quantify the presence and distance to small sheds and other storage structures, the age and condition of the roofing, or individual residents' maintenance practices. The DINS data (e.g., extent of vegetation clearing for defensible space, siding type, type of window glass (single or multi-pane), deck construction, and presence of attached fencing) have value, but missing data and lack of information for structures not damaged or destroyed limit the utility for some analyses. We instead focused on variables that could be consistently evaluated on every home, such as pre-fire overstory canopy cover and distance to the nearest destroyed structure. Our vegetation variables were, however, coarse, and likely missed factors that contributed to home survival.

Lastly, for the damaged home cause and area of damage summary, it is important to acknowledge that the vulnerabilities may differ for damaged and destroyed homes. With evidence for what contributed to loss no longer available for destroyed homes, damaged homes provide a picture of the different vulnerabilities, but the relative contribution of factors involved may not be the same.

Conclusions

The results of this study support the idea that both proximities to neighboring burning structures and surrounding vegetation influence home survival with wildfire. Denser developments, built to the highest standards, may protect subdivisions against direct flame impingement of a vegetation fire, but density becomes a detriment once buildings ignite and burn. Recent examples of losses in areas of higher density housing include the wind-driven 2017 Tubbs Fire in northern California, where house-to-house spread resulted in the loss of over 1400 homes in the Coffey Park neighborhood (Keeley and Syphard 2019), and the wind-driven 2020 Almeda Fire in southern Oregon, which destroyed nearly 2800 structures, many in denser areas in the towns of Talent and Phoenix (Cohen and Strohmaier 2020). Once fire becomes an urban conflagration, proximity to nearby burned structures becomes especially important because occupied structures contain significant quantities of fuel, produce substantial heat when burned, and are a source of additional embers. For density to be protective, home and other structure ignitions would need to be rare. Fifty-six percent of homes in Paradise built during or after 2008 did not survive, illustrating that much improvement is needed in both current building codes and how we live in wildfire prone WUI areas before proximity to nearby structures becomes a benefit rather than a vulnerability. The threat posed by nearby burning structures as well as our finding of an apparent strong influence of vegetation 30–100 m from the home—a distance that in most cases encompasses multiple adjacent properties—demonstrates that neighbors need to work together to improve the overall ability of homes and communities to resist wildfire exposures.

To maximize survivability, homes need to be designed and maintained to minimize the chance of a direct flame contact, resist ember ignition, and survive extended radiant heat exposure. Our analyses demonstrating the strong influence of nearby burning structures on home survival suggests improvements to resist radiant heat exposures may be warranted in the California Building Code—i.e., increasing the standards for buildings within a certain minimum distance of other structures. Some possible improvements might include noncombustible siding with rating minimums tied to proximity to other structures, both panes in windows consisting of tempered glass, or installation of deployable non-combustible shutter systems. Additionally, certain options for complying with Chapter 7A are better for resisting radiant heat and flame contact exposures and could minimize fire spread to other components. Whereas the International Code Council's Wildland Urban Interface Building Code (International Code Council 2017) provides three ignition-resistant construction classes to allow for material restrictions as a function of exposure level, Chapter 7A consists of one level, so is binary in nature in that a building either needs to comply, or it does not. The Australian building code for construction in bushfire prone areas, AS 3959 (Standards Australia 2018), incorporates six different construction classes based on anticipated radiant heat, flame, and ember exposure levels. Interaction between components, for example, siding, window, and the under-eave area on an exterior wall, is not considered.

Our summary of damaged but not destroyed homes in Paradise was in line with other reports showing a high proportion of home ignitions indirectly resulting from embers (Mell et al. 2010). Embers frequently ignited near home combustibles such as woody mulch, fences, and receptive vegetative fuels with flames and/or associated radiant heat then impacting the home itself, supporting awareness of the importance of combustibles within the first 1.5 m (5 ft) of the building on home survival. A re-interpretation of defensible space fuel modifications is needed to increase the building's resistance and exposure to embers and direct flame contact, especially in the area immediately around a building and under any attached deck or steps. This does not diminish the value of defensible space fuel modifications 9 to 30 m (30 to 100 ft) away from the home, which not only reduces fuel continuity and the probability of direct flame contact to the home, but also provides firefighters a chance to intervene.

While our data show a relationship between home loss and vegetative fuels (high pre-fire overstory canopy cover likely associated with a greater litter and woody fuel abundance, as well as other wildland understory vegetation) that can contribute to fire intensity and ember generation, the WUI fire loss issue has been described as home ignition problem more so than a wildland fire problem (Cohen 2000; Calkin et al. 2014). The damaged home data were in line with this view, with few homes showing evidence of continuity with wildland fuels that would contribute to flame impingement, but numerous homes with near home fuels, both from manmade and natural sources, that led to direct or indirect ember ignitions.

California's Mediterranean climate will continue to challenge its residents with regular wildfire exposure throughout the state. Whether through modifying the nearby surface and vegetative wildland fuels or the home itself, adapting to wildfire will take time. The good news is that the trend in survival is improving with newer construction practices. However, with 56% of houses built after 2008 still succumbing to the Camp Fire, much room for improvement remains. Our data suggest it is possible to build (and maintain) buildings that have a high probability of surviving a worst-case scenario type of wildfire, even in fire-prone landscapes such as the Paradise area. Newer homes built after 1972, where the nearest burning structure was >18 m away, and fuels associated with vegetation 30–100 m from the home kept at moderate and lower levels (<53% canopy cover) had a 61% survival rate—an approximately 5-fold improvement over the Paradise housing population as a whole. Survival percentages substantially higher still are potentially possible if all components of risk, including ember generation in nearby wildland fuels, continuity of wildland and other fuels on the property, and home ignitability are sufficiently mitigated.

Abbreviations

DINS: Damage inspection; WUI: Wildland urban interface

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-021-00117-0.

Additional file 1: S1 Table. Raw data for the random sample of 400 single-family homes in Paradise.

Additional file 2: S2 Table. Summary of fire damage cause and damage location for damaged by not destroyed single-family homes in Paradise.

Additional file 3: S3 Text. Metadata for the two data tables used in the analyses for this paper.

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Authors' contributions

EK, YV, and SQ developed the research questions and designed the study, with statistical guidance provided by NJ. Statistical analyses were performed by NJ and EK. All authors contributed to writing the manuscript. The authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analyzed during the study are included in the published article and its supplementary information files.

Declarations

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Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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MANDATED VS. VOLUNTARY ADAPTATION TO NATURAL DISASTERS: THE CASE OF U.S. WILDFIRES

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Mandated vs. Voluntary Adaptation to Natural Disasters: The Case of U.S. Wildfires
Patrick W. Baylis and Judson Boomhower
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ABSTRACT

Despite escalating disaster losses and predicted increases in weather-related catastrophes, takeup of protective technologies and behaviors appears limited by myopia, externalities, and other factors. One response to such frictions is to mandate adaptive investment. We measure the effect of California's wildfire building codes on own- and neighboring structure survival using administrative damage and assessment data for most US homes experiencing wildfires since 2000. Differences across jurisdictions and vintages reveal remarkable resilience effects of building codes initially prompted by the deadly 1991 Oakland Firestorm. Codes also benefit neighbors. We use the results to estimate net social benefits of wildfire building standards.

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Worldwide natural disaster losses averaged $218 billion per year during 2016–2020, a 60% increase in real terms over the preceding 30 years.[1] This trend is predicted to accelerate under future climate change. Efficient investment in adaptation is essential in the face of these escalating risks. Yet takeup of protective technologies and behaviors appears to be hindered by a constellation of market frictions. Homeowners misperceive disaster risks and thus the value of protective investments (Hallstrom and Smith 2005; Donovan, Champ, and Butry 2007; Gallagher 2014; McCoy and Walsh 2018; Bakkensen and Barrage, Forthcoming). Monitoring costs and other insurance market imperfections mean that mitigation behaviors may not be accurately reflected in property insurance prices (Kunreuther and Michel-Kerjan 2011; California Department of Insurance 2018; Wagner, Forthcoming). Public disaster spending programs may reduce private incentives for property protection (Kousky, Luttmer, and Zeckhauser 2006; Deryugina 2017; Baylis and Boomhower 2019). And in some settings, spatial externalities across neighboring properties lead to diverging private and social benefits of mitigation (Shafran 2008; Costello, Quérou, and Tomini 2017).

One widely-adopted approach to these market failures is to provide information and subsidies to increase voluntary takeup.[2] A more controversial but increasingly common alternative is to *mandate* investments in resilience.[3] Mandatory standards ensure wider adoption. However, if the regulator misjudges the effectiveness of the required actions, the level of the hazard, or individual risk

1. Loss data are from Munich RE and are in 2020 dollars.

2. Examples in the U.S. include the Ready campaign and Ready.gov website; the Community Rating System under the National Flood Insurance Program; the StormReady, Hurricane Protection Week, and National Tsunami Hazard Mitigation programs; the Firewise USA program; and the Community Wildfire Protection Plan program.

3. Florida has construction standards for hurricane winds, and codes also exist in various regions for winter storms and non-weather disasters such as earthquakes and tsunamis (Federal Emergency Management Agency 2020). In flood-prone areas, U.S. federal rules require homes to be elevated and some localities have imposed even stricter requirements. California, Utah, Nevada, and Pennsylvania have statewide wildfire building standards while in other states, notably Colorado, wildfire codes have been adopted at the local level (Insurance Institute for Business and Home Safety 2019). Australia, New Zealand, France, and Italy also have wildfire building codes (Intini et al. 2020).

preferences, some individuals may be compelled to make costly investments they would have preferred to avoid even if fully informed and fully accountable. Implementing mandatory standards is also more politically challenging.[4] Despite the important differences between these instruments, there is little empirical evidence about outcomes under a mandated resilience regime compared to a counterfactual of purely voluntary takeup.

In this paper, we consider the case of wildfire building codes in California. California has suffered over $40 billion dollars in wildfire property damages in the past 5 years. The state also has among the strictest wildfire building codes in the world. We provide the first comprehensive evaluation of the effect of these codes on own-structure survival as well as neighbor spillovers via structure to structure fire spread. We then embed these empirical estimates in an economic model to calculate net social benefits of wildfire building codes as a function of local wildfire hazard and number of close neighbors.

This analysis takes advantage of a new dataset that includes property-level data for almost all U.S. homes exposed to wildfire between 2000 and 2020. We compiled the data by requesting post-incident damage censuses from numerous emergency management agencies and individual county assessors. We merged these lists of damaged homes to assessor data for the universe of (destroyed and surviving) homes inside wildfire burn areas. The data show that even during catastrophic wildfires, more than 50% of exposed homes survive. One of the key advantages of the new data is the ability to observe and learn from these surviving homes. The property-level loss information also distinguishes the wildfire data from floods and other disasters where loss data are typically available at the zip code or Census tract level. In addition to the new loss data, the empirical work also leverages emerging tools in spatial analysis, including high-resolution aerial imagery and precise "rooftop" geocoding of structure locations.

The empirical design leverages rich variation in building code requirements

4. For example, efforts to adopt statewide wildfire building standards in Oregon and Colorado have failed politically (Sommer 2020).

across space and over time. The complex nature of building regulation in California creates a patchwork of wildfire standards across localities. We also observe fires in other states that do not have wildfire building codes. In all of these places, we observe homes built before and after changes in California's codes. This identifying variation yields credible counterfactual predictions for how homes would have performed in the absence of California's standards. Our preferred statistical model is a fixed effects regression that compares the likelihood of survival for homes of different vintages on the same residential street during the same wildfire event. These street fixed effects allow us to compare groups of homes that experience essentially identical wildfire exposures.

We find remarkable vintage effects for California homes subject to the state's wildfire standards. A 2008 or newer home is about 16 percentage points (40%) less likely to be destroyed than a 1990 home experiencing an identical wildfire exposure. There is strong evidence that these effects are due to state and local building code changes - first after the deadly 1991 Oakland Firestorm, and again with the strengthening of wildfire codes in 2008. The observed vintage effects are highly nonlinear, appearing immediately for homes built after building code changes. There are no similar effects in areas of California not subject to these codes or in other states that lack wildfire codes.

We also find that code-induced mitigation benefits neighboring homes, consistent with reduced structure-to-structure spread. These neighbor effects are in keeping with anecdotal reports of home-to-home spread as a factor in urban conflagrations (Cohen 2000; Cohen and Stratton 2008; Cohen 2010).[5] Our results imply that, all else equal, code-induced mitigation by a neighbor located less than 10 meters away (within the distance fire experts refer to as the home ignition zone) reduces a home's likelihood of destruction during a wildfire by about 2.5 percentage points (6%). This benefit is even larger when homes have multiple close neighbors.

5. We are also aware of at least one insurance company which will not sell homeowners insurance to homes located next to a home with a wood roof in high-risk areas (Allstate Indemnity Company 2018).

Finally, we embed our estimates of building code benefits in an economic model and calculate the approximate net social benefits of such a policy for a random sample of California homes in wildfire hazard areas. Like other disaster risks, many homeowners are only partially insured (or in the extreme, wholly uninsured) against the full cost of replacing a structure destroyed by wildfire (Klein 2018; California Department of Insurance 2018). This means that the benefits of building codes include not only reductions in expected losses but also additional insurance value due to reduced household exposure to uninsured risk. Our calculations find that wildfire building codes deliver unambiguously positive benefits in the most fire-prone areas of the state, especially where homes are clustered closely together and thus create large risk spillovers. In areas with more moderate wildfire risk, building standards for new homes can also be justified given reasonable assumptions about household risk aversion, future increases in wildfire hazard, and/or co-benefits of building codes (such as reductions in public expenditures on wildland firefighting). On the other hand, the costs of retrofitting existing homes to meet current wildfire building standards are substantial and our analysis suggest full retrofits are only economic in areas with extreme wildfire hazard.

These results are broadly relevant to natural disaster management. In this important setting, a standards-based approach achieved substantially greater compliance with risk mitigation practices. The policy nearly halves loss risk when structures are exposed to the hazard. Moreover, a cost-benefit calculation implies that low takeup in the absence of standards is likely driven by market failures as opposed to a lack of cost-effectiveness. These facts can inform policies to mitigate other risks like floods, hurricanes, tornadoes, and heat waves, where voluntary takeup of adaptation investments also appears to be limited.

This work also has immediate implications for wildfire policy. Our results imply there are gains to be realized from strengthening building codes in other states and countries to match California's. This evidence is relevant to current proposals in Oregon, Washington, and other states.[6] Meanwhile, California is moving to expand the geographic coverage of designated wildfire hazard zones and reduce the ability of local jurisdictions to opt out of recommended standards.[7] Separately, new California legislation from 2020 provides financial incentives for retrofits of existing homes in wildfire-prone areas.[8] The law specifically calls for support of "cost effective" retrofits, a concept for which the evidence in this study is essential. Additionally, policymakers are confronting pressing issues of insurance rate reform in response to mounting wildfire losses. One key debate is the degree to which individual investments improve structure survival and should thus be rewarded through regulated insurance discounts (California Department of Insurance 2018). This paper's evidence on the effectiveness of such investments during real wildfires bears directly on this question.

Our work builds on previous studies of natural hazard mitigation. For wildfires, a number of engineering and forestry studies describe the effects of construction materials and vegetation management on structure resilience (Gibbons et al. 2012; Syphard et al. 2012; Syphard, Brennan, and Keeley 2014; Alexandre et al. 2016; Syphard, Brennan, and Keeley 2017; Kramer et al. 2018; Syphard and Keeley 2019). Our paper focuses on the effects of a mandatory mitigation policy, while these previous studies measure technology effectiveness (i.e., survival of homes whose owners did vs. did not choose to take mitigation measures). Two studies on the related topic of hurricanes do consider building codes, with conflicting results. Dehring and Halek (2013) is a small case study of several hundred homes during Hurricane Charley in 2004. Simmons, Czajkowski, and Done (2018) study aggregate zip-code level data on annual insurance claims by homes built in different decades to infer benefits of hurricane building codes in Florida. In contrast, our study uses highly

6. See, e.g., Profita, Cassandra. "The Labor Day Fires Burned Towns and Homes. Oregon Has a Plan to Avoid a Repeat." Oregon Public Broadcasting, September 7, 2021.

7. S.B. 63, 2021–2022, California. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220SB63.

8. A.B. 38, 2019–2020, California. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201920200AB38.

granular property- and event-level loss data for a large sample of wildfires covering several states. Across a range of natural hazards, a parallel engineering literature attempts to calculate the value of building codes through modeling and simulation (e.g. Federal Emergency Management Agency 2020). Finally, our work is methodologically related to a separate literature in economics on building codes and household energy consumption (Jacobsen and Kotchen 2013; Levinson 2016).

This study makes five contributions. First, we provide the first comprehensive evaluation of the effects of wildfire building codes on structure survival. Beyond the wildfire context, this result improves our understanding of disaster resilience under standards-based vs. voluntary policies. Second, we provide the first empirical estimates of the spillover benefits of wildfire mitigation investments to neighboring properties. Third, we compile a comprehensive dataset of structure-level outcomes in wildfires across several states that, to our knowledge, is the most complete accounting in existence. This new dataset will enable future work on the economics of catastrophic wildfire risk. Fourth, we approach the topic in a causal framework with an explicit empirical design, where previous work is primarily descriptive or relies on regression adjustment. Finally, we embed the empirical estimates in an economic model to calculate net social benefits that account for local hazard, neighbor externalities, and household risk aversion.

The rest of the paper proceeds as follows. Section 1 discusses structure survival in wildfires and California's history of building code updates. Section 2 describes the data and spatial analysis. Section 3 outlines the empirical strategy, and Section 4 presents the results. Section 5 develops the model of net social benefits and Section 6 concludes.

1 Wildfire Building Codes in California and Other States

> *"Unlike a flash flood or an avalanche, in which a mass engulfs objects in its path, fire spreads because the requirements for com-*

bustion are satisfied at locations along the path... A wildland fire cannot spread to homes unless the homes and their adjacent surroundings meet those combustion requirements." Jack D. Cohen, *Journal of Forestry*, 2000.

Established forestry and engineering evidence supports the importance of the so-called home ignition zone in determining structure resilience to wildfires. The home ignition zone includes the design of the home itself as well as an imagined area extending 30 meters away from the structure. Fire scientists emphasize the elimination of flammable materials inside this zone (e.g., Cohen 2000, 2010; Calkin et al. 2014). This guidance applies to both vegetation around the home ("defensible space") and the construction of the home itself, especially the roof.

Among U.S. states, California has gone the furthest in mandating takeup of wildfire resilience investments by property owners. However, the application of these codes varies throughout the state. In areas where CAL FIRE provides firefighting services (State Responsibility Area or SRA), the state directly determines building standards. Within incorporated cities and other areas with their own fire departments (Local Responsibility Area or LRA), local governments have historically had greater control over code requirements.

The development of the modern standards began with the Oakland Hills Firestorm of 1991, which killed 25 people and caused $1.5 billion in property damage. The tragedy led to a series of legislative actions during the mid-1990s that required more fire-resistant roofing and maintenance of vegetation immediately adjacent to the home. The first of these was the so-called Bates Bill of 1992 (Assembly Bill 337). Among other changes, the Bates Bill encouraged stronger building standards in LRA areas by requiring CAL FIRE to produce maps of recommended Very High Fire Hazard Severity Zones (VHFHSZ). In LRA areas, local governments could then choose whether or not to adopt these recommended hazard maps (and thus the accompanying building standards). This designation process unfolded over several years, with hundreds of local governments adopting or rejecting CAL FIRE's proposed VHFHSZ maps at different times. According to Troy 2007, 151 of 208 local governments (73%) either adopted the VHFHSZ regulations or claimed to have promulgated equally strong existing rules.[9]

On the heels of the Bates Bill, Assembly Bill 3819 of 1994 increased requirements for ignition-resistant roofs. These requirements applied in all SRA areas and in the subset of LRA areas where local governments had adopted recommended VHFHSZs. Roofing materials are rated Class A, B, C, or unrated.[10] Starting in 1995, the law required Class B roofs on newly-constructed or reroofed homes in regulated areas. In 1997, the requirement increased to Class A roofs in high-hazard areas (a substantial improvement in fire resistance). Finally, Assembly Bill 423 in 1999 simplified enforcement of the new roofing codes by outlawing the use of unrated roofing materials throughout the state.

The collective effect of these mid-1990s building code reforms was to substantially increase the fire resistance of roofs on newly-constructed homes in regulated areas after about 1997. The roofing requirements also applied to existing homes, but only at the time of roof replacement. Any homeowner in a regulated area who replaced more than 50% of the roof surface in a single year was in principle obligated to comply. The defensible space provisions also applied to existing and new homes. However, in practice, the primary point of enforcement for these codes was at the time of new construction; enforcement effort for existing homes was limited (see e.g., Maclay 1997).

California strengthened its wildfire codes again in 2008 with the so-called Chapter 7A standards of the California Building Code. These requirements apply to all homes built in 2008 or later in SRA areas and in LRA areas where proposed VHFHSZ designations have been accepted. The codes apply to many dimensions of new homes. Roofs must be rated class A or B, eaves

9. For a detailed qualitative study of the determinants of local VHFHSZ adoption decisions, see Miller, Field, and Mach (2020).

10. These ratings are earned through laboratory testing; for example, the Class A test involves placing a 12-inch by 12-inch burning brand on the roof material under high wind conditions. The material must not ignite for 90 minutes.

and exterior siding must be fire resistant, vents must covered by a fine wire mesh to resist ember intrusion, windows and doors must resist fire for at least 20 minutes, and decks and other building appendages must be built of non-combustible materials. Chapter 7A also includes additional requirements for defensible space.

The damage data collected for this study also include wildfires in Arizona, Colorado, Oregon, and Washington. None of these had statewide wildfire building standards at the time of the included fires (Insurance Institute for Business and Home Safety 2019). Some local governments – particularly in Colorado – have adopted local standards that include a diverse mix of rules about roofs, other construction materials, and/or defensible space. Our empirical analysis excludes a small number of fires in the comparison states that overlap areas known to have local wildfire building standards.[11]

While the non-California homes in this study are not subject to mandatory standards, they are targeted by a range of information and incentive programs that seek to increase voluntary home hardening. Programs active in these states include FireWise USA (National Fire Protection Association), the Community Wildfire Protection Plan program (United States Forest Service and Department of Interior), the Fire Adapted Communities Coalition (numerous public agencies and NGOs), the Ready, Set, Go! program (International Association of Fire Chiefs), and numerous other initiatives.

2 Data and Spatial Analysis

This section describes the construction of the database of wildfire damages, property tax assessment information, and structure locations.

11. These are the 2012 Waldo Canyon Fire, 2013 Black Forest Fire, and 2018 Mile Marker 117 Fire in El Paso County, Colorado (Quarles et al. 2013) and the 2012 High Park Fire and 2020 Cameron Peak Fire in Larimer County, Colorado (Larimer County 2020).

2.1 Homes and Damage Data

Damage Inspection Data

We sought to assemble as comprehensive a database as possible of administrative records for homes destroyed or damaged by wildfire in the United States. For recent wildfires in California, this information is managed by CAL FIRE. For earlier California fires and for fires in other states, we contacted individual county assessors (who track these damages in order to update property tax assessments) and other agencies to request historical records of structure damages. To our knowledge, the resulting database is the most complete accounting that exists of U.S. homes lost to wildfire.

California 2013–2020: In California, the CAL FIRE Damage Inspection (DINS) database is a census of destroyed and damaged homes following significant wildfire incidents during 2013–2020. The data include street address and assessor parcel number (APN); limited structure characteristics; and for some fires, an additional sample of undamaged homes. The damage variable has four levels: destroyed ($> 50\%$ damage), major (26–50%), minor (10–25%), and affected (1%–9%). Of these, "destroyed" is the most commonly reported damage category and the only category that appears consistently across all fires. The lack of partially-destroyed structures is consistent with case study observations in Cohen (2000) and subsequent research. We thus follow the literature and focus on "destroyed" as our primary outcome.

California 2003–2013: Data for pre-2013 wildfires in California come from two sources. For the 2003 and 2007 San Diego fire storms, we received damage assessment data from San Diego County. For other counties, CAL FIRE staff provided us with a large collection of unformatted historical damage assessment reports that we compiled and standardized to be usable for research.

Other States: Using ICS-209 incident reports, we identified the 15 counties in states other than California with the greatest number of structures lost to wildfire since 2010. We then contacted county assessors in each of these counties to request damage data. We have successfully received structure-level damage data from 11 of these 15 counties.

Appendix Table 6 includes the full list of wildfires in the dataset.

Property Tax Assessment Data

We merge the damage records to comprehensive assessment data for all U.S. homes from the Zillow ZTRAX database. The ZTRAX data include information on year built, effective year built (in the case of remodels), building square footage, and other property characteristics. The merge from damage data to ZTRAX uses assessor parcel numbers, and we validate the accuracy of this merge by comparing street addresses across the two datasets. We restrict the data to include only single family homes, which account for most properties inside the wildfire perimeters in our sample. For each incident, we merge the damage data to the most recent historical assessment data from the pre-fire period. In other words, we merge to the population of single family homes that existed immediately prior to the start of the fire. Appendix Table 6 shows the number of single family homes inside of each wildfire perimeter and the share destroyed.

2.2 Spatial Analysis and Dataset Construction

Identifying Structure Rooftop Locations

This study uses the physical locations of the homes in the data in two ways. First, homes must be spatially assigned to building code jurisdictions and to wildfire burned areas. Second, the measurement of spillovers across properties requires precise distances between neighboring structures. The street address-based geocoding methods typically used in academic research are not sufficiently detailed for this second purpose, which requires accurate structure locations at a meter scale. We solved this challenge by combining several spatial datasets to identify precise rooftop locations. First, we limit the population of ZTRAX homes to all homes in zip codes where at least one home was destroyed. We then merge these ZTRAX records to parcel boundary maps from county assessors using assessor parcel numbers. This yields a parcel polygon for each home. We then use comprehensive building footprint maps from Microsoft to identify the largest structure overlaying each parcel.[12] We call this location the "footprint location." Figure 1 shows an example for Redding, California in the area of the 2018 Carr Fire. Gray lines are parcel boundaries from the Shasta County Assessor. Blue polygons are building footprints. The purple and yellow markers show the assigned rooftop locations for each structure. Yellow markers show homes that are reported as destroyed in the damage data.

This rooftop geocoding method generates highly accurate locations, but it is dependent on the availability of high-quality parcel boundary GIS data. In areas where such data are not available (representing 13% of homes in the final analysis dataset), we instead geocode home locations using the ESRI StreetMap Premium geolocator, a commercially-available address-based product. Our quality checking shows that these locations (henceforth "address-based locations") are generally reliable to the parcel level but not always to the structure rooftop level. Appendix Section C describes the geocoding in more detail.

Validating Locations and Damage Reports

We quality check the calculated property locations and the damage report data using high-resolution aerial imagery from NearMap. The base image in Figure 1 shows an example. The detailed imagery allows us to manually confirm the accuracy of structure locations, which closely coincide with the blue building footprints in the figure. In addition, the NearMap imagery includes post-fire surveys for many of the incidents in our database. Figure 1 illustrates how destroyed properties are readily visible in these surveys, which allows us to confirm the accuracy and completeness of the damage data. Appendix Table 4 reports accuracy rates in a random sample of homes. For damage reports, 99%

12. The Microsoft U.S. Building Footprints Database is publicly available at https://github.com/microsoft/USBuildingFootprints.

of reported outcomes match the ground truth imagery. For rooftop locations, 98% of the assigned structure locations are on top of the structure rooftop in the ground truth imagery (with 99%+ accuracy in densely developed areas). Locations that rely on street address based geocoding tended to be accurate to the parcel but not always to the actual structure rooftop – about 75% of these assigned locations are on top of the structure rooftop in the ground truth imagery.

Spatial Merge to Wildfire Perimeters and Code Jurisdictions

We restrict the dataset to homes located within final wildfire perimeters (plus a 20-meter buffer). Depending on the state and time period, these digital perimeter maps come from the California Forest and Range Assessment Program (FRAP), the Monitoring Trends in Burn Severity (MTBS) dataset, or the National Interagency Fire Center (NIFC). We merge the homes data to spatial data on fire protection responsibility (SRA vs. LRA) and designated fire hazard (FHSZ) that together determine building codes in a given location in California. We use historical GIS maps provided by CAL FIRE to assign homes to code regimes according to the codes in effect when the home was built.[13]

Calculating Distances Between Neighboring Homes

We construct two measures of distance between homes. The first is the minimum distance between the building footprint polygons associated with the two structures (henceforth the "wall-to-wall" distance). This measure is only available for homes where we assign locations based on building footprints. The second metric uses the distance between assigned point locations, which are available for all homes in the dataset. We call this metric the "centroid to centroid" distance because these points are meant to correspond to the center of the roof. The wall to wall distance is our preferred measure because it more

13. For SRA/LRA boundaries, the historical map data include updates in 1990, 1996, 2003, 2005, and annually from 2010–2020. For FHSZ, the historical map data include updates in 1985, 1998, 2007, and 2008.

accurately captures space between homes and because the footprint-geocoded locations are more accurate than the address-based location points (Appendix Table 4). Our main estimates of neighbor spillovers use the restricted sample of homes for which wall to wall distances are available. For robustness, we also show specifications that use centroid to centroid distances and the full sample of homes.

We identify up to 15 nearest neighbors within one kilometer for each home in the final dataset. Panel (b) of Figure 1 shows two examples. Each image shows wall-to-wall distances (in meters) from the structure marked "0". Appendix Table 2 summarizes the distribution of number of neighbors at various distances.

Data Summary

The final dataset includes 55,408 single family homes exposed to 112 wildfires in California, Arizona, Colorado, Oregon, and Washington between 2003 and 2020. Thirty-nine percent of these were destroyed. Appendix Figure 1 shows the distribution of year built and fraction destroyed by year built for the full dataset. Appendix Table 6 reports the number of exposed and destroyed homes for each fire.

3 Empirical Strategy

This section describes the empirical design used to measure the effect of wildfire building codes on structure survival. To fix ideas, Figure 2 provides an example of the merged dataset for the 2018 Woolsey Fire in Los Angeles County. The green and purple markers indicate locations of surviving and destroyed single family homes inside the final fire perimeter. The street map data give a sense of development density. The intensity of losses varies significantly within the burned area. Near Malibu, a large share of affected homes were lost. Further north, however, there are several areas where most homes inside the fire perimeter escaped destruction. These differences reflect varying fire conditions, firefighter response times, landscape vulnerability, structure characteristics, and potentially numerous other factors. This heterogeneity adds noise to empirical analysis of structure survival. It may also introduce bias if year built or other structure traits vary similarly within burned areas. We address these challenges using an empirical design that compares the likelihood of survival for homes of different vintages on the same residential street during the same wildfire. We attribute these vintage effects to building codes by comparing vintage effects across jurisdictions with and without wildfire building codes.

3.1 Treatment Groups

Throughout the rest of the paper, we consider three types of jurisdiction. The first is SRA, where compliance with California building codes was mandatory. The second is LRA areas that were ever recommended by CAL FIRE as VHFHSZ areas (henceforth, "LRA-VHFHSZ"). To be clear, this group includes all proposed VHFHSZ regardless of whether local governments accepted the designation. There is no centralized database that records local VHFHSZ adoption decisions, but Troy (2007) reports high rates of adoption.[14] The final treatment group is areas without wildfire building codes (henceforth, "no-codes"). This includes LRA areas in California that were never recommended for consideration as VHFHSZ, as well as fires in areas of Arizona, Colorado, Oregon, and Washington without any state or local wildfire building codes. Appendix Table 1 reports the number of homes in each treatment group.

14. In addition, historical news accounts show that cities that rejected the official VHFHSZ designation often still adopted the underlying code requirements in the recommended areas. This seems to have been an attempt to achieve the state-recommended resilience requirements while avoiding the VHFHSZ label due to fears about property values (Sullivan 1995; Snyder 1995; Stewart 1995; Yost 1996; Grad 1996). One state fire official's response: "We didn't care if they called it a nuclear-free zone, as long as they adopted the regulations" (Maclay 1997).

3.2 Own-structure survival

Event study figures

We begin the regression analysis with the following event study-style model for home i on street s exposed to wildfire incident f. We estimate this model separately for the SRA, LRA-VHFHSZ, and no-codes groups.

$$1[Destroyed]_{isf} = \sum_{v=v_0}^{v=V} \beta_v D_i^v + \gamma_{sf} + X_i\alpha + \epsilon_{isf} \tag{1}$$

The outcome variable is equal to one for destroyed homes and zero otherwise. The V variables $D_i^{v_0}, ..., D_i^V$ are indicator variables equal to one if house i's year built falls into bin v. The main parameters of interest are the coefficients β that correspond to these vintage bins. These give the effect of each vintage on probability of survival when exposed to wildfire. The street fixed effects γ_{sf} include separate indicator variables for each street name-zip code combination within fire perimeter f. These fixed effects sweep away arbitrary patterns of damage across streets within the fire perimeter, so that the model is identified by average differences in survival between homes of different vintages on the same street. We also estimate models with finer and coarser fixed effects, including models with incident instead of street fixed effects.

The additional control variables X_i include controls for wildfire vulnerability at the home site. These include ground slope, aspect, and vegetation type from LANDFIRE (Rollins 2009). Some specifications also include property characteristics (lot size, building square footage, number of bedrooms).

Difference in differences

We summarize the overall effects of the wildfire building standards using a difference-in-differences (DiD) model that pools jurisdictions and time periods. We divide the sample into 3 time periods: before 1998; 1998–2007; and 2008 onwards. The latter two periods correspond to the end of the mid-1990s roofing reforms and the introduction of the Chapter 7A requirements.

3.3 Structure to structure spread

To measure the effect of code-driven mitigation on likelihood of structure-to-structure spread, we estimate the effect of building vintage on likelihood of survival for neighboring homes. Our regression models are of the form,

$$1[Destroyed]_{isf} = \sum_{j=1}^{J} \rho_j NoCode_j + \sum_{j=1}^{J} \phi_j Code_j + \sum_{v=v_0}^{V} \beta_v D_i^v + \gamma_{sf} + X_i\alpha + \epsilon_{isf} \quad (2)$$

Like Equation (1), this specification controls for own year of construction and street-by-incident fixed effects. The additional regressors $NoCode_j$ and $Code_j$ are the number of neighbors within various distance bins j that were built before and after wildfire building codes. Homes are considered post-code in 1998 in SRA areas and in the year the area was first recommended as a VHFHSZ in LRA VHFHSZ areas. The coefficients ρ_j and ϕ_j for $j = 1, ..., J$ give the effect of these neighbors on own-structure survival. Our preferred specification uses 10-meter bins of wall-to-wall distance. For robustness, we also estimate a specification using centroid to centroid distances. With this latter measure, we define the closest bin as 0-30 meters because 30 meters roughly corresponds to 10 meters of wall-to-wall distance.[15] We apply some additional sample exclusions when estimating Equation 2: The sample is restricted to California since we can only reliably calculate footprint locations for California homes. We further drop condominiums and townhomes to focus on detached single family homes.

This regression identifies the causal effect of code-induced mitigation by neighboring homes if the code regime for neighboring homes is uncorrelated with other determinants of structure- and neighborhood-level risk. This assumption is bolstered by the street fixed effects, which focus on highly local variation.

15. The median building footprint area in the sample is 260 m^2. A hypothetical circular roof would thus have a radius of 9.1 meters and the centroid-to-centroid distance between two such homes would be 18.2 + wall-to-wall distance.

Intuitively, this specification compares homes on the same street during the same wildfire whose nearest neighbors were built in different years. One might still worry, however, that even within these narrow comparisons and even after controlling for own age, the age of a home's neighbors may still be correlated with other wildfire risk factors. We address this concern by exploring estimates for homes located slightly further away as a placebo check. Properties located 50 to 100 meters away are outside of the 30-meter home ignition zone and so present more limited direct ignition threat, but should otherwise be subject to the same potential omitted variables as directly adjacent homes.

4 Results and Discussion

4.1 Own-structure survival

4.1.1 Graphical Evidence

Figure 3 shows the raw mean of *Destroyed* for State Responsibility Area homes according to year of construction. About 35% of exposed homes built prior to the mid-1990s were destroyed. These destruction probabilities begin to fall for homes built after the mid-1990s, decreasing quickly to about 20%. This sharp improvement in resilience corresponds in time to the post-Oakland Firestorm building reforms.

There is also some evidence in Figure 3 that homes built before about 1980 may be less likely to be destroyed than homes built just prior to the roof requirements. This may reflect the fact these older homes are more likely to have been re-roofed at least once after the mid-1990s and complied with the requirement for ignition-resistant materials at roof replacement. This pattern would imply a replacement cycle of about 30-40 years. Actual data on roof service lifetimes is scarce, but this period is within the range proposed by the National Association of Home Builders and other sources (National Association of Home Builders 2007). To the extent that some pre-building code homes may be re-roofed with code-compliant materials, our estimates of building code effects are conservative.

Appendix Figure 2 shows that homes built before and after the building code changes are otherwise comparable. There are no meaningful changes in site-level predictors of fire risk, like ground slope, or in structure characteristics such as building square footage.

Figure 4 presents the event study estimates from Equation (1). The top panel shows homes in SRA, where WUI building codes are mandatory. The markers show estimates and 95% confidence intervals for two-year vintage bins. The omitted bin is 1987-1988, so that these estimates can be interpreted as percentage-point differences in likelihood of destruction relative to a 1987 home. The vintage effects are flat prior to about 1993, and then begin to decrease clearly during the 1995–1999 period. The point estimates suggest additional reductions in loss probability following the adoption of the Chapter 7A codes in 2008, although the small number of homes in those bins leads to somewhat noisy vintage estimates. The overall difference in loss probability between a 1987 home and a 2008+ home is about 15 percentage points.

The middle panel shows homes in LRA areas that CAL FIRE recommended for Very High Fire Hazard Severity Zone designation. These areas again show flat trends in resilience prior to the 1991 Oakland Firestorm and subsequent Bates Bill. After the Bates Bill takes effect, the figure shows steady improvements that persist for about 12 years. The slope of these improvements appears more gradual than in SRA areas, which would be consistent with varied timing of adoption of the recommended codes across hundreds of individual municipalities. The post-2008 estimates are again noisy but imply further improvements in resilience following adoption of the Chapter 7A bulding codes.

Finally, the bottom panel of Figure 4 shows vintage effects for homes in areas not subject to California's codes. This includes fires in areas of Arizona, Colorado, Oregon, and Washington with no state or local wildfire building codes. It also includes LRA areas in California that were never recommended as Very High Fire Hazard Severity Zones. There are relatively few homes in these groups (Appendix Table 1), so we pool them together and use wider ten-year vintage bins to increase precision. Unlike the top two panels, there is little evidence of improved resilience for homes built since the mid 1990s in areas without wildfire building codes.

4.1.2 Difference-in-Differences Estimates and Robustness Checks

The regression estimates in Table 1 summarize the effects of building code regimes on structure resilience. We show estimates for SRA, LRA-VHFHSZ, and no-codes areas. The various group by time period estimates can be interpreted as percentage point differences in likelihood of destruction relative to the reference category, which is pre-1998 homes in no-code areas. Column (1) shows the results with street by fire fixed effects. The near-zero coefficient on SRA $*$ Before 1998 implies that SRA homes built before the end of the mid-1990s building codes reforms perform similarly to homes of the same vintage in no-code areas. In contrast, SRA homes built during 1998–2007 or 2008–2016 perform 11.2 percentage points and 15.9 percentage points better, respectively. Differencing the pre-post differences across code areas yields a DiD estimate of 13.1 percentage points. The same pattern exists for LRA VHFHSZ areas, with no difference before 1998 and substantial improvements in the post-code periods. The DiD estimate for LRA VHFHSZ areas is 12.2 percentage points. Lastly, these improvements are smaller or absent in the no-codes comparison group, where homes built in the latter two time periods show only minor improvements that are not statistically distinguishable from zero. This is further evidence that the improvements in the code areas are due to building codes as opposed to other time-varying factors. The regression also includes controls for topography and vegetation. As expected, slope steepness at the home site increases vulnerability. A home on a 10 degree slope would be six percentage points less likely to survive than an otherwise-identical home on flat ground. This specification also includes fixed effects for the dominant vegetation type in the area of the home.[16]

The remaining columns of Table 1 explore alternative specifications. Col-

16. We assign vegetation types as the most common fuel model in a 25-meter radius around the home.

umn (2) adds building characteristics from the assessor data. Building square footage, number of bedrooms, and lot size do not appear to have meaningful effects on survival after controlling for year built and street. Home characteristics data are missing for about 20% of homes, which shrinks the sample in this third column. The final three columns show different sets of fixed effects. Column (3) includes separate fixed effects for each group of 100 adjacent homes on each street (ordered by house number). This specification addresses a potential concern that some streets in the sample include many hundreds of homes. The more granular fixed effects do not materially change the estimates. Column (4) groups homes on the same street and side of the street, assuming that house numbers follow the convention of odd and even numbers on opposite sides. This specification also does not change the results. Finally, Column (5) omits the street fixed effects and instead uses incident fixed effects. These incident dummies absorb fire-specific severity and arbitrary time trends in preparedness, but unlike the street fixed effects they do not adjust for differences between exposed homes within the same wildfire incident. The point estimates are slightly larger in SRA areas and slightly smaller in LRA VHFHSZ areas. Notably, the R^2 with incident fixed effects is smaller than with street fixed effects (0.39 vs 0.63). This difference implies that the street fixed effects remove variation in fire severity and other factors within incidents that might otherwise threaten identification. Nevertheless, the estimates are broadly stable across specifications. None of the estimated effects in Columns (2) through (5) are statistically different from those in Column (1).

In principle, the street fixed effects design could underestimate the effect of building codes due to the spillover benefits that we document in the next section. If code-induced investments also benefit nearby pre-code homes, the difference in outcomes between post-code and pre-code homes will understate the true effect of codes on survival.[17] This attenuation could be exacerbated by street fixed effects, which by construction are focused on homes located relatively close to each other. Such reasoning might lead one to prefer incident

17. This is a violation of the Stable Unit Treatment Value Assumption, or SUTVA (Rubin 1980).

fixed effects. In practice, as we show in the next section, spillovers are highly localized and are small compared to the own-resilience effects. In the spirit of exhaustiveness, Appendix Table 3 investigates the quantitative significance of SUTVA concerns by controlling directly for the number of pre- and post-code near neighbors in the street fixed effects regression. Ultimately, the differences in the estimated building code effects across these approaches – street fixed effects, incident fixed effects, and street fixed effects directly controlling for spillovers – are small enough that the various results are not statistically different.

4.2 Spillovers to neighboring properties

This section discusses the spillover benefits of code-induced mitigation to neighboring homes. Figure 5 shows regression results for Equation (2). The top panel shows effects of the presence of pre-code neighbors at various wall-to-wall distances. One or more pre-code neighbors within 0-10 meters increases own-structure loss probability during a wildfire by about 3 percentage points. These effects attenuate with distance, going to zero at 30-40 meters. Notably, this is the distance that wildfire managers consider to be the home ignition zone - the distance within which flammable material presents a risk of structure ignition (Cohen 2000, 2010; Calkin et al. 2014). The near-zero estimates beyond 40 meters bolster the validity of our research design. If our estimates for the nearest neighbors were biased by omitted predictors of resilience that co-vary within neighborhoods, one would expect that bias to also appear in estimates for homes another few dozen meters away (Figure 1b provides a useful illustration of these small distances).

The bottom panel shows the estimates for post-code neighbors. The confidence intervals for these estimates are wider since we observe fewer post-code homes. However, the point estimates suggest that the presence of close neighbors built under WUI building codes does not increase own-structure loss probability. There is also no implied effect of further-away post-code neighbors on own survival, offering additional placebo evidence to support the identifying assumptions behind this regression.

Table 2 reports regression estimates for near neighbors that allow effects to vary with the number of neighbors. Column (1) considers neighbors at a wall-to-wall distance of less than 10 meters. A single pre-code neighbor increases own-structure loss risk by 2 percentage points. Two or more pre-code near neighbors increases the effect to 3.1 percentage points. This latter category mostly represents the effect of homes with two neighbors, given that very few homes have more than two neighbors within 10 meters (Appendix Table 2). The estimated effects of nearby post-code neighbors are close to zero. Column (2) shows the same regression using a restricted sample of areas where our measured distances between homes are likely to be particularly accurate. This sample includes denser areas (homes with at least 10 neighbors within a 200 meter radius; see Appendix Table 4) and fires since 2013 (for older incidents, it is more likely that parcel boundaries have changed since the fire). The estimated risk posed by pre-code neighbors is slightly larger in this specification, perhaps due to measurement error in wall-to-wall distances in the full sample. The estimates for post-code neighbors are again zero. As another robustness check, Columns (3) and (4) present similar results based on the centroid-to-centroid distance measure. One pre-code neighbor within 30 meters of centroid distance – roughly equivalent to 10 meters of wall distance – increases own loss risk by 2.6 percentage points, and two or more increases risk by 5 percentage points. Again, the point estimates for post-code neighbors are much smaller and close to zero.

5 Net Social Benefits of Building Standards

The empirical results show that compared to reliance on voluntary action alone, California's wildfire building codes substantially reduced average structure loss risk during a wildfire. They also reduced the risk to a close neighbor's home. Having documented these large resilience benefits, we now embed the results in a simple economic model in order to benchmark the approximate net social benefits of wildfire building codes. We use our estimates to explore the minimum annual disaster probability at which universal mitigation investment is welfare-improving, given various values of neighborhood density and household risk aversion. This exercise is intentionally simple and abstracts from many theoretical and practical details that warrant investigation in future work.[18]

5.1 An Empirical Model of Hazard Mitigation

N identical individuals own homes in a neighborhood with an annual probability p^F of a disaster. In the event of a disaster, each home i's baseline probability of destruction is p_0^D. Up-front investment in a binary mitigation measure with cost m by homeowner i reduces own loss risk during a disaster by τ_{ii} and also reduces loss risk by τ_{ji} for a subset of neighbors $j \neq i$ (for example, in our application τ_{ji} is non-zero for neighbors within some distance of home i and zero for the remaining homes). Mitigation benefits are additive so that a home's destruction probability during a disaster is $p_i^D = p_0^D - M_i\tau_{ii} - \sum_{j\neq i} M_j\tau_{ij}$, where $M_i \in \{0, 1\}$ is the homeowner's binary mitigation decision. We capture myopia with perceived disaster probabilities $\hat{p}_i^F \leq p^F$. These perceived probabilities vary across households.

Consistent with stylized facts (e.g., Klein (2018)), disaster losses are partially insured: destruction of the home imposes insured losses L^I for the insurer and uninsured losses L^U for the homeowner. We initially assume frictionless property insurance markets that offer coverage at actuarially fair annual premia $k_i = p^F p_i^D L^I$. The coexistence of uninsured risk exposure and actuarially fair premiums reflects uninsurable losses (for example, mental and emotional distress) and/or household myopia. The exposition in this section uses a static model with no discounting. Our actual calculations assume that households discount future costs and benefits at a 5% annual rate.

We define two potential measures of net benefit, *risk-neutral cost effectiveness* and *expected utility benefit*. Risk-neutral cost effectiveness is simply the

18. A more detailed theoretical treatment of private risk mitigation can be found in Costello, Quérou, and Tomini (2017).

difference in expected cost with and without mitigation. Expected utility benefit accounts for additional benefits from reduced exposure to uninsured risk. Appendix Section D presents a sketch of the expected utility model. Actually calculating expected utility requires strong assumptions about households' risk aversion, permanent income, ability to smooth across time periods, and other factors. We focus the derivation in this section on risk-neutral cost effectiveness (hereafter, "cost effectiveness"). We note that cost effectiveness is a lower bound on net benefits as long as homeowners are not risk-loving.

Total expected cost across households is,

$$\sum_{i=1}^{N}[p^F(p_0^D - \sum_{j=1}^{N} M_j\tau_{ij})(L^I + L^U) + M_i m] \tag{3}$$

The social benefit of mitigation by a homeowner is the sum of private and external benefits (reduced loss probability) minus mitigation costs,

$$p^F(\tau_{ii} + \sum_{j\neq i}\tau_{ji})(L^I + L^U) - m \tag{4}$$

In contrast, a homeowner's perceived change in private expected losses with mitigation is,

$$\hat{p}_i^F\tau_{ii}(L^I + L^U) - m \tag{5}$$

The presence of internalities ($\hat{p}_i^F$) and externalities (τ_{ji}) means that Expression (5) is weakly less than Expression (4). If households minimize perceived private expected cost, the voluntary takeup rate will be,

$$\mu = \frac{1}{N}\sum_{i=1}^{N}\mathbb{1}[\hat{p}_i^F\tau_{ii}(L^I + L^U) \geq m] \tag{6}$$

which depends on the distribution of perceived probabilities. Assuming $\hat{p}_i^F$ is independently distributed, total actual expected costs under voluntary takeup are $\sum_{i=1}^{N}[p^F(p_0^D - \sum_{j=1}^{N}\mu\tau_{ij})(L^I + L^U) + \mu m]$.

Now consider a policy requiring mitigation by all households. Total expected cost is given by setting $M_i = 1$ for all households in Expression (3). The difference in expected cost under the mandate vs. the voluntary regime is,

$$(1-\mu)\Big[p^F[\sum_{i=1}^{N}\sum_{j=1}^{N}\tau_{ij}(L^I + L^U)] - Nm\Big] \tag{7}$$

The Samuelson (1954)-style expression inside the outer brackets is the sum of private and external mitigation benefits minus total mitigation costs. The factor of $(1-\mu)$ reflects takeup by a fraction μ of the population without the mandate. A mandate weakly reduces total expected cost if the social value of mitigation (Expression 4) is positive and strictly increases expected cost if the social value of mitigation is negative.

Before proceeding, it is worth noting some restrictions in this model. We assume additive mitigation benefits. There is some support for this in the data - for example, the approximate linearity of risk spillovers for one vs. two near neighbors in Table 2. A more complex model could instead allow the benefits of mitigation to vary with mitigation effort by others, so that mitigation becomes a strategic game between homeowners.[19] We also assume identical homes and homeowners within the neighborhood and independently distributed perceived disaster probabilities. We explore heterogeneity in fire risk and neighborhood density across neighborhoods (zip codes) in the empirical implementation. Expanding the model to allow for greater heterogeneity within neighborhoods would allow a more nuanced exploration of the distribution of net benefits. We see these extensions as useful areas for future work, but prefer this simple and transparent model for the purposes of benchmarking approximate net benefits.

5.2 Implementation

We implement the model for a random sample of 100,000 homes in 424 California zip codes in wildfire hazard areas. Each zip code is modeled as a separate

19. Shafran (2008) develops such a model for vegetation maintenance in wildfire areas.

neighborhood with its own fire probability and number of close neighbors affected by risk spillovers.

Mitigation Benefits

The empirical results in Section 4 allow us to estimate τ_{ii} and τ_{ij}. The reduced form estimates of the effect of building codes on structure survival can be seen as intent-to-treat estimates of the effect of mitigation investment. Given a rate of voluntary takeup for the bundle of mitigation measures in the building code, the standard Wald estimator gives τ_{ii} and τ_{ij} as the ratio of the reduced form estimates and the difference in takeup rates in the codes and no-codes areas.[20] In the theoretical model, voluntary takeup μ depends on beliefs about fire risk and might thus be expected to vary between neighborhoods. In practice, survey data on voluntary mitigation is scarce and the available data do not allow us to calculate neighborhood-specific voluntary takeup rates. Our base calculation uses a voluntary takeup rate of one-third. Appendix Section E describes how we calculate this takeup rate based on CAL FIRE inspections of destroyed and surviving homes for a sample of recent California wildfires, including caveats about limitations of the data (which is nevertheless the best existing survey evidence for our purposes).

Our reduced form estimate for own survival benefit for SRA homes implies a value of τ_{ii} of 0.195 ($\frac{.13.1}{1-0.33} = 0.195$). For τ_{ij}, our reduced form estimate of neighbor benefits in Table 2 is 2.3 percentage points for neighbors up to 10 meters away in wall-to-wall distance (and close to zero beyond 10 meters). The effect also appears approximately linear in number of neighbors that mitigate, at least over the limited range of number of neighbors that we can observe in the data. Thus, our estimate of τ_{ij} is 0.034 for each neighbor within 10 meters ($\frac{-.0.023}{1-0.33} = -0.034$) and zero for all further-away neighbors.[21]

20. See e.g., Angrist and Pischke (2009) p. 127-133. This calculation assumes perfect compliance by homes subject to codes and a homogeneous effect of mitigation on structure survival.

21. In principle, mitigation at further-away homes also benefits home i through potential "domino effects": a near neighbor becomes less likely to ignite due to action by that neighbor's neighbor. Our estimates imply that these effects are small on average (on the order of

Sampling at-risk homes

Unlike the empirical analysis of building code effects, which uses homes located inside historical wildfire perimeters, the net benefits calculation considers a group of homes sampled randomly from *all* California homes in fire hazard areas. To construct this sample, we start from all California homes in designated wildfire severity zones (SRA or LRA) and filter out zip codes containing fewer than 100 homes. We then randomly draw $min(n, 250)$ homes from each remaining zip code where n is the number of homes in the zip code. This yields a sample of 100,230 homes subject to wildfire building codes in 424 zip codes.

We identify each home's annual wildfire exposure probability p^F using data from the United States Forest Service (USFS) Wildfire Risk to Communities project. This measure captures the annual probability of moderate to severe wildfire exposure (Scott et al. 2020).[22] We also identify each home's number of neighbors within 30 meters of centroid to centroid distance. This roughly corresponds to the number of neighbors within 10 meters of wall-to-wall distance (see footnote 15) and is less demanding to calculate in this new random sample of homes.

Costs and Losses

Our main estimates of mitigation costs come from Headwaters Economics (2018). That study uses construction estimating tools from R.S. Means to calculate the additional cost to build a home that complies with California's Chapter 7A wildfire code. Overall, that study reports zero cost difference between code-compliant and standard designs. This counter-intuitive result arises because one aspect of code-compliant construction (exterior siding) is substantially *less* expensive than standard designs. These savings offset increased costs for roofing, landscaping, and other areas. Our main estimate of

0.034^2).

22. We use the product of Burn Probability (the total annual wildfire probability) and Flame Length Exceedance Probability 4 (conditional on any fire, the probability that the fire will reach moderate or greater threat status).

code compliance costs ignores savings from code-compliant siding on the theory that owners would make this choice even without standards. This gives a cost estimate of $15,660. We also report results using alternative cost estimates from the National Association of Home Builders. Their estimated wildfire code compliance costs for newly-built California homes include a low scenario of $7,868 and a high scenario of $29,429 (Home Innovation Research Labs 2020).[23] Finally, we show a "retrofit" scenario based on Headwaters Economics' estimate of $62,760 to fully replace roofing and exterior walls on an existing home.

Our assumed losses for a home destroyed by wildfire include rebuilding costs, belongings and contents of the home, alternative living costs while the home is rebuilt, and costs for debris removal and hazardous waste cleanup. Rebuilding, contents, and alternative living arrangements costs come from the FEMA Hazus model (Federal Emergency Management Agency 2021). We match as closely as possible the characteristics of the model home used to estimate code compliance costs in Headwaters Economics (2018).[24] We regionally adjust these costs to California using geographic adjustment factors from R.S. Means provided in the Hazus model. The resulting cost of reconstruction and contents losses is $766,725. The Hazus cost for alternative living arrangements and disruption (e.g., moving costs) for 24 months is $61,696. For debris removal (which is borne by homeowners) and hazardous waste cleanup (borne by governments), we add a total of $150,000.[25]

We assume that mitigation investments have a protective lifetime of 40 years.

23. These are costs to meet the International Wildland Urban Interface Code, which is similar to the Chapter 7A code. In the low scenario, we ignore $3,839 of gross savings from code-compliant siding as we do for Headwaters Economics (2018).

24. The model home in Headwaters Economics (2018) is a 2,500 square-foot single-story home with 2-car garage constructed in Montana for $140 per square foot. We use Hazus cost estimates for the same size, number of stories, and garage in the "custom" construction class, the closest corresponding cost category.

25. For cleanup and debris removal costs, see Klein (2018); Lewis, Sukey, "Cleaning Up: Inside the Wildfire Debris Removal Job That Cost Taxpayers $1.3 Billion." *The California Report*, July 19, 2018; and Bizjak, Tony, "State's Effort to Clean Up After the Camp Fire is Off to a Rocky Start", *Sacramento Bee*, January 13, 2019.

In the absence of mitigation investment, the probability of loss when exposed to wildfire for a home with no close neighbors is 44%.[26] Households discount future costs and benefits at 5% per year.

5.3 Results of Net Benefit Calculation

Figure 6 illustrates the results of this calculation. The scatter plot shows zip code-level averages of annual wildfire hazard and number of near neighbors. The wildfire hazard reaches strikingly high levels: several zip codes face annual event probabilities above 2% per year, implying a significant wildfire exposure every 50 years on average. The color scale shows the social benefit of mitigation investment in each zip code following Expression (4). The dashed black line shows a threshold for positive net benefits of building standards. Homes to the right of this line have lower expected costs with mitigation investments than without. The threshold bends to the left as the average number of neighbors increases due to the spillover benefits of mitigation across properties. For a home with zero near neighbors, the break-even annual wildfire hazard is about 0.45%. The break-even annual hazard for a home with 1 near neighbor is 0.39% and for a home with 4 near neighbors it is 0.27%.

These cost effectiveness estimates are a lower bound on the net benefits of universal mitigation. One important reason for this is that many homeowners are substantially underinsured for natural disaster losses. Mitigation investments yield additional welfare benefits by reducing exposure to uninsured risk. Even for properties covered by homeowners insurance, Klein (2018) reports that coverage limits for wildfire-destroyed properties are often up to 50% below actual losses. Table 3 reports break-even annual wildfire probabilities for a home with 1.2 near neighbors (the sample mean) based on the expected utility model in Appendix Section D. Although this model requires additional strong assumptions, these back-of-the-envelope numbers depict how risk aversion might affect program benefits. For example, if code compliance costs $15,660, a homeowner

26. The approximate destruction probability for SRA homes under current codes is $0.4 - .156 = .244$ (Table 1). Combined with the own-structure mitigation effect, this gives the implied loss probability in the absence of mitigation: $.244 + .195 = 0.44$.

with a coefficient of relative risk aversion of 5 and an insurance policy covering two thirds of total losses would be better off investing in mitigation wherever the annual probability of a damaging wildfire exceeds 0.33%.[27]

Table 3 also reports results using other estimates of mitigation cost. The zero net cost estimate from Headwaters Economics (2018) leads to positive benefits for any level of hazard. The two additional estimates from Home Innovation Research Labs (2020) bracket the main cost estimate. Finally, the estimated retrofit cost of $62,760 results in much higher break-even hazard levels for existing homes. This kind of full retrofit to existing homes appears to generate positive benefits only for a handful of areas with extreme fire hazard.

Beyond risk aversion, WUI building codes likely have additional benefits that are not included in our calculations. These include reductions in public expenditures on firefighting during large wildfires (Baylis and Boomhower 2019), reduced demand for public assistance among fire victims (Deryugina 2017), avoided emotional and mental distress, and less need for public safety power shutoffs that interrupt electricity service during high fire-risk periods.[28] Moreover, if imperfections in property insurance markets cause premiums to systematically exceed expected damages, then mitigation becomes more attractive because it reduces the risk which must be insured in the imperfect insurance market. Scientists also agree that annual wildfire probabilities are increasing throughout North America such that net benefits of WUI building codes will grow in the future. On the other hand, a more detailed analysis would need to consider possible heterogeneity in household net benefits. If some individuals have very high perceived private costs of choosing fire resistant materials and landscaping (perhaps due to strong aesthetic preferences), building standards could be costly for these households.

27. Studies of the property insurance market generally report high implied levels of relative risk aversion. Cohen and Einav (2007) and Sydnor (2010) examine deductible choices in auto and homeowners insurance respectively and find double-digit values for the mean household across a variety of specifications. Evidence from other markets suggests values closer to the low single digits (e.g., Gertner 1993; Chetty 2006).

28. For a systematic review of catastrophic wildfire costs, see Feo et al. (2020).

In summary, our empirical estimates and model calculations suggest that wildfire building codes yield unambiguous benefits in the most fire-prone areas of California, especially when homes are clustered closely together such that there are large risk spillovers. For areas with lower fire risk, the sign of net benefits is more sensitive to modeling choices and the assumed co-benefits of building codes. Further work on the cost-effectiveness of wildfire mitigation measures in low- and moderate-risk areas is an important area for additional research.

6 Conclusion

Efficient investment in adaptation is essential in the face of rapidly accelerating disaster losses. Yet takeup of protective technologies and behaviors is thought to be constrained by misperception of risk, insurance market failures, spatial externalities, and other frictions. The pressing question facing researchers and policymakers is how to best respond to these market barriers. One suite of policies focuses on increasing voluntary takeup through information or subsidies. Another option is to override individual decisions and mandate certain investments in hazard areas. These policies may differ substantially in their effects and their political acceptability.

This study contributes evidence on the effects and net economic benefits of a mandatory adaptation policy. We provide the first comprehensive empirical evaluation of California's strict wildfire building codes. The analysis uses a new dataset of property-level data on U.S. homes destroyed by wildfire that was created for this study. The new data combine nationwide property characteristics information with post-fire damage assessment records collected from numerous local and state agencies. This resource has three important advantages: it collects and harmonizes previously disparate damage data; it contains a complete record of homes that survive as well as homes that are destroyed; and unlike data for floods and other losses, it is reported at the individual property level. Beyond this study, the new data will enable additional important research on disaster losses.

The empirical analysis in this study is bolstered by our ability to observe differences in building code regimes over time, across jurisdictions within California, and between California and other states. The empirical strategy isolates the effect of building code changes using a fixed effects design that compares outcomes for pre- and post-code homes on the same residential street. This approach narrows the comparison to homes experiencing essentially identical wildfire exposures.

The results show that compared to reliance on voluntary action alone, California's wildfire building codes reduced average structure loss risk during a wildfire by 16 percentage points, or about a 40% reduction. They also reduced the risk to a close neighbor's home by about 2 percentage points or 6%. These striking results imply materially different levels of resilience in communities with and without such codes. Moreover, the spatial externalities provide a classic rationale for public policy intervention even if homeowners were fully informed and rational about wildfire risk.

Having documented these large resilience benefits, we then show how the empirical results can be embedded in an economic model that accounts for mitigation costs, spatial spillovers, and risk preferences. We use our results and other values from the literature to provide a back-of-the-envelope approximation of the minimum annual wildfire risk at which universal mitigation generates positive net benefits. In the most fire-prone areas of California, the calculation shows large net benefits of building codes for new homes. Given the high cost of fully retrofitting existing homes to modern standards, full retrofits do not pass a benefit-cost test in most areas. An important task for future research is to identify individual low-cost investments that can cost-effectively improve the resilience of existing homes in high hazard areas.

In summary, the data show that an adaptation mandate substantially improved resilience to wildfires and a cost-benefit approximation suggests that low takeup without standards is more likely driven by market failures than by fully-informed individual decisionmaking. These results are immediately applicable to policy debates in the U.S., Canada, Australia, the European

Union, and other jurisdictions that are seeking to respond to escalating wildfire risk. More broadly, these facts should be of interest to policymakers and researchers confronting other hazards like floods, hurricanes, and heat waves where voluntary takeup of self-protective investments seems to be constrained by similar barriers. As climate change continues to increase disaster losses, this type of research on the role of public policy and market incentives in shaping adaptation is increasingly urgent.

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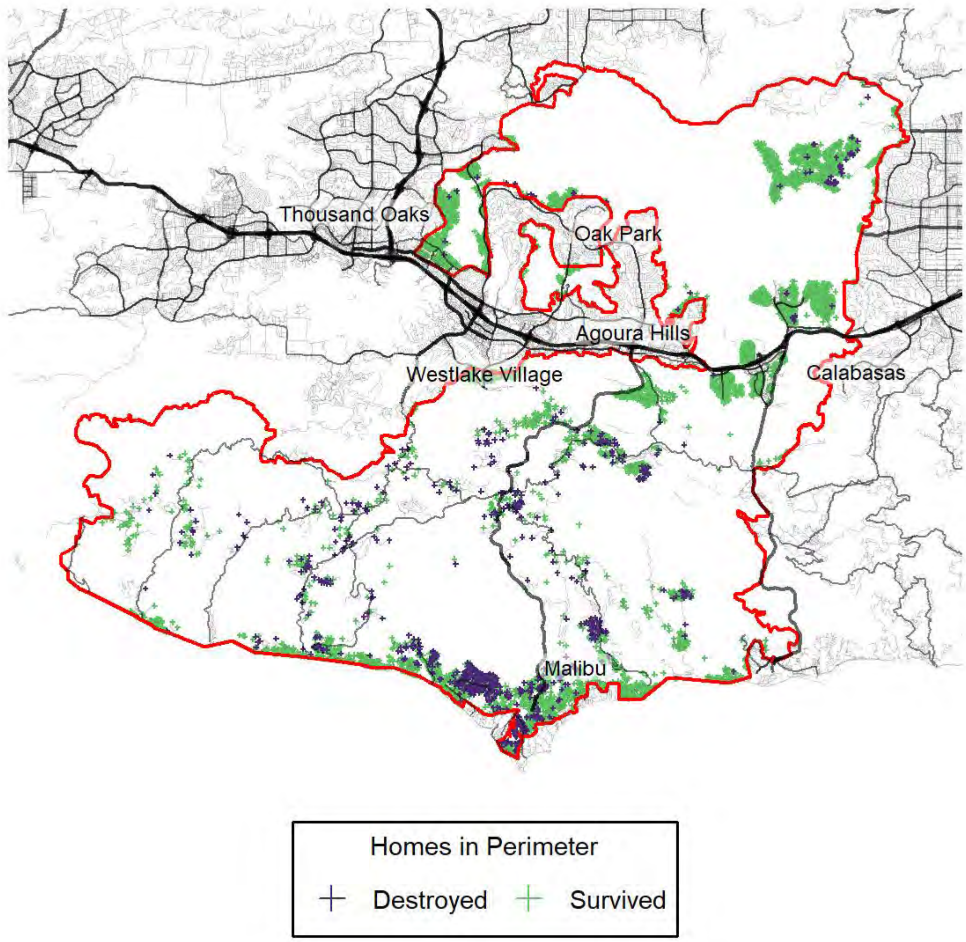
Figure 1: Building and Validating the Dataset

(a) Roof Locations and Damage Reports

(b) Distance Between Structures

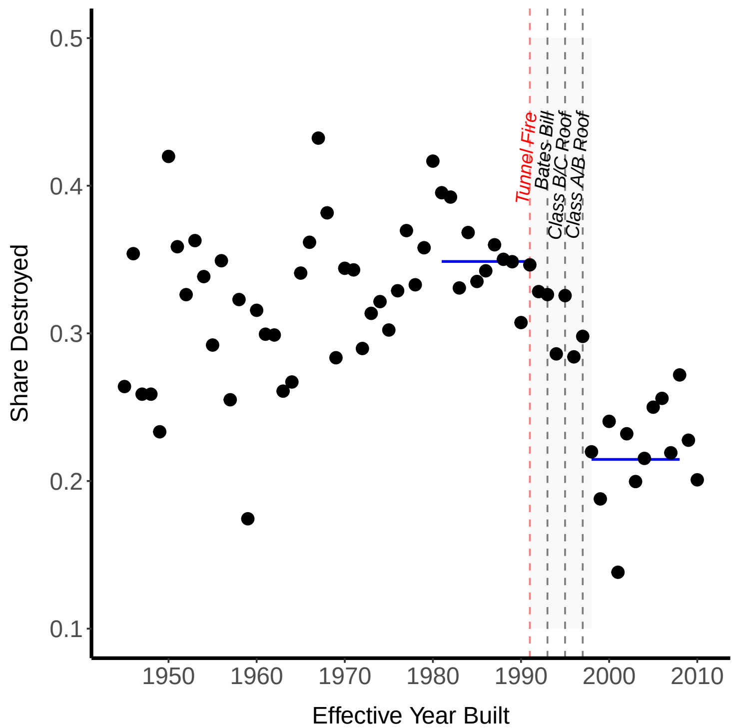
Notes: Best viewed in color. **(Panel a)** Homes affected by the Carr Fire (2018). Markers are geocoded structure locations. Green square markers are structures reported as destroyed in the damage inspection data; yellow circular markers are all other homes in the data. The background image is aerial imagery before and after the Carr Fire from NearMap. Blue building shapes and gray parcel outlines are the building footprint data and assessor parcel boundary data used to identify structure locations (see text for details). **(Panel b)** Examples of calculated distances between structure walls. Images are pre-fire aerial imagery of homes affected by the Thomas Fire (2017) and Tubbs Fire (2017). Figure shows the wall-to-wall distance from the structure marked '0' to the other homes.

Figure 2: Merged data example: Structure-level outcomes in the Woolsey Fire



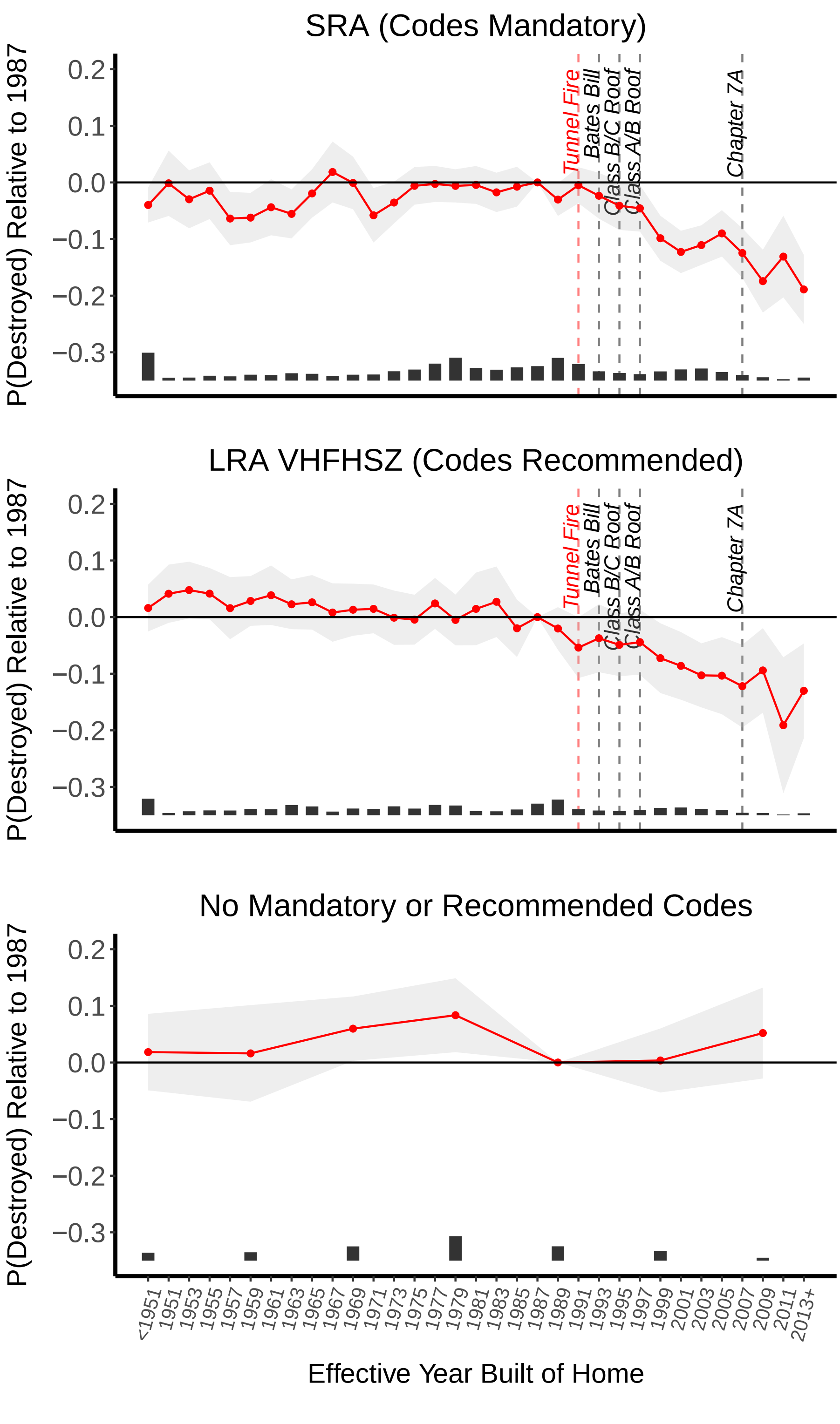
Notes: Best viewed in color. Example of merged inspection, assessor, and fire perimeter data for one fire in our dataset. Markers indicate the locations of single family homes inside the final Woolsey Fire perimeter (shown in red). Purple homes are reported destroyed in damage inspection data; green homes are all remaining homes in the ZTRAX assessment data. Street map data are from Open Street Map.

Figure 3: Share Destroyed by Year Built in Mandatory Code Areas



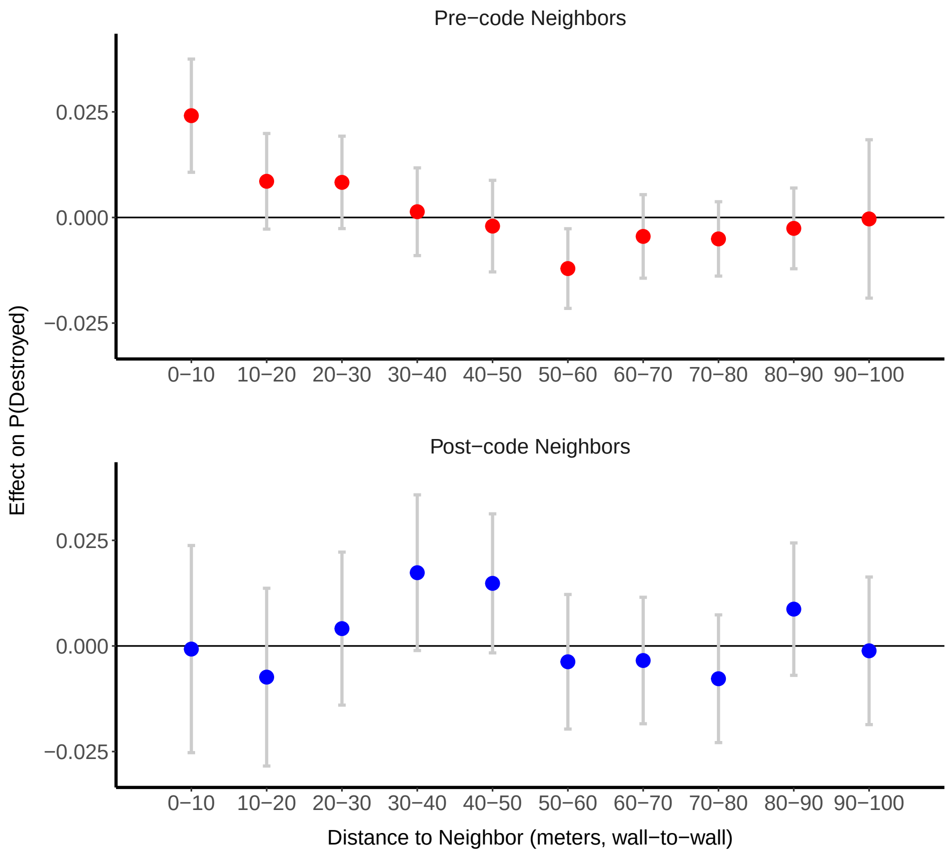
Notes: This figure shows the share of homes inside wildfire perimeters that were destroyed, according to the year that the home was built. The sample is limited to homes in State Responsibility Area. The blue lines show ten-year averages.

Figure 4: Estimated Vintage Effects by Building Code Jurisdiction



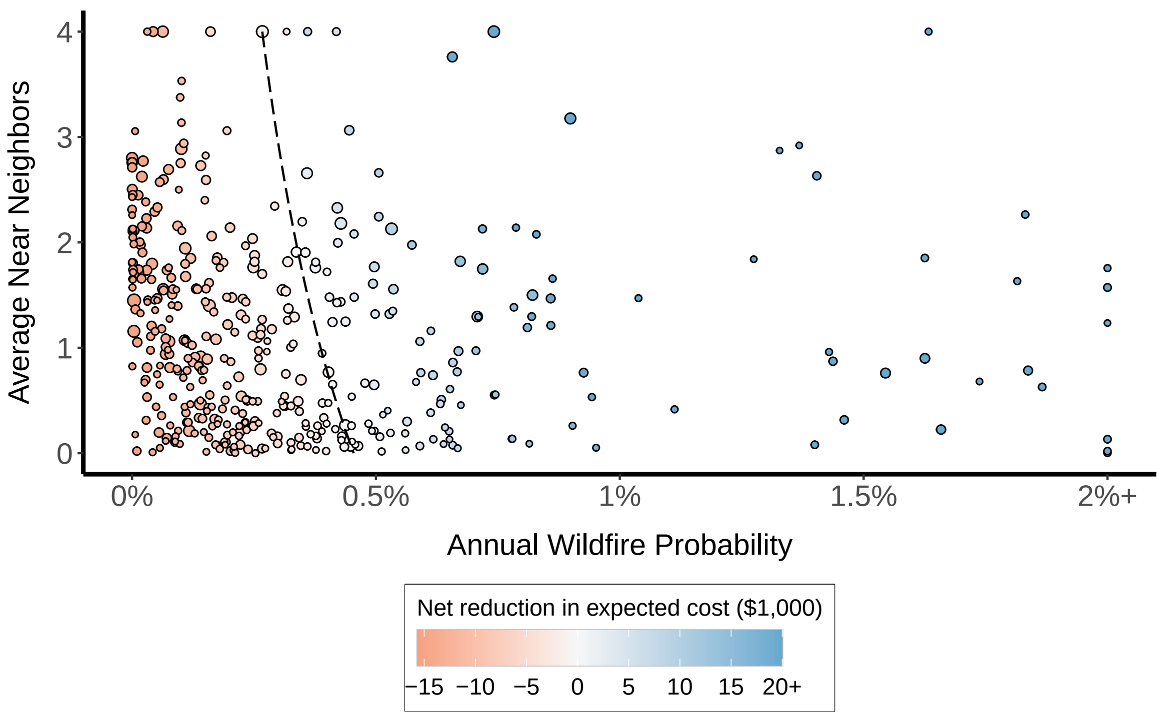
Notes: Figure plots point estimates and 95% confidence intervals from 3 separate OLS regressions of an indicator for Destroyed on bins of effective year built. Each regression includes street by incident fixed effects and other controls described in the text. Panel (a) shows homes in state responsibility area (SRA). Panel (b) shows homes in local responsibility area (LRA) inside state-recommended Very High Fire Hazard Severity Zones (VHFSZ). Panel (c) shows homes in states without wildfire building codes (AZ, CO, OR, WA) and LRA areas in California outside of state-recommended VHFHSZ. Standard errors are clustered by street. The histogram below each panel shows the relative number of observations in each bin.

Figure 5: The effect of neighboring homes on survival



Notes: Figure shows coefficients and 95% confidence intervals from a single OLS regression of "Destroyed" on the presence of pre- and post-code neighbors at various distances. The top panel shows estimates for indicator variables for the presence of one or more neighbors built without wildfire building codes. The bottom panel shows estimates for indicator variables for the presence of one or more neighbors built after wildfire building codes. The regression also includes own year built (in four year bins), street by incident fixed effects, and topographic controls. Distance to neighboring home is wall-to-wall distance. See text for details.

Figure 6: Lower-bound Net Benefits by Fire Hazard and Number of Neighbors



Notes: This figure plots the annual probability of a damaging wildfire and average number of close neighbors for a random sample of 100,230 California homes in areas subject to the Chapter 7A building codes. Markers represent zip-code averages. Marker color indicates average net benefits in the zip code using the cost-effectiveness measure, which is a conservative lower bound on total net benefits. Annual wildfire hazard is from Scott et al. (2020) and represents a snapshot as of 2014. Number of neighbors is the number of homes within a 30-meter centroid to centroid distance. Marker size is proportional to number of homes in the zip code. The dashed line shows a threshold for zero net reduction in expected cost. See text for discussion and alternative scenarios.

Table 1: Regression estimates of building code effects on own survival

	(1)	(2)	(3)	(4)	(5)
SRA * Before 1998	-0.022	-0.045	-0.027	-0.021	-0.029
	(0.033)	(0.041)	(0.029)	(0.037)	(0.020)
SRA * 1998–2007	-0.112***	-0.138***	-0.117***	-0.113***	-0.160***
	(0.034)	(0.043)	(0.031)	(0.039)	(0.022)
SRA * 2008–2016	-0.159***	-0.190***	-0.164***	-0.151***	-0.204***
	(0.036)	(0.044)	(0.033)	(0.041)	(0.027)
LRA VHFHSZ * Before 1998	-0.031	-0.048	-0.038	-0.028	-0.005
	(0.033)	(0.050)	(0.030)	(0.037)	(0.021)
LRA VHFHSZ * 1998–2007	-0.121***	-0.142***	-0.126***	-0.127***	-0.095***
	(0.034)	(0.048)	(0.032)	(0.038)	(0.025)
LRA VHFHSZ * 2008–2016	-0.159***	-0.178***	-0.162***	-0.163***	-0.130***
	(0.037)	(0.050)	(0.035)	(0.041)	(0.030)
No Codes * 1998–2007	-0.038	-0.029	-0.045*	-0.044*	-0.035
	(0.025)	(0.026)	(0.026)	(0.024)	(0.030)
No Codes * 2008–2016	-0.006	0.035	0.012	-0.010	-0.071
	(0.033)	(0.040)	(0.041)	(0.033)	(0.044)
Ground slope (degrees)	0.006***	0.005***	0.006***	0.006***	0.005***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Lot size (acres)		-0.000			
		(0.000)			
Building square feet		-0.000			
		(0.000)			
Bedrooms		0.001			
		(0.003)			
Street FE	✓	✓			
Fuel model FE	✓	✓	✓	✓	✓
Street X 100 homes FE			✓		
Street X side of street FE				✓	
Incident FE					✓
Observations	48,843	38,991	48,843	48,843	48,843
R^2	0.62	0.63	0.63	0.66	0.39
Dep. Var. Mean	0.41	0.46	0.41	0.41	0.41

Notes: Table shows estimates and standard errors from five separate OLS regressions. The outcome variable is an indicator for Destroyed. Street fixed effects includes separate dummies for each street-by-incident. Incident fixed effects are dummies for each wildfire. Fuel model fixed effects are dummies for Anderson fire behavior fuel models. Standard errors are clustered by street.

Table 2: Neighbor Effects

	Destroyed			
	(1)	(2)	(3)	(4)
1 pre-code nearby homes	0.020***	0.023***	0.026***	0.027***
	(0.007)	(0.007)	(0.007)	(0.007)
2+ pre-code nearby homes	0.031***	0.039***	0.050***	0.051***
	(0.009)	(0.010)	(0.009)	(0.009)
1 post-code nearby home	0.001	0.002	0.010	0.001
	(0.013)	(0.013)	(0.012)	(0.013)
2+ post-code nearby homes	-0.001	0.001	0.003	-0.009
	(0.016)	(0.018)	(0.018)	(0.021)
Own Year Built	✓	✓	✓	✓
Topography	✓	✓	✓	✓
Street FE	✓	✓	✓	✓
Observations	38,226	23,564	44,923	26,842
R^2	0.64	0.68	0.63	0.68
Distances	Walls	Walls	Centroids	Centroids
Subsample		✓		✓
Dep. Var. Mean	0.40	0.49	0.40	0.51

Notes: Table shows estimates and standard errors from 4 separate OLS regressions. The outcome variable is an indicator for Destroyed, and each regression also includes dummy variables for own year built (in four year bins) and street-by-incident fixed effects. Columns (1) and (2) use wall-to-wall distances to assign neighbors, while Columns (3) and (4) use the centroid-to-centroid distance measure. Columns (1) and (3) use the full sample of single family homes, while columns (2) and (4) use a subsample in areas where our distance measures are likely to be particularly accurate. See text for details. Standard errors are clustered by street.

Table 3: Break-even Hazard under Risk Aversion and Alternative Costs

	Insured %	100	67		33	
			$\gamma = 2$	$\gamma = 5$	$\gamma = 2$	$\gamma = 5$
Cost Estimate	Source					
New Home						
$ 0	*HE-Low*	0	0	0	0	0
$ 4,029	*NAHB-Low*	0.10%	0.09%	0.08%	0.08%	0.05%
$15,660	*HE*	0.38%	0.36%	0.33%	0.30%	0.20%
$29,429	*NAHB-High*	0.71%	0.68%	0.63%	0.58%	0.41%
Retrofit						
$62,760	*HE*	1.50%	1.46%	1.40%	1.33%	1.15%

Notes: Table shows estimated minimum annual wildfire probability for which building standards yield positive net benefits under various assumptions about cost, share of losses insured, and risk aversion. Probabilities are reported as percentages (e.g., 0.32% per year). For partial insurance scenarios, γ is the coefficient of relative risk aversion. Calculations assume 1.2 near neighbors. See text for details of these calculations. Source code HE represents Headwaters Economics (2018) and NAHB represents Home Innovation Research Labs (2020).

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Roadside vegetation planning and conservation: New approach to prevent and mitigate wildfires based on fire ignition potential

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Highlights

- Wildfires on roadsides are a growing problem due to the higher ignition probability.
- Distance to roads and distance to settlements are the most meaningful variables in fire ignition.
- Wildfire risk is rarely taken into account by road design and road maintenance projects.
- The best method to mitigate the likelihood of fire ignition is to decrease the roadside flammability.

Abstract

Wildfires in urban landscapes spreading into forested landscapes are a growing problem due to socioeconomic and climate changes. Fire ignition and flame spread depend on meteorological and environmental conditions and the physicochemical traits of the fuel. In this approach, environmental variables and geostatistical techniques (maximum entropy model) identify distance to roads (37.9% of importance) and distance to settlements (18.4% of importance) as the most meaningful variables explaining fire ignition potential at a regional scale. Hence, the assessment of the ignition potential of roadside vegetation may play a cornerstone role in fire prevention management.

In this research, our aim was to identify the fire ignition potential on roadsides according to fire ignition likelihood and the flammability of the main species at particle level. The flammability of 14 species found on Spanish roadsides was studied at the bench-scale using flammability categories classification, combustion index and flammability index. *Nerium oleander, Tamarix gallica* and *Washingtonia filifera* limited the potential to fire spread based on ability to start a fire. *Chamaerops humilis, Pistacia lentiscus, Olea europaea* var. *sylvestris, Retama shaerocarpha* and *Spartium junceum* would be useful due to their less severe fire spreading in order to improve the landscape and biodiversity components of the road projects. Due to the global importance of human risk (road presence) in fire occurrence, this approach should be a suitable tool for planning the construction and maintenance of roads, from the perspective of fire prevention and fire impacts mitigation.

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Keywords

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Rapid growth of the US wildland-urban interface raises wildfire risk

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The wildland-urban interface (WUI) is the area where houses and wildland vegetation meet or intermingle, and where wildfire problems are most pronounced. Here we report that the WUI in the United States grew rapidly from 1990 to 2010 in terms of both number of new houses (from 30.8 to 43.4 million; 41% growth) and land area (from 581,000 to 770,000 km^2; 33% growth), making it the fastest-growing land use type in the conterminous United States. The vast majority of new WUI areas were the result of new housing (97%), not related to an increase in wildland vegetation. Within the perimeter of recent wildfires (1990–2015), there were 286,000 houses in 2010, compared with 177,000 in 1990. Furthermore, WUI growth often results in more wildfire ignitions, putting more lives and houses at risk. Wildfire problems will not abate if recent housing growth trends continue.

wildfires | housing growth | sprawl | development | fragmentation

The wildland-urban interface (WUI), defined as the area where houses are in or near wildland vegetation, is the area where wildfires pose the greatest risk to people due to the proximity of flammable vegetation (1). Wildfires frequently burn houses in the WUI (2, 3), and are most difficult to fight there. Furthermore, the WUI is where people often ignite wildfires (4), and the vast majority of fires are human-caused (5). While fires are an integral part of many ecosystems and the Earth system as a whole (6), humans have changed fire regimes globally (7) and throughout the United States (5), and climate change will increase fire frequency in the future, including in the WUI (8).

The close proximity of houses and wildland vegetation does more than increase fire risk (9). As houses are built in the WUI, native vegetation is lost and fragmented (10); landscaping introduces nonnative species and soils are disturbed, causing nonnatives to spread (11); pets kill large quantities of wildlife (12); and zoonotic disease, such as Lyme disease, are transmitted (13). Thus, understanding WUI patterns and WUI growth is important with respect to wildfires and many other environmental problems.

The WUI is widespread in the United States (1, 14) and in many other parts of the world (15, 16), including Argentina (17), Australia (18), France (19), and South Africa (20). Furthermore, both the annual area burned (8, 21, 22) and fire suppression costs (23) have rapidly increased in the United States. The area burned annually nearly doubled, from an average of 18,000 km^2/y in 1985–94 to 33,000 km^2 in 2005–14 (22). Concomitantly, federal wildfire suppression expenditures tripled from \$0.4 billion/y to \$1.4 billion/y (23), and exceeded \$2 billion in 2017.

While there is ample evidence that houses in the WUI pose problems, it is not clear how fast the WUI is growing. Overall, the US population grew by 60 million people and 29.2 million homes from 1990 to 2010, but how much of that growth occurred in the WUI is uncertain. Previous assessments of WUI growth (24, 25) analyzed only housing data up to 2000, and did not account for changes in wildland vegetation. Post-2000 housing data are important, because the United States entered a recession after 2008, accompanied by a strong downturn in the housing market. Similarly, without data on vegetation change, the major cause of WUI growth is unclear. Areas where forests are regrowing on abandoned farmland, such as in the New England states (26), could see WUI growth without any additional houses. Fundamentally, two processes can create new WUI: construction of new homes in or near existing wildland vegetation, and an increase in wildland vegetation within and near previously developed areas. The prevalence of each process is unclear.

Knowing how the WUI is growing, and why, is essential when evaluating management and policy responses (3, 8). In the United States, federal wildfire management policy prioritizes fuel treatments and the promotion of fire-adapted communities in the WUI. Local jurisdictions use a variety of land use planning tools to limit the environmental impacts of housing growth in the WUI. The importance of the WUI for the environment and for national policy, accompanied by the lack of information about WUI growth in the most recent decade, highlight the need to both assess WUI growth and identify its causes. Thus, we addressed three major questions: (*i*) how much has the WUI in the conterminous United States grown from 1990 to 2010; (*ii*) whether WUI growth is caused mainly by housing growth or by vegetation growth; and (*iii*) how much WUI growth has occurred within recent wildfire perimeters.

The lack of consistent, fine-resolution longitudinal housing data has been the biggest impediment to a nationwide assessment

Significance

When houses are built close to forests or other types of natural vegetation, they pose two problems related to wildfires. First, there will be more wildfires due to human ignitions. Second, wildfires that occur will pose a greater risk to lives and homes, they will be hard to fight, and letting natural fires burn becomes impossible. We examined the number of houses that have been built since 1990 in the United States in or near natural vegetation, in an area known as the wildland-urban interface (WUI), and found that a large number of houses have been built there. Approximately one in three houses and one in ten hectares are now in the WUI. These WUI growth trends will exacerbate wildfire problems in the future.

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of WUI growth. The decennial US Census provides fine-resolution housing data for 1990, 2000, and 2010, but the boundaries of the smallest units for which housing units are reported (i.e., census blocks) often shift between decades, precluding direct change analyses (27). We have developed algorithms to convert the decennial Census data at census block resolution into a consistent dataset on housing growth across the conterminous United States (*Methods*), which we combined with 1992, 2001, and 2011 National Land Cover Data (NLCD) on wildland vegetation: forests (classes 41–43), shrublands (classes 51 and 52), grasslands (class 71), and woody wetlands (class 90). We mapped decadal WUI change from 1990 to 2010 within 2010 census block boundaries, based on the WUI definitions in the *Federal Register* and our previously developed WUI mapping algorithms (1, 14), and conducted several robustness checks of our new dataset (*Supporting Information*). Because of concerns about housing growth and wildfire management, we calculated housing growth for 1990–2010 within WUI burned areas identified in Landsat imagery between 1990 and 2015 (22).

We found that the WUI was widespread in 2010, covering 9.5% of the conterminous United States (Fig. 1), and that the WUI grew rapidly from 1990 to 2010 in all its aspects (Fig. 2).

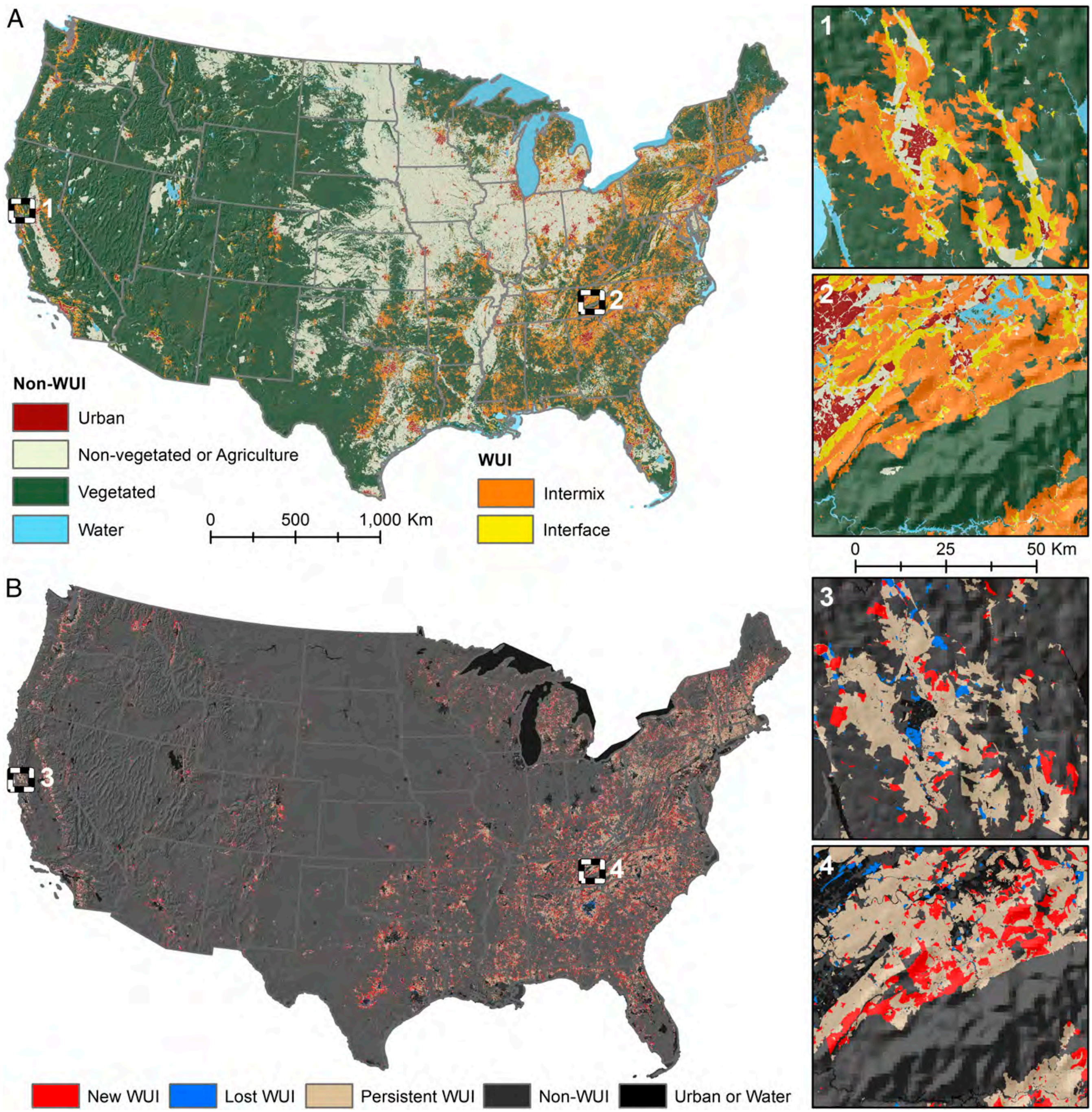

Fig. 1. The WUI in the United States was widespread in 2010 (*A*), as were changes in WUI area (*B*), for example, in and around Santa Rosa, California (1, 3), and Gatlinburg, Tennessee (2, 4), areas where wildfires destroyed many homes in 2017 and 2016, respectively.

The number of housing units ("houses" hereinafter) in the WUI grew fastest, followed by the number of people in the WUI and then WUI area (Fig. 2*B* and Table S1). New WUI area totaled 189,000 km^2, an area larger than Washington State. At 33%, WUI area growth is faster than that of any of the level I land cover categories included in the NLCD (28). Increases in houses and people were also strong, with 12.7 million more houses and 25 million more people in the WUI in 2010 compared with 1990. The overall combination of more WUI area (7.2% of the conterminous United States in 1990 vs. 9.5% in 2010; Fig. 2*C*) and higher growth rates for both houses and people in the WUI, compared with the nationwide averages (Table S1), increased the percentage of houses (from 30.3% to 33.2%) and people (from 29.4% to 31.9%) in the WUI from 1990 to 2010 (Fig. 2*C*). Even though the WUI occupies less than one tenth of the land area of the conterminous United States, 43% of all new houses were built there, and 61% of all new WUI homes were built in areas that were already in the WUI in 1990 (and remained in the WUI in 2010) (Tables S1 and S2).

There are two main types of WUI: intermix WUI, the area where houses and wildland vegetation directly intermingle, and interface WUI, where settled areas abut wildland vegetation (1). We found that intermix WUI was both more extensive and expanded much more rapidly in area (from 5.6% to 7.5% of the conterminous United States from 1990 to 2010) than interface WUI (from 1.6% to 2.0%). However, interface WUI had higher housing growth rates (43% from 1990 to 2010) than intermix WUI (38%) and non-WUI areas (23%; Table S1). In absolute numbers, there were 4.7 million more houses in the intermix WUI and 8.0 million more in the interface WUI in 2010 than in 1990.

Regional differences in WUI growth were striking (Fig. 3). The highest absolute gains in WUI area occurred in the East, whereas high gains in houses and people in the WUI were most common in the South and Southwest. Absolute gains are most

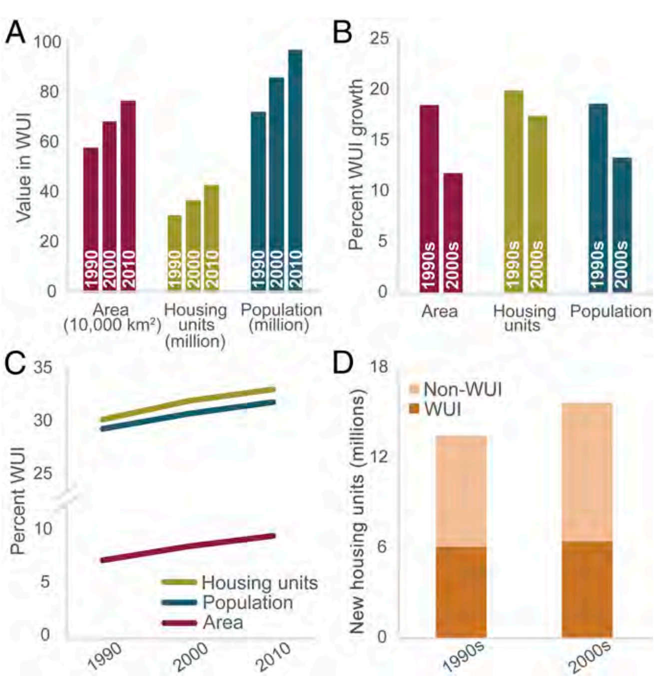

Fig. 2. WUI growth was rapid in terms of the absolute numbers of the area, houses, and people in the WUI in 1990, 2000, and 2010 (*A*); WUI growth rates during the 1990s and the 2000s (*B*); the proportion of all houses and people, as well as the land area in the WUI in 1990, 2000, and 2010 (*C*); and the absolute number of all new housing units within and outside the WUI during the 1990s and 2000s (*D*).

relevant for management agencies, because they indicate how much area and how many people and houses may require management actions; however, rapid growth often garners the most attention. Across the United States there is an interesting dichotomy in that states in the East had large absolute gains, but relatively low WUI growth rates, largely because WUI was already so widespread in 1990. In contrast, states in the northern Rockies saw much smaller absolute gains in WUI area and houses, but rapid WUI growth rates.

New WUI areas arise either when new houses are built in or near wildland vegetation or when wildland vegetation regrows in or near settled areas. Between these two possible causes, housing growth was unambiguously the main cause for new WUI areas, with increases in vegetation contributing minimally. Of all new WUI areas, 97% were caused by housing growth in sparsely settled areas, pushing these areas over the threshold of 1 house per 40 acres (6.17 homes/km^2). Only 2% of new WUI area was due to vegetation growth alone, and 1% was due to the combination of both housing and vegetation growth (Table S2). Similarly, new houses were the cause of >80% of WUI growth in all states except Delaware, the District of Columbia, Maryland, and New Jersey (Fig. S1).

Among areas that were WUI in 1990, the vast majority were still WUI in 2010, and both homes and population increased in those areas over that time (Table S2). A small proportion (6%) of the 1990 WUI areas dropped out of the WUI by 2010. Among all WUI changes (i.e., gains and losses combined), 13% of the changes in WUI area and 23% of the changes in WUI houses from 1990 to 2010 were losses. In terms of the causes of WUI area loss, reduced housing density was the most important (65.0%), whereas the loss of vegetation accounted for 32.6%. Housing density may have declined due to actual removal of housing units, or possibly due to enumeration errors in the Census data. Loss of vegetation was the dominant driver of loss of homes from the WUI (65.0%), which occurred largely in densely settled areas where additional housing development, deforestation, or fuel management may have removed wildland vegetation.

The number of houses within burned areas in the different decades is a strong indication of how much WUI growth can exacerbate wildfire problems. In 1990, there were 177,000 houses within the perimeters of the fires that occurred in the subsequent 25 y. By 2010, there were 286,000 housing units in the same fire perimeters, i.e., 109,000 more, which corresponds to 62% growth (far outpacing the average US housing growth rate of 29%). Of these new houses, those built before the wildfires occurred complicated firefighting because more houses had to be protected and more residents had to be evacuated. Similarly, houses built after fires occurred are of concern because new development in areas that burned recently, and thus are known to have a high fire risk, suggests that there is little adaptation to fire risk (2).

Our results provide compelling evidence that the WUI in the United States has grown rapidly, despite the risks that wildfires pose to homes and lives (3) and despite the other environmental problems caused by housing development in or near wildland vegetation (9). Our findings are generally in alignment with previous studies that found rapid previous WUI growth (24) and widespread potential for future WUI growth (25, 29), even though absolute numbers are not comparable because of differences in WUI definitions, datasets, and time periods (30). Furthermore, the WUI is not unique to the United States, but is widespread in many other countries as well (15, 16, 18–20). Rampant WUI growth demonstrates that the social and economic factors that together propel WUI growth are strong. WUI areas are attractive places to live because of affordability and ready access to natural settings and recreation (31). As WUI areas attract new residents, the number of houses per capita often increases as well, due to increasing rates of seasonal homeownership and declining family size (32). Indeed, despite the economic downturn after 2008, the absolute number of

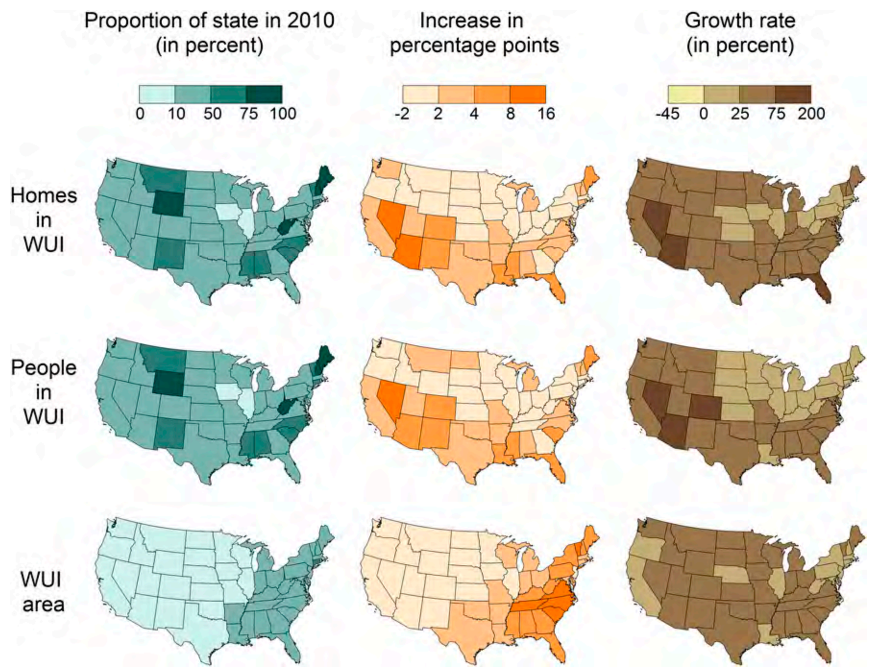

Fig. 3. WUI growth differed greatly among states, especially in the Southwest versus the Southeast, in terms of houses in the WUI, people in the WUI, and WUI area, calculated as the percentage of the state total in 2010, change in the WUI percentage from 1990 to 2010, and the growth rate (in percent) of the WUI from 1990 to 2010. Only the District of Columbia had negative absolute growth in the WUI (homes, people, and area). Fig. S2 summarizes these metrics at the county level.

houses built in the WUI, and in the United States as a whole, was higher between 2000 and 2010 than between 1990 and 2000 (Table S1). Demographic trends do not suggest slower future WUI growth. Furthermore, climate change projections indicate that conditions favorable for wildfires will occur more frequently in the future (8). Thus, increased wildfire ignition rates due to WUI expansion will initiate more wildfires in vegetation that is more susceptible to fire spread, leading to more widespread fires and possibly more severe fire behavior (33). This suggests that WUI growth and climate change together will compound the existing problems with wildfires in the WUI.

As WUI growth continues, there are many management options and policy tools to consider for addressing both wildfire and other environmental problems. Just as WUI-related problems involve actors (e.g., homeowners, community leaders) at many levels, so too must their solutions involve actors at multiple levels (i.e., local, regional, state, and national) (3, 8). Homeowners can reduce their individual fire risk by removing vegetation directly adjacent to their house (i.e., the home ignition zone; refs. 3 and 34), changing roofing and building materials, and following additional Firewise recommendations (35). To limit some of the other environmental problems associated with living in the WUI, homeowners can keep cats inside and dogs on a leash, limit fertilizer and pesticide use, and landscape with native plants (9). To reduce wildfire impacts, communities can coordinate fuel reduction efforts, educate homeowners, train firefighters, and establish wildfire management plans. Insurance companies can offer reduced premiums for communities taking mitigation action to incentivize community-level efforts to reduce wildfire losses. Communities and local jurisdictions could anticipate wildfires and environmental impacts more explicitly when planning future land use to avoid housing expansion in high-risk wildfire areas and other environmentally sensitive areas (36). State and federal agencies typically do not regulate development directly, but can allocate resources to areas experiencing rapid WUI growth, support local and regional planning efforts, and provide important research data and information to help communities adapt to fire-prone environments. Agencies managing public lands could consider targeted purchases of private inholdings to limit future housing growth within the administrative boundaries of public lands, which has been particularly rapid (37). In summary, there are many concrete management actions and policy responses that can limit the negative effects of WUI growth on wildfire risk and other environmental problems, but changes will require efforts at all levels by homeowners and community leaders, local and county governments, and state and federal agencies.

Housing development in the WUI greatly exacerbates wildfire problems and other environmental issues in the United States (1, 5, 8), and globally (16, 18–20). Our results highlight the magnitude and rapid rates of WUI growth in the US, underscoring the urgency of identifying what can be done to address WUI growth and its associated wildfire challenges (3). Past federal fire policy has focused largely on fighting and preventing wildfires and on fuel reduction, public outreach campaigns, and other actions (38). Although laudable, such efforts are unlikely to be successful by themselves, because housing growth is clearly the dominant cause of WUI growth, as well as a major factor contributing to wildfire occurrence and cost. As long as WUI growth is unchecked, wildfire problems will likely worsen. On a more hopeful note, to the extent that WUI growth reflects an affinity for nature, the evident consequences and costs of growth could prompt discussions on how to sustain those highly valued ecosystems in which so many people have chosen to live.

Materials and Methods

Our WUI definition is based on the definition published by the US government in the *Federal Register* (39) and that has been widely used for WUI assessments in the past (1, 14, 40). It specifies two types of WUI, intermix and interface. Intermix WUI is where houses and wildland vegetation intermingle, with both a housing density of >1 house per 40 acres (6.17 houses/km^2) and >50% of the area in wildland vegetation. Interface WUI represents settled areas that have <50% vegetation, but lie within

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1.5 miles (2.4 km) of a densely vegetated area (at least 75% wildland vegetation) that is at least 5 km^2 in size (so that settlements near small urban parks are not included in the WUI).

Our WUI assessment was based on two main datasets: US Census data, which provided housing data (TIGER shape files for block boundaries, plus Census summary files for attribute data), and the US Geologic Survey's NLCD, which provided information on wildland vegetation. We derived housing data from the US Decennial Censuses for 1990, 2000, and 2010 at its finest resolution, the census block level. However, a major obstacle to conducting change analyses is that census block boundaries frequently change from one decade to the next, preventing direct change analyses (27). Indeed, 62% of all blocks changed their boundaries from 1990 to 2000, and 56% changed from 2000 to 2010, invalidating any housing density change analysis that does not account for these boundary changes. We used additional information available from the US Census Bureau as relationship files that details for each decade which blocks of the starting date were at least partly contained by which block in the second decade, and vice versa, to calculate the number of 1990 and 2000 housing units for the boundaries for each 2010 census block.

Based on the Census Bureau relationship files, we first allocated 1990 housing units to 2000 block boundaries by identifying the type of relationship for each 1990 block to 2000 block(s), classifying the relationship as one-to-one, one-to-many, many-to-one, or many-to-many. For one-to-one and many-to-one relationships, 1990 housing units were allocated directly to corresponding 2000 blocks. For one-to-many relationships, 1990 housing units were allocated proportionally based on the number of housing units in the 2000 blocks. For many-to-many relationships, we identified the least common denominator of polygons that fully contained groups of both 1990 and 2000 blocks. For each least common denominator polygon, we then summed the 1990 housing units and allocated them based on the proportion of the 2000 housing units. To minimize instances of many-to-many relationships and maximize direct relationships, we removed blocks that were classified as water in 1990 and as vacant in 2000, as well as all 1990 and 2000 blocks that intersected by <1% of their area. Once 1990 housing units were allocated to 2000 census block geometry, we repeated the process using the 2000–2010 relationship files to allocate 2000 housing units to 2010 block boundaries. We then joined the 1990 housing units allocated to 2000 block boundaries with the 2000–2010 relationship files, and repeated the process to allocate 1990 housing units to 2010 block boundaries. The end result of our algorithms are 1990 and 2000 housing units allocated to the 2010 block geometry across the conterminous United States, i.e., a dataset that permits valid analyses of housing growth across the United States at fine spatial resolution and that minimizes erroneous changes due to changing census block boundaries.

We further refined census block boundaries by integrating them with information on the boundaries of protected areas. The boundaries of protected areas were provided by the Protected Area Database, version 2. Where protected areas intersected census block boundaries, we assumed that the houses in that block were located in nonprotected areas only. However, where census blocks with houses were entirely within a protected area, we made no changes, and assumed a uniform housing density throughout the block.

The 30-m resolution NLCD provided us with data on wildland vegetation. We analyzed both the 1992/93–2001 and the 2001–2011 land cover change products and calculated the percentage of each NLCD land cover class within each census block after refinement by the protected area boundaries. We included forest and grass/shrub land cover classes as wildland vegetation and excluded open water, urban, barren, wetlands, and ice/snow.

For each decade, we mapped the WUI separately, by combining 1990 Census data with 1992/93 data from the 1992/93–2001 land cover change product, and 2000 and 2010 Census data with 2001 and 2011 data from the 2001–2011 land cover change product. We first identified all intermix WUI areas based on the housing and vegetation thresholds. We then identified contiguous vegetation areas that were at least 5 km^2 in size and had >75% wildland vegetation, selecting areas within 2.4 km that were above the housing threshold (but below the 50% vegetation threshold), and labeling these as interface WUI. When census blocks were only partly within this distance, we split them.

The NLCD change products are not fully consistent, in that the 2001 land cover in the 1992/93–2001 change product differs from the 2001 land cover in the 2001–2011 change product. Thus, we conducted a sensitivity analysis and mapped the 2001 WUI twice, based on the two representations, and then compared the resulting WUI maps. The differences between the two WUI maps were very minor.

To calculate the number of homes within fire perimeters over time, we analyzed all fire perimeters of fires that burned between 1990 and 2015 according to the Monitoring Trends in Burn Severity (MTBS) dataset, which includes all fires >404 ha (1,000 ac) in the West and 202 ha (500 ac) in the East. We then assessed which census blocks were at least partially within these fire perimeters and calculated an area-weighted estimate of the number of housing units within the fire perimeters in 1990 (177,000), 2000 (210,000), and 2010 (286,000). We note that this is a conservative estimate of the number of houses affected by wildfires because the MTBS dataset does not include small fires.

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Multiple-Scale Relationships between Vegetation, the Wildland–Urban Interface, and Structure Loss to Wildfire in California

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Abstract: Recent increases in destructive wildfires are driving a need for empirical research documenting factors that contribute to structure loss. Existing studies show that fire risk is complex and varies geographically, and the role of vegetation has been especially difficult to quantify. Here, we evaluated the relative importance of vegetation cover at local (measured through the Normalized Difference Vegetation Index) and landscape (as measured through the Wildland–Urban Interface) scales in explaining structure loss from 2013 to 2018 in California—statewide and divided across three regions. Generally, the pattern of housing relative to vegetation better explained structure loss than local-scale vegetation amount, but the results varied regionally. This is likely because exposure to fire is a necessary first condition for structure survival, and sensitivity is only relevant once the fire reaches there. The relative importance of other factors such as long-term climatic variability, distance to powerlines, and elevation also varied among regions. These suggest that effective fire risk reduction strategies may need to account for multiple factors at multiple scales. The geographical variability in results also reinforces the notion that "one size does not fit all". Local-scale empirical research on specific vegetation characteristics relative to structure loss is needed to inform the most effective customized plan.

Keywords: fire risk; intermix; interface; vegetation pattern; scale; fire; fuel; housing density; land use; land cover; defensible space

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1. Introduction

In the last three out of four years, California has experienced record-setting wildfires that have cumulatively added up to more than 50,000 structures destroyed. Although California is arguably a worldwide leader in these types of catastrophic events, large-scale human impacts from wildfires are also occurring more frequently in fire-prone ecosystems across the world [1–3] with the 2019–2020 bushfire season in Australia being of notable impact. As losses accrue, the urgency of understanding the factors influencing structure loss is growing. Hence, scientific study of structure loss in wildfire—and why it occurs—is starting to mature. One of the most important overall conclusions resulting from this research is that structure loss is a complex function of multiple interacting factors that vary geographically [4–6], and that much more work is needed to parse out the relative importance of different factors at different scales.

One of the factors that has been difficult to quantify empirically is the role of vegetation surrounding structures and in surrounding landscapes. Defensible space—the reduction of woody vegetation within a buffer surrounding the structure—is widely advocated for its potential to minimize structure loss. Although few studies have been conducted to evaluate its role empirically, its beneficial effects on reducing fire risk have been demonstrated via simulation or theoretical modeling studies, field experiments, and case studies of individual fire events [7–11].

Two empirical studies in Southern California found a significant benefit of the State-mandated 100′ defensible space guideline in reducing house losses [12,13]. In both studies, the most significant effect was observed for vegetation reduction approximately 5–20 m from a structure, after which the protective effect of fuel treatments farther away was not evident. A remote sensing study in Colorado and an analysis of structures lost in 27 fires in Australia also found the most protective benefit of reduced vegetation was in the area immediately surrounding structures [14,15]. In a coarser-scale analysis in Australia, defensible space closest to the structure (i.e., within the first 40 m) was significantly more important than vegetation cover at farther distances [16]. However, vegetation arrangement and fuel moisture could provide the same protective benefit as removing trees and shrubs 40 m around the structure [17].

Although these modeling and empirical studies collectively suggest that reducing vegetation cover close to the structure can minimize the potential for structure loss, broad conclusions remain difficult to assess because the studies were conducted at different scales of analysis using different measurements and were restricted to the unique geographies of the study regions. In addition, the relative importance of defensible space compared to other factors remains unclear, although some studies suggest its relative importance varies based on location, housing pattern, structural characteristics, and scale [11,12,18].

In a statewide and regional-scale analysis using building inspectors' data, Syphard and Keeley [18] found evidence to suggest that structural characteristics were more significantly associated with structure survival than defensible space. In that work, however, defensible space distance may have been unreliably assessed because of the uncertainty in quantifying vegetation in a post fire environment. It is also possible that both surviving and destroyed homes had the same amount of defensible space, so it did not come out as a significant factor. In Southern California, Syphard et al. [12] found that housing arrangement and pattern were more influential than defensible space for explaining structure loss. This result is consistent with other studies that have more broadly revealed housing pattern and topographic variables to be more influential in explaining structure loss than vegetation amount and configuration [6,19] or other proxies for vegetation [4].

An important consideration when examining the factors associated with structure loss in wildfires is that vulnerability to a hazard is a combination of both exposure and sensitivity to the hazard [20]. Exposure means that the geographical location of an asset at risk (e.g., housing pattern and location) can predict its chance of encountering a hazard to begin with; and sensitivity means that, once the hazard is present, the potential for damage is related to local-scale, intrinsic characteristics (e.g., defensible space and structural characteristics). Given that most structures are lost to either direct ember attack, or to the ignition of surrounding elements from ember attack [21], both defensible space and structural characteristics minimize sensitivity by either preventing ember entry to the structure or reducing the flammability of whatever an ember lands upon. Thus, risk of structure loss to wildfires operates at different scales and the role of vegetation may also operate at different scales.

One of the most widely recognized indicators of exposure to wildfire is the wildland–urban interface (WUI [22,23]), which is where human communities are close to natural wildlands. Recent work has confirmed expectations that structure loss is significantly higher in the WUI than in non-WUI areas [24,25]. Although the definition and spatial delineation of the WUI varies widely [26], and may even explicitly account for wildfire probability [27], the most widely used definition and mapping rules are based on the US Federal Register, with two distinct types of WUI defined along with other map classes for varying degrees of development density and vegetation [22,23]. The difference between the two WUI types is the relative housing density and percentage cover of wildland vegetation.

The relationship between the WUI and structure loss is an example of how vegetation can influence fire risk at multiple scales. At a landscape scale, vegetation reflects exposure to the hazard. Wildfire behavior is obviously a function of vegetation amount and configuration, which in turn mediates the potential for wildfire to reach a structure. At the local scale, vegetation plays a role in the structures' sensitivity to the hazard, with different features of the vegetation becoming more important than others.

In this study, we evaluate the relative importance of vegetation cover at local and landscape scales in explaining structure loss from 2013 to 2018 in California—statewide and separately for three of the most fire-prone regions. We compared vegetation metrics along with several human and biophysical variables associated with structure loss at the locations of destroyed and unburned structures within fire perimeters to assess their relative role.

We ask:

(1) Is vegetation cover substantially greater at locations of destroyed structures than unburned structures? Does this effect vary by region or distance?
(2) What is the relative importance of vegetation calculated at local and landscape scales in relation to other factors previously associated with structure loss?
(3) Does structure loss vary across different classes of the wildland–urban interface?
(4) Do these relationships vary by geographical region within California?

2. Materials and Methods

2.1. Structure Locations and Study Regions

We acquired the locations of destroyed structures via a public records request to Cal Fire, and divided them into three regions as in Syphard and Keeley [18] (Figure 1). These included the central and northern coast areas surrounding San Francisco Bay ("Bay Area"), the regions surrounding the northern cismontane Sierra Nevada ("North Interior"), and the region comprising coastal counties south of San Luis Obispo ("Southern California"). To derive data for unburned structures, we placed a point within the centroid of building polygons that overlaid fire perimeters using the open-access Microsoft Building Footprint dataset (https://www.microsoft.com/en-us/maps/building-footprints). For fire perimeters, we used the State of California Fire and Resource Assessment Program (FRAP) fire perimeter data from 2013 to 2018 (https://frap.fire.ca.gov/frap-projects/fire-perimeters/). After combining the unburned points with locations of destroyed structures within fires, we took a random sample of the data with a minimum of 500-m distance between points to reduce potential for statistical bias due to overlapping buffers.

2.2. Variables

To measure defensible space in previous studies, researchers have used fine-scale aerial photography to calculate the range of metrics that collectively define the legal definition of defensible space in California [12,13]. Calculating these types of measurements for large numbers across broad scales, however, would be prohibitively time-consuming. Alternatively, remotely sensed satellite imagery can provide unbiased calculations of vegetation biomass that was present before the fire (e.g., [14,16,28]). Here, we calculated the mean annual maximum Normalized Difference Vegetation Index (NDVI) values within three concentric circles around structures, averaged for the two years prior to the fire. Using the annual maximum NDVI and averaging across the two years prior to fire minimized potential uncertainties relative to fine-scale temporal fluctuation from weather variables [29]. We used NDVI data calculated from Landsat remote sensing products, at 30 m spatial resolution, provided by climateengine.org/data. To evaluate whether the distance of measurement differentially influences structure loss, we compared NDVI values from concentric circles surrounding the structure at three distances—30, 90, and 300 m (Table 1). We included all cells overlapping the concentric circles in our calculation of mean NDVI. Due to the resolution of the satellite data, we did not calculate distances shorter than 30 m.

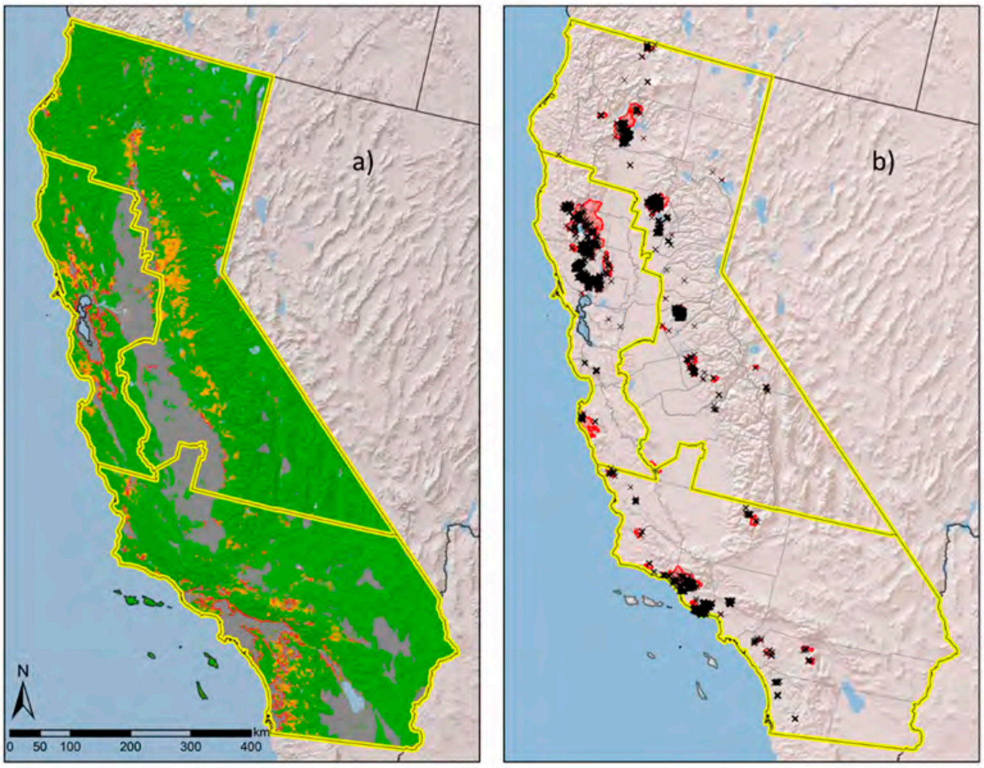

Figure 1. Study area illustrating three California regions: the Bay Area (northwest), the North Interior (northeast), and Southern California (south). The WUI classes in (**a**) depict Interface WUI (red), Intermix WUI (orange), Unvegetated (gray), and Low-density vegetated (green). The fires included in the study (red perimeters) and location of destroyed structures (black) are shown in (**b**). Hillshade basemap from ArcGIS Online (https://www.arcgis.com/index.html).

2.2. *Variables*

To represent landscape-level vegetation pattern, we used a landscape pattern metric to calculate the proportion of highly flammable vegetation within a circular moving window at a 2.5 km radius (the approximate distance the wind may carry an ember [8]) around all structures (as in Alexandre et al. [19]), using Fragstats v4.2.1 [30]. For this variable, we used the U.S. Geological Survey National Land Database (NLCD, mrlc.gov) from 2016 to create a binary class of flammable versus non-flammable vegetation, grouping together grass, shrubs, and trees into flammable vegetation.

The variable that represents the landscape-level pattern of houses and vegetation together is the WUI. For each structure, we used the 2010 WUI map created by Radeloff et al. [23] to extract the corresponding WUI class in which it was located. Intermix WUI is defined as areas in census blocks that have ≥6.18 houses per km^2 and ≥50 percent cover of wildland vegetation. Interface WUI is defined as areas with ≥6.18 houses per km^2 with large areas (at least 5 km^2) of at least 75% vegetation within 2.4 km. In addition to Intermix and Interface WUI, we grouped unvegetated classes together (including inhabited and uninhabited areas at different housing densities) and areas that were vegetated, either uninhabited or inhabited, but with housing density lower than 6.18 structures km^2.

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Table 1. Name and description of explanatory variables used to explain structure loss in California.

	Variable Name	*Definition*	*Source*	*Resolution*
Climate	Actual evapotranspiration (AET)	Average AET (Water available between wilting point and field capacity; mm), 1981–2020	Flint and Flint [31]	270 m
	MaxTemp	Average Maximum Monthly Temperature (deg. C), Annual, 1981–2010	Flint and Flint [31]	270 m
Topography	Elevation	Elevation (m)	U.S. Geological Survey	30 m
	Topographic heterogeneity	The range in elevation values from a center cell and the three-cell radius immediately surrounding it using a digital elevation model. Values were converted to a 0–1 scale using the standard deviation.	NatureServe (https://databasin.org)	90 m
Human	Dist_powerline	Euclidean distance from electric transmission lines (status = operational AND type = OH; m)	California Energy Commission	30 m
	Dist_rd	Euclidean distance from roads (excluding 4WD and OHV; m)	TIGER/Line 2016 (www.census.gov)	30 m
Vegetation				
	NDVI_30	Mean NDVI max averaged for 1 and 2 years before fire across 30 m buffer around structure	Climate Engine (http://climateengine.org/)	30 m
	NDVI_90	Mean NDVI max averaged for 1 and 2 years before fire across 90 m buffer around structure	Climate Engine (http://climateengine.org/)	30 m
	NDVI_300	Mean NDVI max averaged for 1 and 2 years before fire across 300 m buffer around structure	Climate Engine (http://climateengine.org/)	30 m
	Flammable veg in 2.5 km	Proportion highly flammable vegetation (grass, trees, and shrubs) across circular moving window with 2.5 km radius	NLCD 2016 Land Cover www.mrlc.gov	30 m
Vegetation and human	WUI Class	Intermix, Interface, Unvegetated; Low-density vegetated	Radeloff et al. [23]	Polygon converted to 30 m grid

In addition to the vegetation-related variables, we explored other biophysical and human factors as potential predictors (Table 1). Given their demonstrated overall relationship with the spatial distribution of fire probability [4,32–34], we considered two long-term climate variables—average maximum monthly temperature from 1981 to 2010 and average actual evapotranspiration (AET), a measure of the water available between wilting point and field capacity (mm), 1981–2010. We also included two topographic variables, which mediate fire behavior and vegetation properties: elevation and topographic heterogeneity. The elevation grid was provided by LANDFIRE (landfire.gov/elevation.php) at 30 m resolution and the topographic heterogeneity index was calculated from a 90 m digital elevation model (DEM) to capture surrounding diversity in terrain (https://databasin.org/datasets/1f86100938b544a3b6361eee6ac05945/). Finally, we included two anthropogenic variables to assess their relative influence on structure loss. These included distance to roads, which can serve as a proxy for firefighter access, derived using the 2015 TIGER Roads data, U.S. Dept. of Commerce, U.S. Census Bureau (www.census.gov), and distance from electric transmission line, with data provided by the California Energy Commission, Electric Transmission Lines (https://cecgis-caenergy.opendata.arcgis.com/datasets/260b4513acdb4a3a8e4d64e69fc84fee_0). We also included distance to powerline because several of the recent destructive fires were ignited by powerlines. As the building characteristics provided by Cal Fire for destroyed structures were not available for the unburned homes within the fire perimeter, we did not incorporate these into our analysis, as these numbers are available in Syphard and Keeley [18].

2.3. Analysis

Statewide and for the three regions, we summarized and compared the average NDVI within the buffer distances around destroyed and unburned structures. Although we used the spatially filtered data to ensure more robust statistical analysis, we assembled these summary statistics for the full dataset to reflect the full population. We additionally summarized all point data for destroyed and unburned structures according to their WUI classification.

To quantify the relative importance of the explanatory variables, we developed generalized linear regression models (GLMs) [35] for single predictor variables using a logit link and a binomial response, i.e., destroyed versus unburned structures, as in Syphard and Keeley [18]. We then calculated the deviance explained (D^2) for each variable, a comparable metric to R-squared in linear regression. Given that the WUI data were presented in different classes, we also calculated the relative risk (RR) [36] among all class pairs to determine if there were significant differences in risk and to identify which classes were most strongly associated with destroyed structures. The RR is based on the ratio of pairwise class proportions (i.e., destroyed versus unburned structures in each WUI class) and identifies whether classes have the same risk (a value of 1), or if one class has a higher (values > 1) or lower (values < 1) risk compared to another.

We developed statewide and regional multivariate classification trees using the RPART package (https://cran.r-project.org/web/packages/rpart/rpart.pdf) in RStudio version 1.1463 (rstudio.com) to assess the relative importance of variables in terms of how well they split the data between destroyed and unburned structures. Classification trees are also useful for illustrating variable effects and interactions in a multi-variate environment [37]. Given the large number of potential predictor variables, we only performed this analysis statewide to ensure sufficient sample size. There was a strong correlation ($r > 0.7$) between the NDVI measurements in different buffer sizes, so we only evaluated NDVI at the 30 m buffer distance, as that was the measurement with the largest difference between destroyed and unburned structures. Additionally, elevation was correlated with mean annual temperature ($r = -0.8$), so we removed that variable because temperature is a more direct measurement of the spatial distribution of climatic variability. There were no other high correlations among explanatory variables. Thus, the variables that we included in the tree were: NDVI, topographic heterogeneity, distance to roads, distance to powerlines, WUI class, mean annual maximum temperature, mean actual evapotranspiration, and vegetation within 2.5 km. We pruned the trees using the complexity parameter that best minimized overfitting with the smallest cross-validated error and calculated model performance of the training data using the area under the curve (AUC) for receiver operating characteristic plots (ROC) [38].

3. Results

The comparison of destroyed versus unburned structures did not reveal a strong influence of surrounding vegetation as measured through NDVI statewide or in the Bay Area (Figures 2 and 3). There, and in Southern CA where the differences were larger, the NDVI was greater for destroyed structures than unburned structures at all three buffer distances. However, the differences among buffer distances were minimal, with a larger separation of destroyed and unburned structures at 30 m than the other two distances. In the North Interior region, the relationship was inverse in that there was greater NDVI in unburned than destroyed structures at all three buffer distances (Figure 2).

The ranking of the deviance explained for surrounding vegetation compared to other explanatory variables was low statewide and in all regions except for Southern CA, where the deviance explained for NDVI in the 30-m buffer was the top-ranking explanatory variable (Figure 3). In all cases, the amount of vegetation within 30 m was relatively more important than that in 90 or 300 m. The broader metric of vegetation, at 2.5 km, explained more than NDVI statewide and in the North Interior.

Vegetation pattern combined with housing pattern—as measured through the WUI—was consistently more important than the other vegetation-related variables, and it was one of the top two ranking variables for all analyses in all regions (Figure 3). The ranking of the non-vegetation variables varied from region to region, although elevation was one of the top two variables along with WUI class statewide (Figure 3). Otherwise, distance to powerline was one of the top two variables in the Bay Area, maximum average temperature

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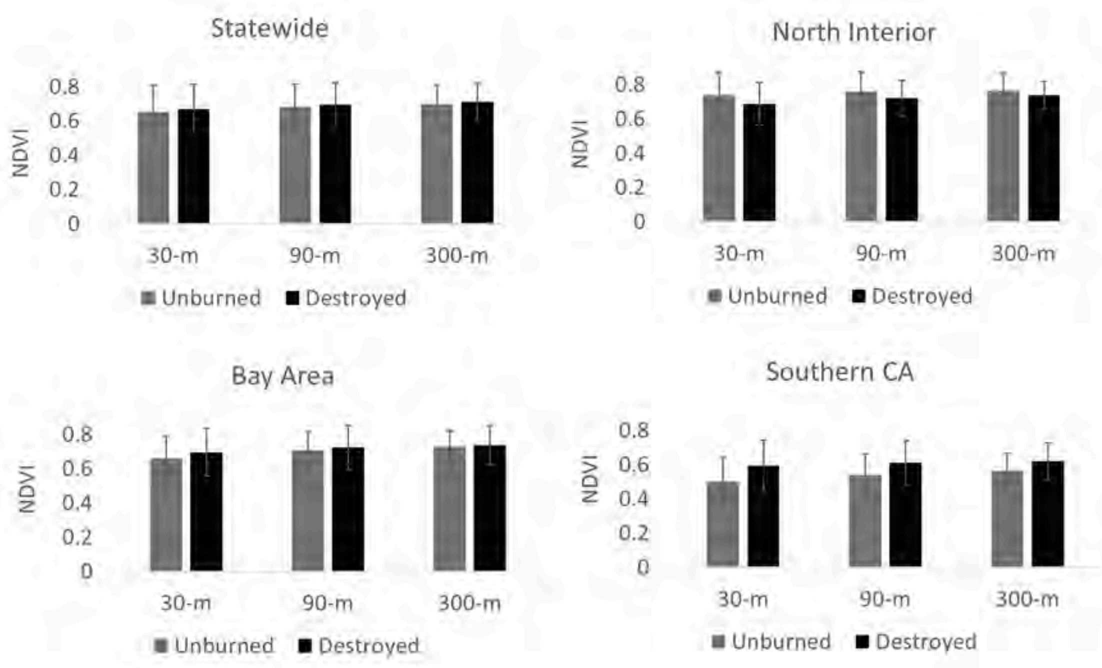

Figure 2. Mean NDVI in unburned and destroyed structures in wildfire perimeters statewide and in three regions of California. Error bars depict the standard deviation.

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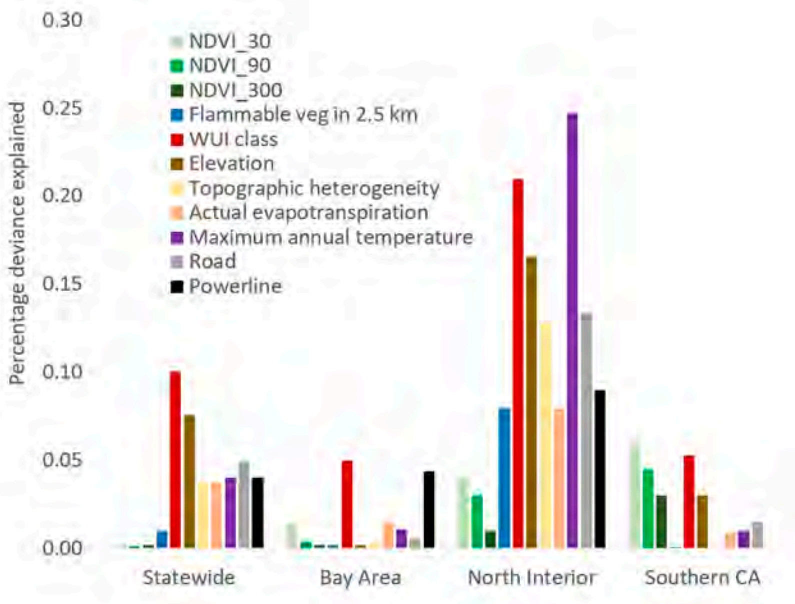

Figure 3. Percentage deviance explained for unburned versus destroyed structures in binomial regression models statewide and for three regions in California. The numbers following "NDVI" represent the buffer distance surrounding structures for which the Normalized Difference Vegetation Index (NDVI) was calculated.

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Of the four WUI classes evaluated, the Intermix WUI and Low-density vegetated classes were the most common for all structures in the analysis (Figure 4). Most of the unburned structures were distributed in the Low-density vegetated class while most of the destroyed structures were distributed within the Intermix WUI class. The RR assessment within different WUI classes showed that the Intermix WUI had disproportionately larger

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Of the four WUI classes evaluated, the Intermix WUI and Low-density vegetated

numbers of destroyed structures than the three other classes statewide (RR = 1.15–2.5) and in all three regions (RR = 1.14–1.95), except for the Bay Area (RR = 0.93) and the North Interior (RR = 0.89) study areas where there were disproportionately fewer destroyed structures in the Intermix versus the Interface WUI classes (Table 2). Although all comparisons at the statewide scale were significant, the Intermix versus Interface comparisons were not significant for the three regions separately or for the Intermix versus Unvegetated class in the Bay Area. Among other classes, Interface WUI generally had disproportionately more destroyed structures than the two non-WUI classes, unvegetated and low-density vegetated (RR = 1.29–4.64). The vegetated class had consistently lower RR than the unvegetated class (RR = 0.5–0.79).

Intermix vs. Unvegetated	1.15	<0.001	1.17	0.31	1.17	0.01	1.55	0.009
Intermix vs. Low-density vegetated	2.25	<0.001	1.66	<0.001	4.14	<0.001	1.95	<0.001
Interface vs. Unvegetated	0.96	0.004	1.29	0.19	2.34	0.006	1.34	0.11
Interface vs. Low-density vegetated	1.85	<0.001	1.78	<0.001	4.64	<0.001	1.7	<0.001
Vegetated vs. Unvegetated	0.51	<0.001	0.71	0.03	0.5	0.02	0.79	0.177

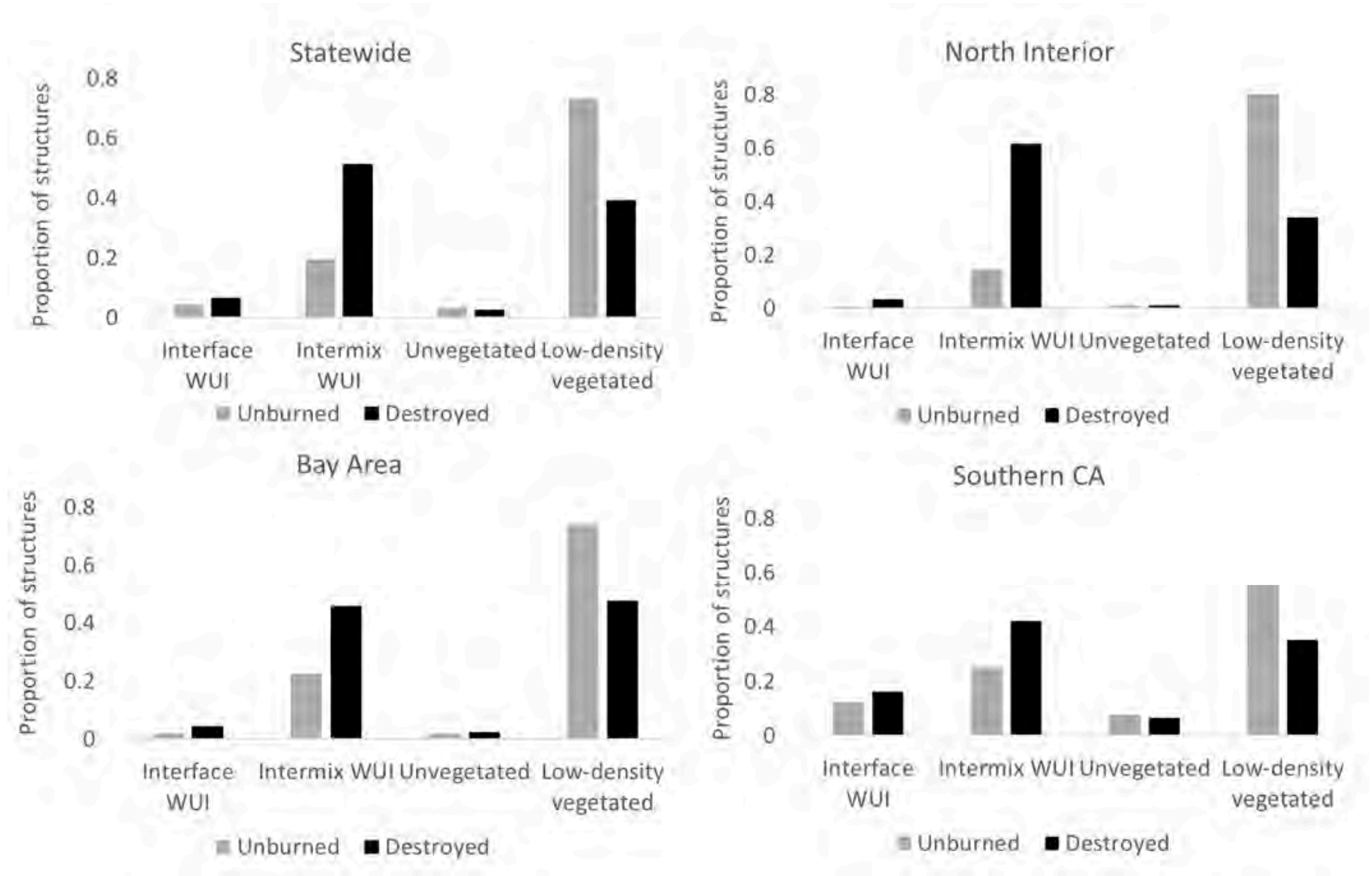

Figure 4. Proportion of unburned and destroyed structures distributed among four Wildland–Urban Interface cover classes statewide and in three regions of California.

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Table 2. Relative risk (RR) among WUI classes statewide and for three California regions. In the class comparisons, an RR > 1 means the first class listed had disproportionately more destroyed than unburned structures, < 1 means the first class listed had disproportionately fewer destroyed than unburned structures, and 1 means no difference between the two classes.

	Statewide	*p-Value*	*Bay Area*	*p-Value*	*North Interior*	*p-Value*	*Southern CA*	*p-Value*
Intermix vs. Interface	1.22	<0.001	0.93	0.4	0.89	0.25	1.14	0.2
Intermix vs. Unvegetated	1.15	<0.001	1.17	0.31	1.17	0.01	1.55	0.009
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The classification trees showed that statewide, the WUI was the most influential factor separating destroyed from unburned structures (Figure 5), and in this case, the two WUI types, Intermix and Interface, were two types associated with destroyed versus unburned structures. The second split in the data was NDVI within a 30-m buffer, with destroyed structures tending to occur above a threshold of 0.49. The last variable selected in the tree was mean annual maximum temperature, with destroyed structures tending to occur in areas that average between 20 and 23 degrees Celsius. The AUC for this tree was 0.68.

The separate classification trees for each region showed variability in the factors that best separated the destroyed from unburned structures (Figure 5). In all cases except Southern CA, landscape-scale factors related to spatial distribution and exposure were responsible for the first split in the data, and WUI was the second split in the data followed by other variables. For the North Interior region, the first split was maximum average temperature, followed by WUI class—again with Interface and Intermix separating destroyed from unburned structures, and mean actual evapotranspiration. The training AUC for the tree in this region was 0.84. In the Bay Area, the first split was distance to powerline followed by WUI class in which Interface, Intermix, and Unvegetated were grouped together as those best separating destroyed from unburned structures. Depending on which WUI class the structure belonged, the final splits were for mean annual maximum temperature and distance to road or NDVI. The AUC for the Bay Area tree was 0.70. In Southern California, the first split in the data was the amount of vegetation within 30 m of the structure, with an NDVI of >= 0.49 being the threshold. In this region, the WUI was the second most important split, followed by distance to powerline and mean annual evapotranspiration, again with Unvegetated combined with Intermix and Interface defining the split in data. The AUC for this tree was 0.69.

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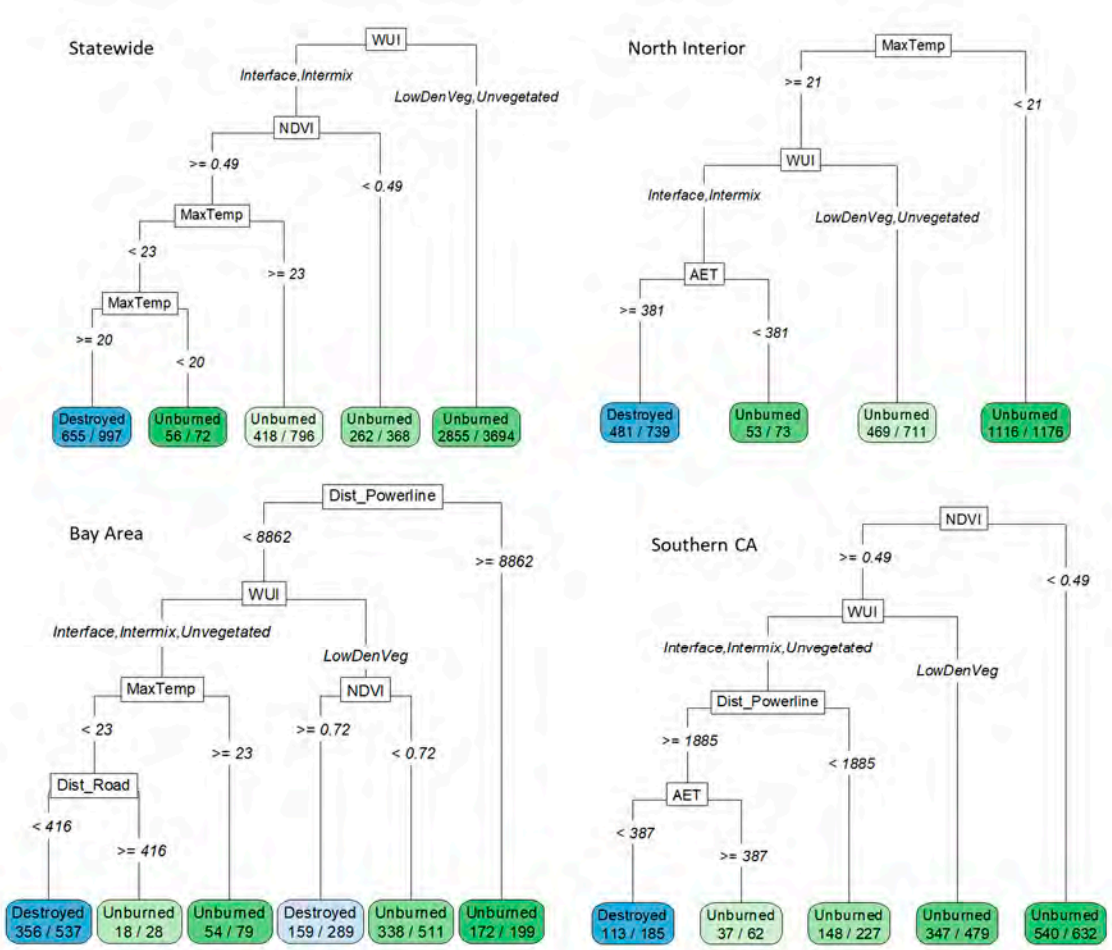

Figure 5. Classification trees illustrating variables explaining unburned versus destroyed structures statewide and for three California regions. The NDVI variable is for 30 m distance around structures (90 and 300 m not included). The intensity of the blue and green node colors is proportional to the percentage of observations. For variable explanations, refer to Table 1.

Figure 5. Classification trees illustrating variables explaining unburned versus destroyed structures statewide and for three California regions. The NDVI variable is for 30 m distance around structures (90 and 300 m not included). The intensity of the blue and green node colors is proportional to the percentage of observations. For variable explanations, refer to Table 1.

The separate classification trees for each region showed variability in the factors that best separated the destroyed from unburned structures (Figure 5). In all cases except Southern CA, landscape-scale factors related to spatial distribution and exposure were responsible for the first split in the data, and WUI was the second split in the data, followed by other variables. For the North Interior region, the first split was maximum average temperature, followed by WUI class—again with Interface and Intermix separating destroyed from unburned structures, and mean actual evapotranspiration. The training AUC for the tree in this region was 0.84. In the Bay Area, the first split was distance to powerline followed by WUI class in which Interface, Intermix, and Unvegetated were grouped together as those best separating destroyed from unburned structures. Depending on which WUI class the structure belonged, the final splits were for mean annual maximum temperature and distance to road or NDVI. The AUC for the Bay Area tree was 0.70. In Southern California, the first split in the data was the amount of vegetation within 30 m of the structure, with an NDVI of >= 0.49 being the threshold. In this region, the WUI was the second most

4. Discussion

Vegetation is the primary means by which wildfire propagates; is something that can be managed; and thus, is often considered key among strategies to reduce wildfire risk. Yet, the relationship between vegetation and structure loss is complex, and this study underlines the fact that vegetation has different relationships with fire risk at different scales, representing different operative mechanisms. These relationships also vary in relative effect depending upon geographical region. Overall, landscape-level vegetation and housing pattern provided better separability of unburned and destroyed structures across the state than local-scale vegetation amount. None of the variables analyzed, however, had deviance explained higher than 25%, which reaffirms the notion that structure loss is a important split, followed by distance to powerline and mean annual evapotranspiration, again with Unvegetated combined with Intermix and Interface defining the split in data. The AUC for this tree was 0.69.

4. Discussion

Vegetation is the primary means by which wildfire propagates; is something that can be managed; and thus, is often considered key among strategies to reduce wildfire risk. Yet, the relationship between vegetation and structure loss is complex, and this study underlines the fact that vegetation has different relationships with fire risk at different scales, representing different operative mechanisms. These relationships also vary in relative effect depending upon geographical region. Overall, landscape-level vegetation and housing pattern provided better separability of unburned and destroyed structures across the state than local-scale vegetation amount. None of the variables analyzed, however, had deviance explained higher than 25%, which reaffirms the notion that structure loss is a function of multiple factors interacting simultaneously, including factors not explored here.

Although multiple definitions of the WUI have been proposed and incorporated into policy, even explicitly accounting for fire risk [27], the underlying conceptual premise for most definitions that focus on fire is that risk and ignitions are likely to be higher where houses meet or intermingle with vegetation [23,39–42]. Thus, the two conditions that must be present are vegetation and housing, with different classes of WUI defined based on variations in housing density and vegetation cover.

In previous studies examining structure loss probability, housing location and pattern have consistently been found to be top-ranked among a wide range of explanatory variables [4,6,19,43]. Although the specific structural pattern and housing density where risk is highest vary geographically [4,6,19], lower-density housing at a landscape scale has been the most consistent housing pattern with the highest risk. The reason for the strong significance of housing variables, particularly ones that reflect dispersed or low-density housing, is that they represent high exposure to wildfire, which is the first condition that must be met for structure loss to occur [5,20]. If a fire does not reach a structure, the other factors become irrelevant.

A primary reason explaining why low- to intermediate-density housing is so strongly tied to fire risk is because these are the houses most likely to be adjacent to flammable wildland vegetation—and this is what creates the exposure. This is also the reason that the WUI as defined here is so strongly associated with fire risk [23]—because it is a measurement that combines housing with adjacency and distance to wildland vegetation [44]. The WUI definition incorporates a measurement of vegetation out to 2.4 km, and this variable was more influential than our measurement of vegetation to 2.5 km, which suggests it is the specific pattern of houses and vegetation that matter most—more than vegetation by itself.

In this study, the largest proportion of destroyed structures was in the Intermix WUI class, followed by the non-WUI, low-density, vegetated class. Intermix also had the highest RR compared to Interface and non-WUI classes statewide. Regionally, however, the relative ranking between Intermix and Interface varied, and the differences were non-significant. Both Intermix and Interface WUI had higher RRs than the other two non-WUI classes across all regions.

This finding, that WUI classes have disproportionately higher fire risk than non-WUI classes, and that relationships vary by region and scale, has been observed in other empirical studies. Kramer et al. [24] found that, across the United States, the majority of destroyed and threatened structures were within areas designated as WUI, but a large proportion of destroyed structures were also in non-WUI areas with housing density that was too low to meet the definition of WUI defined here. Ciggiano et al. [44] also found that most buildings lost in recent fires across the US from 2000 to 2018 were within WUI-designated areas. Furthermore, all destroyed structures in their study were close to wildland vegetation (from 100 to 850 m), and more burned buildings were in the Intermix rather than the Interface. On the other hand, Kramer et al. [25] found that from 1985 to 2013 in California, more structures were destroyed in Interface rather than Intermix WUI; that is, in areas with less wildland vegetation. This empirical research on WUI types is generally consistent with the finding that low-intermediate housing density is where most structures are destroyed [4,43]; but clearly there are regional, and perhaps temporal, differences in the relative importance of the predominant type of WUI.

The geographical differences in the relative housing density or type of WUI where structure loss is most likely to occur likely reflects the influence of other factors that combine to contribute to structure loss probability, and the fact that fires tend to be idiosyncratic. For example, in several recent California fires, the role of winds and structural characteristics of buildings were clearly dominant factors. While the average structure density where structures were lost fires was low, there were also portions of the fires evaluated here in which significant structure-to-structure spread occurred throughout high-density housing. High housing density that facilitates structure-to-structure spread has been observed in other fires with large numbers of destroyed buildings [10,45], in part because certain structural features and surrounding materials can facilitate fire spread [46].

The difference between a structure surviving and being destroyed could also be due to factors that have yet to be quantified, such as firefighter presence or serendipitous factors such as a sudden shift in wind velocity or direction. The scale of measurement can also affect the relative importance of different housing and vegetation patterns [11]. Different regions have different baseline housing densities with unique arrangements of housing interspersed with vegetation. Empirical studies have also been conducted at different spatial scales, where the average housing density may vary with the overall range and variation of the structures in the sample.

Comparison of destroyed with unburned structures may also yield different results depending upon whether the unburned structures are within fire perimeters as they are in this study. That is, if housing density and the WUI are indices of exposure to fire, houses in the perimeter are already biased in that they have been exposed. This is likely why the second most common WUI class in this study was non-WUI low-density vegetated housing.

This study also shows that structure exposure to wildfire can be a function of other sources of spatial variation across a landscape. Depending upon the region, factors such as elevation, climatic variation as measured by maximum annual temperature, and distance to powerline were similar in variable importance to WUI class. These factors illustrate how parts of some landscapes are more fire-prone than others, and that structure loss tends to occur in the most fire-prone facets of a landscape. For example, the importance of temperature in the North Interior likely reflects how climatic variation is a strong driver of fire activity in this region of California [47], and structures were destroyed more often in areas with hotter temperatures. Given that the most destructive fires in the Bay Area were caused by powerline ignitions, spatial proximity to powerline was a strong separator of unburned and destroyed structures in that region. In Southern CA, distance to powerline was one of the lower-ranking variables included in the classification tree, and the direction of the relationship was counter-intuitive. This may reflect the lower number of destructive powerline-ignited fires during the study period here; it may also reveal an interaction with the higher-ranking variables in the tree, suggesting powerline proximity is serving as a proxy for something else. As the definition of WUI used here is a function of housing and vegetation alone, other approaches that additionally account for variation in fire risk [27] or that are scaled for specific geographies [44] may be even more useful for planning purposes.

The one region in which local-scale vegetation amount explained structure loss better than landscape-scale vegetation pattern (i.e., the WUI) was Southern CA. The classification tree showed that NDVI at 30 m was the first split in the classification tree, followed by the WUI. This result is somewhat surprising because Southern CA has the largest extent of WUI of the three regions. Additionally, in Southern CA, housing density was found to explain more variation in structure loss than other factors, including defensible space [48]. However, it may be that the extensive nature of WUI in the region may partly explain why it was second in importance to local-scale vegetation. Here and in the Bay area, unvegetated areas (largely urban) were included with the WUI class in the first split of the classification tree, suggesting that these fires were all at least partially surrounded by high-density development, and there may not be much variability in the spatial pattern of development where the fires in this study occurred. It may also suggest structures with large amounts of exotic landscaping in urban areas are most at risk in this region.

The use of NDVI to measure local vegetation amount was appropriate for a broad-scale study such as this, to rank the relative importance of factors across large regions; and while NDVI captures vegetation abundance, it cannot distinguish vegetation type, condition, or structure, all of which are important for fire behavior [49]. NDVI also cannot indicate where abundance is high within a 30 m grid cell. The empirical studies evaluating the role of defensible space in this region used a wide range of factors to quantify defensible space at scales much finer than 30 m [12,13], and these studies found that the most effective distance of defensible space is shorter than 30 m, particularly when vegetation is touching or overhanging a structure.

That vegetation is most important closer to the house may be seen in this study in that the deviance explained was smaller for larger buffer distances; however, given the low overall deviance explained, further analysis is needed. A regional study exploring four of the fires included in the two northern regions of our analysis also found that vegetation cover near the structure, as measured by NDVI within a 25 m buffer, was an important predictor of structure loss. However, wind speed dampened the relationship to the point that all vegetation classes in that study had loss rates above 80% [50]. Syphard and Keeley [18] found that defensible space distance was much less important than structural characteristics and speculated that this result might be because the distances measured were not at fine enough scales to capture the importance of vegetation close to the structure. Another important component of defensible space is irrigation and vegetation moisture. Gibbons et al. [17] found that irrigation and vegetation arrangement can be just as effective as minimizing vegetation amount. This is likely because wind-borne embers are more likely to be extinguished if they land on something with high fuel moisture.

Although we did not repeat the analysis here, Syphard and Keeley [18] found that structural characteristics play an important role in protecting structures once a fire reaches there. This may also reflect how preventing ember entry to the building may be one of the most significant factors in increasing probability of survival. In that study and this one, none of the factors we evaluated explained a substantial amount of variation in destroyed structures.

The low deviance explained may be due to uncertainty introduced with spatial data or a low overall variability in our spatial data. As all structures in our analysis had been, to some extent, exposed to a fire, the measurements of exposure used here, such as the WUI, distance to roads, or broad climatic variation, are only able to explain the difference between degrees of exposure. The reason for this restriction was that we could not compare pre-fire NDVI with structures that did not have a fire. Nevertheless, given the many large fires in this study, factors such as distance to powerline or road, or the distance to the ignition location, can still vary significantly across the dataset. We are unsure why the deviance explained was higher overall for the North Interior region, but it may reflect a higher vegetation heterogeneity in the fire perimeters than the other regions, given that conifer forest is more prevalent here. The low deviance overall also suggests, as mentioned previously, that a range of other characteristics play into the ultimate outcome of a fire event. Thus, this research illustrates differences in the relative importance of the variables analyzed, but additional work and more extensive empirical research will be needed to obtain a full understanding of why some structures are destroyed in fires and others are not.

5. Conclusions

There are multiple ways that vegetation can influence fire risk. At broad scales, vegetation pattern is an important determinant of exposure. At finer scales, vegetation affects sensitivity to the hazard and mediates fire behavior through fuel load (i.e., amount) or fuel moisture and flammability [20]. Our comparison of vegetation pattern and amount generally identified the pattern of vegetation and housing to better explain structure loss than local-scale vegetation amount. This is likely because exposure to fire is a necessary first condition determining structure survival, and sensitivity is only relevant once the fire reaches a structure. This finding could help develop the ranking of regions for focus of fire management efforts. These results also suggest that the most effective fire risk reduction approach will account for multiple factors at multiple scales and will incorporate multiple simultaneous strategies. The widespread geographical variability in results reinforces the notion that "one size does not fit all". Our study indicates that effective fire management plans will need additional customized, local-scale empirical research on specific vegetation characteristics relative to structure loss.

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LETTER

Fitting the solutions to the problems in managing extreme wildfire in California

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Abstract

Agencies are busy within California developing prioritization strategies to increase the pace and scale of forest treatment in an effort to reduce damage to ecosystems and people by large severe wildfire. A tacit assumption of this effort is that building forest resilience to wildfire will resolve California's extreme wildfire challenge. Specifically, the management focus is on coniferous forests where there is abundant evidence of increased tree density and a history of timber production. However, much of the state is covered by non-forested ecosystems, which is also where a lot of structure loss has occurred. We use more than twenty years of wildfire data in California to identify the relative proportion of wildfire area, ignitions and the number of structures destroyed by wildfire categorized by vegetation type. Using five general categories of vegetation (annual dominated, shrubland, woodland, mixed hardwood forest and coniferous forest) we show that a majority of area burned, ignitions and the vast majority of structures damaged by wildfire occur in vegetation types other than coniferous forests. Comprising 19% of the vegetation of California, coniferous forests garner the lion's share of interest in management strategies to reduce the adverse impacts of wildfire. Simply summary statistics clearly show, however, that most of the damage from fire is in systems where forest management is not likely to result in increased wildfire resilience.

Introduction

California led the country in both the total number and total area burned in 2020 (www.nifc.gov). California is consistently ranked as the state with the most fatalities, largest wildfire-related loss of structures, and high suppression costs (https://iii.org/fact-statistic/facts-statistics-wildfires). As wildfire area burned and associated property losses accelerate, much attention has turned to how to manage California's natural ecosystems toward higher fire resilience. California and the federal government have engaged in initiatives (e.g., https://gov.ca.gov/2020/08/13/california-u-s-forest-service-establish-shared-long-term-strategy-to-manage-forests-and-rangelands/) and teams (e.g., California Forest Management Task Force, https://fmtf.fire.ca.gov/, Tahoe-Central Sierra Initiative, https://sierranevada.ca.gov/what-we-do/tcsi/) to find solutions for the wildfire challenge. These efforts focus on vegetation management to reduce fuels, with numerous calls to amplify mechanical thinning and prescribed fire within forested ecosystems (Kalies and Kent 2016, Little Hoover Commission 2018, Kolden 2019, Miller *et al* 2020). The goals of managing wildfire risk are varied, but include both the protection of life and property and to maintain ecosystem structure and function in fire-maintained ecosystems. California is characterized by a diversity of vegetation types that are highly flammable, fire maintained, and in close proximity to human habitation. These attributes create fire risk that has garnered the attention of the public and politicians. But, like many public environmental crises, there is a tendency for problems to become over-simplified. Understanding the distribution of fire across vegetation types and the corresponding capacity for management to reduce this risk can lead to a more efficient allocation of limited wildland management resources.

Our focus is on the effort to deploy forest management techniques to reduce the risk of wildlife to property. The debate regarding the best ways to minimize the risks of and damage from wildfires focuses primarily on forests and forest fire. With a common understanding that some forests contain more trees now than they did 50 or 100 years ago, a debate has erupted on the drivers of tree density increase (e.g., Little Hoover Commission 2018) and the best pathway forward for reducing this stand density (e.g., Little Hoover Commission 2018). The debate often revolves around the relative impacts of fire suppression and reduced timber cutting driving these increases (Little Hoover Commission 2018). There remains considerable uncertainty regarding the degree to which reducing stand density actually reduces fire hazard (Keeley and Syphard 2019). All of this assumes an operational hypothesis that wildfire is predominantly a problem that occurs in forests and that changing *forest management* can substantially alter wildfire outcomes. The prominence of fire and structure loss in the southern California chaparral, however, provides an obvious example of how managing wildfire requires more than managing forests.

Understanding the extent to which vegetation management choices (i.e., timber harvest, biomass removal, prescribed fire, managed wildfire) affect risk reduction of high intensity wildfire is important. It is also important to identify areas where treating fuels is likely to be less effective. As California moves to invest millions into forest v management, a fundamental issue is ascertaining what fraction of extreme wildfire that puts lives at risk, burns structures and damages ecosystems is actually found in vegetation types where risk can be reduced through forest management. Here we focus on the most easily addressed of these three issues: assessing the nature of wildfire that places human property at risk.

We sought to answer four simple, but important questions. What fraction of the state of California is in various vegetation cover types, including forests? What fraction of the areas recently burned or ignited in California is in each of these flammable vegetation types? How has that changed through time? What fraction of structures burned in wildfires are found in each of the various flammable vegetation types? Understanding the fraction of the wildfire problem that occurs in the various vegetation types that burn is a precursor to understanding the extent that management choices can reduce the risk of damages through wildfire.

Methods

To answer our questions, we performed a series of calculations by overlaying digital maps and deriving summary statistics within the ArcGIS 10.7 Geographical Information System (GIS).

For estimating the area found by vegetation type, we used a 2015 vegetation map (hereafter 'fveg') developed by the Fire and Resource Assessment Program (FRAP) of the California Department of Forestry and Fire Protection (Cal Fire) (https://map.dfg.ca.gov/metadata/ds1327.html). To develop the map, Cal Fire assembled a range of remote sensing land cover data products and prioritized them according to detail, date of imagery, and consistency. Using a consistent crosswalk system, Cal Fire then classified the maps into the California Wildlife Habitat Relationships (CWHR) System. For this analysis, we used the WHR 13-level classification of vegetation types, including: coniferous forest, hardwood forest, woodland (created by combining hardwood and coniferous woodland), shrub, and herbaceous vegetation. For lower-flammability and only partially vegetated classes, including barren, urban, wetland, water, agriculture, and desert woodland and shrub, we grouped them into a separate 'other' class.

Also provided by Cal Fire, we used the historical overlapping fire perimeter data (https://frap.fire.ca.gov/mapping/gis-data/) to calculate area burned within vegetation types for years 1950–2019 to assess long-term trends, and for 2000–2018 to correspond to the time period for which we had destroyed structure data. For these calculations, we summarized the total area burned for all vegetation types within the boundaries of all wildfire perimeters that occurred within those dates. The source of data for the location of ignitions was from the National

Interagency Fire Program Analysis, Fire-Occurrence Database (FPA FOD) (Short 2017). These data span the years 1992–2015 and include fires of all sizes on all land ownership types. We overlayed these point data on the vegetation map to extract the type of land cover for each point.

We assembled the locations of destroyed structures from a dataset that combined digitized points based on analysis of pre- and post-fire Google Earth imagery and points that were provided via public records request from the Cal Fire Damage INSpection Program (DINS) (Keeley and Syphard 2019). After merging the two datasets, we visually inspected all locations to ensure accuracy and to remove any duplicates. For these data, we extracted the vegetation type at the point location of the building destroyed. We also selected all the wildfire perimeters that corresponded to a fire that had at least one structure destroyed and summarized the area burned by vegetation type for the entire area within the boundaries of the wildfire perimeters. The resulting synopsis

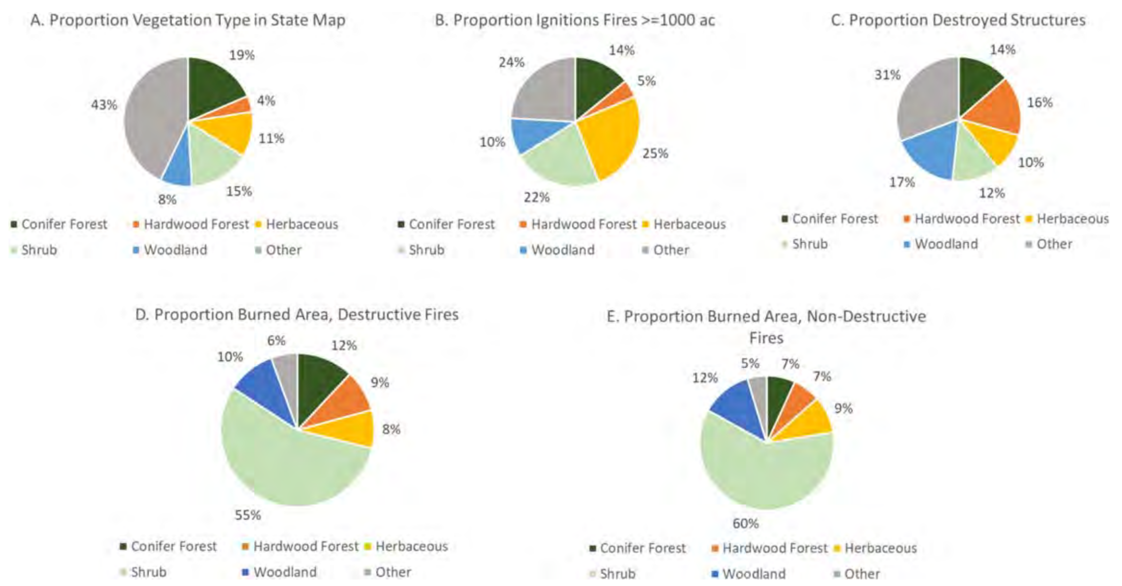

Figure 1. Pie charts of proportional representation of (a) amount of vegetation type; (b) ignitions of large fires; (c) location of structures destroyed; (d) area burned in fires that destroyed buildings; and (e) area burned in fires that did not burn structures plotted by five major vegetation types (conifer forests, hardwood forest, woodlands, herbaceous dominated communities and shrubland communities) addressed in this paper. Deserts, agricultural crop lands and urban areas are lumped into 'other'.

reflected area burned within vegetation types of 'destructive fires.' As a control, we selected all other fires from the same period (2000–2018) and again summarized area burned by vegetation type. As a primarily descriptive assessment, we include no specific statistical analysis of statistical inference.

Results

California is characterized by a variety of vegetation and vegetation types (Van Wagtendonk *et al* 2018). A coarse classification scheme places coniferous forest as the largest category of flammable cover types at 19% (figure 1(a)). We place a special emphasis on coniferous forest because more than 99% of timber cut in California is from coniferous forest types (McIver *et al* 2015). Similarly, seed planting, prescribed fire, biomass removal programs all focus largely on coniferous forest types making coniferous forests synonymous with managed forest. Another 38% of California is characterized by four other types of flammable vegetated landscape: woodland, shrubland or grasslands. This leaves 43% of California as relatively non-flammable (urban, row crops, desert and open water) systems (figure 1(a)).

Over the course of good fire records, since 1950, the area burned by wildfire in California has disproportionately been found in shrubland and herbaceous dominated vegetation (figure 2). While wildland fire has increased since 2000 in most vegetation types, fire in coniferous forest has shown the most marked rate of increase (figure 2). Nevertheless, the cumulative acres burned has consistently remained dominated by non-coniferous habitats (figure 2).

An important component of managing wildfire risk is to understand where, when and why fires ignite. While analyzing ignitions fully is beyond our scope here, we can say that ignitions, among those recorded for all wildfire, are over-represented in grassland and shrubland habitats (figure 1(b)) relative to the abundance of those cover types (figure 1(a)).

Examining patterns of structure loss by wildfire provides yet another perspective on management need. The largest number of structures were lost in locations classified as 'other.' This includes residential areas along the wildland-urban interface (WUI). Discerning the vegetation that was burning that led to these losses is beyond the current scope. However, this can be inferred from the natural vegetation types associated with structure loss. The largest fraction of destroyed structures since 2000 in natural vegetation types are found in hardwood forests and woodlands, at their point location (figure 1(c)). Since 2000, 88% of the wildland area burned where structures were destroyed was in non-coniferous vegetation types (figure 1(d)). Fires that destroyed property were, by far, most strongly associated with shrubland habitats (figure 1(d)). Woodlands and grasslands also both exceeded coniferous forest in terms of area burned in destructive fires (figure 1(d)). The relative proportions of vegetation types burned in destructive and non-destructive fires is roughly the same (figures 1(d), (e)).

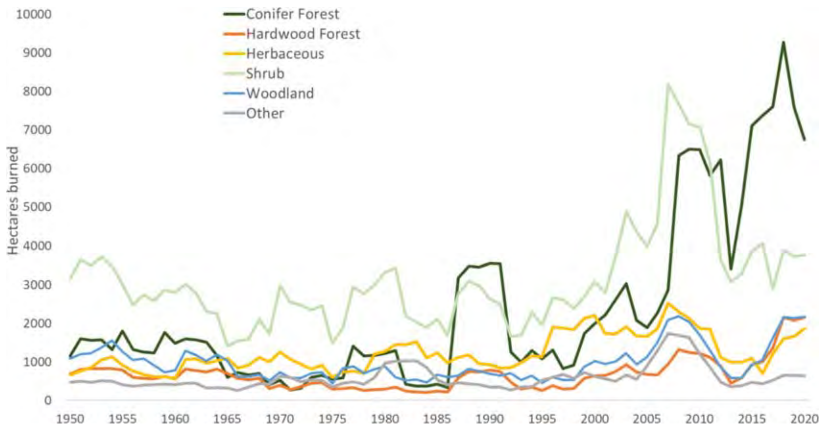

Figure 2. Area burned through time by the major vegetation types addressed in this paper. Area burned is smoothed on a five year window. The 'other' category includes primarily agricultural lands and desert.

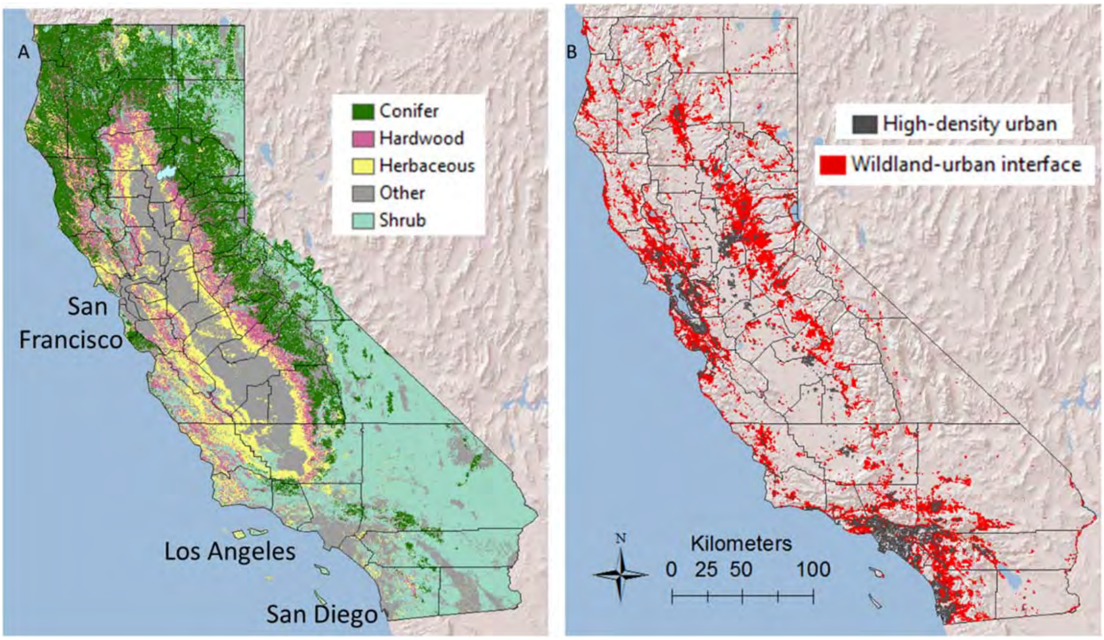

Figure 3. Maps of California depicting (a) the distribution of dominant vegetation types addressed, from Fveg, and (b) the wildland—urban interface in 2010.

Discussion

Understanding the distributional patterns of wildfire across vegetation types is important for several reasons. We address the five focal vegetation types sequentially to better understand measures that might be used to reduce risks from wildfire. We recognize that these are coarse descriptions and, particularly for coniferous forests, there is much variation across sub-types. We further recognize that most large, high intensity fires burn across more than one type, Nevertheless, we felt that a summarization at this scale allows for a useful perspective on managing wildfire risk.

These wildfire summary statistics suggest that while fire in coniferous forests is both notable and increasing, it represents a minority of the total area burned and an even smaller fraction of where structures are burned by wildfire. Since 2000, 88% of the wildland area burned where structures were destroyed was in non-coniferous vegetation types (figure 3). Thus, coniferous forests are not the dominant vegetation type of wildfire (figure 2). In fact, less than 35% of all area burned in the state of California since 2000 has been in coniferous forests. These observations run counter to likely popular impressions left by the 2018 Camp Fire, which partly burned through coniferous forest systems to kill 85 people and burn nearly 19,000 structures. Even in this fire, however, coniferous forest only represented 32% of the area burned, with 55% of the area burned being in hardwood forest and herbaceous vegetation. In short, human losses are far more common in vegetation types other than the coniferous forests that are under scrutiny for management options to reduce risk.

Many coniferous forest types, particularly in montane regions, historically experienced frequent, low-intensity surface fires (Stephens *et al* 2007). Throughout the 20th century, wildfires in these frequent-fire forests were effectively suppressed. In addition, timber extraction has declined sharply over the past 50 years (McIver *et al* 2015). The consequence has been an increase in number and density of trees (Dolanc *et al* 2014, McIntyre *et al* 2015). This uncharacteristic fuel accumulation has also increased the occurrence of wildfires (Miller *et al* 2009) and increased the frequency of high severity wildfire (Mallek *et al* 2013). Reducing fuel accumulation to increase fire resiliency of coniferous forests would reduce overall fire risk within the state. Nevertheless, this often appears as both the beginning and end of the discussion of wildfire management.

Hardwood forest represents just 4% of habitat area, yet 7% of total area burned, 9% of area burned in destructive fires, and 16% of structures destroyed (figure 1(c)). Although hardwood forests have undergone increases in forest stand density in some areas (McIntyre *et al* 2015), this increase has been less substantial than in coniferous forest types. Further, the management options within this system are limited. The state of California has virtually no infrastructure associated with harvesting hardwood for timber (McIver *et al* 2015). Fuels reduction through mechanical means may be an infeasible strategy in most hardwood dominated systems. Hardwood forests, in general, tend to be less flammable than coniferous forests. As a consequence, these may be good habitats in which to favor early season let burn policies, when fuel moisture makes it less likely to have a large, high intensity wildfire (Boisrame *et al* 2017). Given the lower elevation of hardwood forests, most of these lands are privately owned and found in the wildland- urban interface (WUI) (figure 3). The high fraction of structures destroyed in this habitat relative to total area reflects this pattern. With a limited applicability of fuels reduction, low capacity to prescribe fire on private lands, and low capacity to deploy let burn strategies on private lands, the best possible strategies for reducing risk of losses to wildfire in these vegetation types may be through building fire resilience in the built environment.

In most years (45 out of 69), shrublands were the habitat that showed the most area burned (figure 2), and fires that destroyed property were, by far, most strongly associated with shrubland habitats (figure 1(d)). Shrublands, in contrast to forests, have not experienced increased fuels as a consequence of fire suppression, and in fact, fires in shrublands have increased dramatically relative to historical estimates (Safford and Van de Water 2014). Regardless, although most of the shrubland landscape is currently quite young due to so much fire, fuels are not strongly limiting in the large fires of this vegetation type anyway. Healthy shrublands tend to regenerate quickly post-fire, and empirical analysis shows that wildfire and prescribed fire have do not effectively reduce subsequent wildfire in this vegetation type (Price *et al* 2012). Instead, annual foehn winds coupled with human-caused ignitions are the primary factor (Keeley and Syphard 2019). While mechanical vegetation treatments in forests focus on removing surface fuels, the approach in shrublands is to intentionally convert woody biomass to grassland, which is necessary given there is no understory in chaparral shrublands. While these grassy fuel breaks can effectively increase firefighter access to defend communities (Syphard *et al* 2013), they are also corridors for increased spread of invasive annual grasses (Merriam *et al* 2006). Mechanical treatments of shrublands via mastication also increase the potential for grass expansion (Brennan and Keeley 2017). Observing that ignitions are most skewed above average in herbaceous vegetation, we find that grassland conversion is likely to have the unintended negative consequence of increasing fire frequencies in adjacent highly flammable shrublands by igniting easily near roads, trails, human settlements, or even fuel breaks (Syphard and Keeley 2015) and carrying fire quickly into more intensely burning shrublands. Given the challenge of managing fires in shrublands it seems that a dominant effort should be focused on managing the built environment and ignitions in and around them.

Grasslands and open woodlands are also systems where fuel build-up is not driving increased fire and managing fuels is not a likely solution. Open woodlands are generally grasslands with occasional trees, deriving most of their fuels, and flammability, from grasses. Thus, managing open woodlands would be similar to managing grasslands. Both of these vegetation cover types can have very high fire return intervals and recuperate fuels quickly following fire. Grasslands are easily ignited, highly flammable, and contribute to a positive feedback cycle of fire (Fusco *et al* 2019). In addition to shrublands converting to grass under frequent fire, there is also evidence of and potential for fire-catalyzed type conversion of coniferous forests to shrub- or grass-dominated vegetation types (Coop *et al* 2016, Syphard *et al* 2019a, 2019b, Kerns *et al* 2020). Grassland fires under high winds often move very fast. These systems, similar to shrublands, require managing the human environment in order to reduce risk of damage from wildfire.

These simple analyses demonstrate that, while coniferous forests are strong contributors to wildfire and wildfire damage, fire risk to humans overall is not predominantly a forest issue in California. Well-designed fuel treatment strategies in dry mixed coniferous forests may substantially reduce fire hazard in surrounding areas (Stevens *et al* 2016). Further, fuels management in coniferous forests is likely to have longer lasting positive effects, as coniferous forests accrue fuels more slowly than many other vegetation cover types. Although vegetation management is also performed in other woody vegetation types, these treatments are more effective at controlling fire behavior under non-extreme weather conditions (Syphard *et al* 2011, Schoennagel *et al* 2017, Brown *et al* 2012) when structures are rarely destroyed (Keeley and Syphard 2019).Thus, we fear that the heavy attention to wildfire in coniferous forests may blind policy-makers to management opportunities that may more broadly confer safety from the damaging effects of wildfire.

The geographical distribution of the human population and assets at risk is, unsurprisingly, also highly heterogeneous (Syphard *et al* 2019a, 2019b). Thus, understanding how to best manage the wildfire problem requires understanding of where management tools such as prescribed fire or mechanical removal of wood fuels provide opportunities to reduce risk, and the majority of fire-prone locations where they do not. Just as addressing the wildfire issue in California requires considering wildfire in all vegetation types, it also requires a focus on people and the built environment. Just as wildfire is not evenly distributed amongst vegetation types, the most damaging impacts of those wildfires (e.g. loss of lives and property) are not evenly distributed across fire-prone vegetation types. Recent trends indicate that the WUI is rapidly increasing in California (Radeloff *et al* 2018), and projected future increases in the WUI are far higher in non-forested areas than forested areas: increasing the risk of damage from wildfire in non-forested areas.

Recent studies have provided empirical evidence documenting the most significant factors explaining structure loss to wildfire via comparison of structures previously destroyed with those that were unburned. Consistently, the results have shown that the most important factors explaining structure loss in California (e.g., Syphard *et al* 2012, 2019, Alexandre *et al* 2016, Kramer *et al* 2018) and elsewhere (Abatzoglou *et al* 2018, Kramer *et al* 2018, Nagy *et al* 2018) are the coincidence of human-caused ignitions with severe wind and weather conditions and the location and pattern of housing development. Studies also show significant protective benefits of homeowner mitigation strategies including defensible space (Syphard *et al* 2013, Gibbons *et al* 2018) and structural characteristics (Syphard *et al* 2017a, 2017b, 2019a). Strategically located fuel breaks around communities allowing firefighter access for defensive strategies may also be helpful (Syphard *et al* 2011). These collective strategies that focus on fire prevention and land planning in the built environment may be a more efficient means to the goal of minimizing human risk to wildfire across all habitats.

Further, as climate changes, we should expect damaging wildfire to become less of a managed forest issue and more of an 'other' flammable vegetation type issue. Predictions of 21st century vegetation type change suggest that coniferous forest extent will be reduced and shift upslope, away from the WUI (Thorne *et al* 2017. Liang *et al* 2017). This will make California's wildfire problem less and less of a managed forest problem. Fire-vegetation interactions accelerate this problem by driving type conversion of forests to other physiognomic types through fire (Keeley *et al* 2019, Coop *et al* 2020). The net consequence is that climate-driven vegetation change may shorten expected fire return intervals, at least in the near term, and reduce the capacity of forest management to manage damaging wildfire.

Principally, a focus on making communities more fire safe (Calkin *et al* 2014, Moritz *et al* 2014) is both a more general, more extensively relevant, and potentially more certain strategy to reduce losses to wildfire. However, our investment in social solutions to wildfire lags significantly behind investment in fixing a vegetation challenge that impacts a minor subset of the vegetation that carries damaging wildfire. California spends roughly $2.5 billion in firefighting each year (Petek 2020). In addition, the budget for reducing fuels and cutting fire breaks is $364 million. In contrast, the budget for improving emergency services is just $122 million, and this includes non-fire emergency services (Petek 2020). The Governor's assessment of the wildfire challenge identifies the Wildland Urban Interface (WUI) as a critical region where most of the fire damage occurs, and this is supported through empirical research (Kramer *et al* 2018, 2019). The number of households in the fire-prone California WUI grew 11% to 2.9 between 2000 and 2012 (Petek 2020). The WUI continues to grow (Radeloff *et al* 2018). Given the importance of the WUI in terms of fire risk, and the lack of capacity to prevent wildfires in the WUI through fuels management in non-coniferous regions, it would make sense to invest in creating safer living spaces in the WUI. Yet, the Governor is proposing just $110 million for 'home hardening', of which $100 is one-time spending (Petek 2020). Considering the scope of the problem in non-managed forested systems, these budget priorities do not align with the magnitude of the problem. If we accept wildfire as a natural component of California's natural vegetation types then the lack of policies and investment in the non-coniferous WUI is setting California up for continued human impacts from wildfires.

Together these observations lead to sobering conclusions. We are not suggesting that we are over-investing in resolving the wildfire challenge in coniferous forests where management may significantly reduce fire risk. There are many good reasons to address fuels in coniferous forests. Fuel treatment has longer lasting impacts than in many other systems, fires may be more likely to drive unwanted ecosystem change in coniferous forests, and the controllability of intense forest wildfire is low. We agree that more needs to be done in forested systems to create resilient ecosystems. However, there is clear evidence that damage to human structures from wildfire is predominantly outside of these managed forests systems. This leads to a clear conclusion that vegetation management, of any sort, may have a limited capacity to significantly reduce risk of property damage due to wildfire. This observation suggests a need for robust parallel efforts to increase the resilience of human communities that are found in and adjacent to environments that experience frequent fires and that no amount of natural vegetation management will completely resolve risk to human structures.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors. https://map.dfg.ca.gov/metadata/ds1327.html.

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HUMAN INFLUENCE ON CALIFORNIA FIRE REGIMES

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Abstract. Periodic wildfire maintains the integrity and species composition of many ecosystems, including the mediterranean-climate shrublands of California. However, human activities alter natural fire regimes, which can lead to cascading ecological effects. Increased human ignitions at the wildland–urban interface (WUI) have recently gained attention, but fire activity and risk are typically estimated using only biophysical variables. Our goal was to determine how humans influence fire in California and to examine whether this influence was linear, by relating contemporary (2000) and historic (1960–2000) fire data to both human and biophysical variables. Data for the human variables included fine-resolution maps of the WUI produced using housing density and land cover data. Interface WUI, where development abuts wildland vegetation, was differentiated from intermix WUI, where development intermingles with wildland vegetation. Additional explanatory variables included distance to WUI, population density, road density, vegetation type, and ecoregion. All data were summarized at the county level and analyzed using bivariate and multiple regression methods. We found highly significant relationships between humans and fire on the contemporary landscape, and our models explained fire frequency ($R^2 = 0.72$) better than area burned ($R^2 = 0.50$). Population density, intermix WUI, and distance to WUI explained the most variability in fire frequency, suggesting that the spatial pattern of development may be an important variable to consider when estimating fire risk. We found nonlinear effects such that fire frequency and area burned were highest at intermediate levels of human activity, but declined beyond certain thresholds. Human activities also explained change in fire frequency and area burned (1960–2000), but our models had greater explanatory power during the years 1960–1980, when there was more dramatic change in fire frequency. Understanding wildfire as a function of the spatial arrangement of ignitions and fuels on the landscape, in addition to nonlinear relationships, will be important to fire managers and conservation planners because fire risk may be related to specific levels of housing density that can be accounted for in land use planning. With more fires occurring in close proximity to human infrastructure, there may also be devastating ecological impacts if development continues to grow farther into wildland vegetation.

Key words: California, USA; fire; fire history; housing density; nonlinear effects; regression; wildland–urban interface.

Introduction

Fire is a natural process in many biomes and has played an important role shaping the ecology and evolution of species (Pyne et al. 1996, Bond and Keeley 2005). Periodic wildfire maintains the integrity and species composition of many ecosystems, particularly those in which taxa have developed strategic adaptations to fire (Pyne et al. 1996, Savage et al. 2000, Pausas et al. 2004). Despite the important ecosystem role played by fire, human activities have altered natural fire regimes relative to their historic range of variability. To develop effective conservation and fire management strategies to deal with altered fire regimes, it is necessary to understand the causes underlying altered fire behavior and their human relationships (DellaSalla et al. 2004). Nowhere is this more critical in the United States than in California, which is the most populous state in the nation, with roughly 35×10^6 people. Most of the population lives in lower elevations dominated by hazardous chaparral shrublands susceptible to frequent high-intensity crown fires.

In California, as elsewhere, the two primary mechanisms altering fire regimes are fire suppression, resulting in fire exclusion, and increased anthropogenic ignitions, resulting in abnormally high fire frequencies (Keeley and

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Fotheringham 2003), though climate change, vegetation manipulation, and other indirect factors may also play a role (Lenihan et al. 2003, Sturtevant et al. 2004). For most of the 20th century, fire suppression effectively excluded fire from many western U.S. forest ecosystems, such as ponderosa pine. In these ecosystems, fire exclusion contributed to unnatural fuel accumulation and increased tree density (Veblen et al. 2000, Allen et al. 2002, Gray et al. 2005). Recently, when wildfires have hit many of these forests, hazardous fuel loads have contributed to high-intensity crown fires that are considered outside the historical range of variability (Stephens 1998). While these patterns are widely applicable to many forested landscapes in the western United States, California chaparral shrublands have experienced such substantial human population growth and urban expansion that the increase in ignitions, coupled with the most severe fire weather in the country (Schroeder et al. 1964), have acted to offset the effects of suppression to the point that fire frequency exceeds the historic range of variability (Keeley et al. 1999). Because anthropogenic ignitions tend to be concentrated near human infrastructure, more fires now occur at the urban fringe than in the backcountry (Pyne 2001, Keeley et al. 2004). Profound impacts on land cover condition and community dynamics are possible if a disturbance regime exceeds its natural range of variability, and altered fire regimes can lead to cascading ecological effects (Landres et al. 1999, Dale et al. 2000). For example, too-frequent fire can result in habitat loss and fragmentation, shifting forest composition, reduction of small-mammal populations, and accompanying loss of predator species (Barro and Conard 1991, DellaSalla et al. 2004).

Landscape-level interactions between human activities and natural dynamics tend to be spatially concentrated at the wildland–urban interface (WUI; see Plate 1), which is the contact zone in which human development intermingles with undeveloped vegetation (Radeloff et al. 2005). The WUI has received national attention because housing developments and human lives are vulnerable to fire in these locations and because anthropogenic ignitions are believed to be most common there (Rundel and King 2001, USDA and USDI 2001). The majority of WUI fire research has focused on strategies to protect lives and structures (e.g., Cohen 2000, Winter and Fried 2000, Winter et al. 2002, Shindler and Toman 2003) or on the assessment of fire risk using biophysical or climate variables that influence fire behavior (Bradstock et al. 1998, Fried et al. 1999, Haight et al. 2004). However, it is also important to understand how the WUI itself (or other indicators of human activity) affects fire and to quantify the spatial relationships between human activities and fire (Duncan and Schmalzer 2004).

The influence of proximity to the WUI and other human infrastructure appears to vary markedly with region. In the northern Great Lakes states, areas with higher population density, higher road density, and lower distance to nonforest were positively correlated with fire (Cardille et al. 2001). Also, in southern California, a strong positive correlation between population density and fire frequency was reported (Keeley et al. 1999). However, no relationship between housing count and fire was found in northern Florida counties (Prestemon et al. 2002); population density and unemployment were positively related, and housing density and unemployment were negatively related to fire in a different analysis of Florida counties (Mercer and Prestemon 2005). A negative relationship between housing density and fire was also found in the Sierra Nevada Mountains of California (CAFRAP 2001).

In addition to potential regional differences, it is also difficult to draw general conclusions from these studies because they used different indicators of human activities, their data sets differed in spatial and temporal scale, and they were conducted in small areas where ranges of variability in both fire frequency and level of development were limited. Human–fire relationships may also vary based on factors that were not accounted for, such as pattern of development. Another explanation for the discrepancy is that relationships between human activities and fire may be nonlinear in that humans may affect fire occurrence positively or negatively, depending on the level of influence. These nonlinear effects were apparent in data from a recent study in the San Francisco Bay region, where population growth was positively related to fire frequency over time up to a point, but then fire frequency leveled off as population continued to increase (Keeley 2005).

Whether positive or negative, the significance of the relationships between human activities and fire that were detected in previous studies stresses the importance of further exploring links between anthropogenic and environmental factors and their relative influence on wildfire patterns across space and time. Therefore, our research objective was to quantify relationships between human activities and fire in California counties using temporally and spatially rich data sets and regression models. Although fire regimes encompass multiple characteristics, including seasonality, intensity, severity, and predictability, we restricted our analysis to questions about fire frequency and area burned to determine: (1) what the contemporary relationship between human activities and fire is; (2) how human activities have influenced change in fire over the last 40 years; and (3) whether fire frequency and area burned vary nonlinearly in response to human influence.

Humans are responsible for igniting the fires that burn the majority of area in California (Keeley 1982); therefore, we expected our anthropogenic explanatory variables to significantly explain fire activity on the current landscape and over time. In addition to population density (which simply quantifies the number of people in an area), we expected the spatial pattern of human development (indicated by housing density and

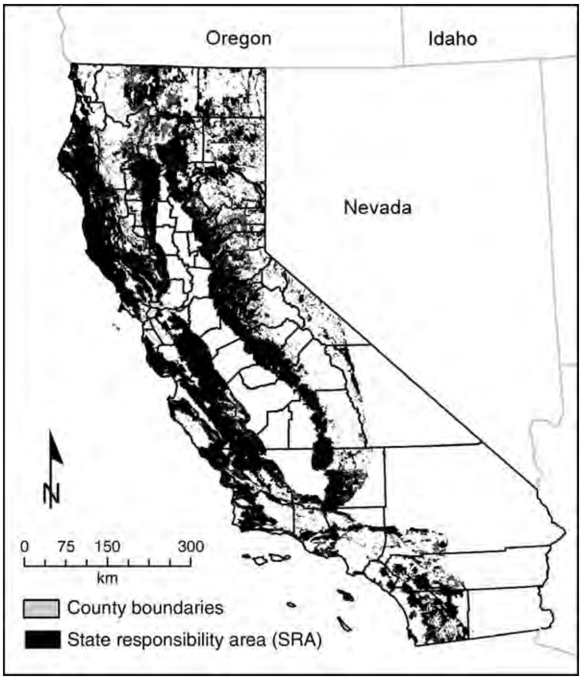

FIG. 1. Map of California Department of Forestry and Fire Protection (CDF) state responsibility areas (SRAs) within county boundaries of California, USA.

land cover combinations and distance variables) to be an important influence on fire because we assumed that anthropogenic ignitions are most likely to occur where human presence is greatest. We also expected that the relationships between human activities and fire would be both positive and negative because humans ignite fires, but development patterns affect fuel continuity and the accessibility of fire suppression resources. Finally, we included several environmental variables in the analysis because we expected the human relationships to be mediated by these other biophysical variables that shape the pattern and frequency of fire (Wells et al. 2004).

METHODS

Study area

California is the second largest state in the continental United States and is the most populous and physically diverse. Most of the state has a mediterranean climate, which, along with a heterogeneous landscape, contributes to tremendous biodiversity (Wilson 1992). Because the state contains a large proportion of the country's endangered species, it is considered a "hotspot" of threatened biodiversity (Dobson et al. 1997). There is extensive spatial variation in human population density: large areas in the north are among the most sparsely populated in the country, but metropolitan regions in the south are growing at unprecedented rates (Landis and Reilly 2004). Much of the landscape is highly fire-prone, but fire regimes vary, and fire management is divided among many institutions. Humans have altered California's fire regimes, and its fire-related financial losses are among the highest in the country (Halsey 2005).

Data

Dependent variables: fire statistics.—We assembled our fire statistics from the California Department of Forestry and Fire Protection (CDF; Sacramento, California, USA) annual printed records, which included information on all fires for which the CDF took action between 1931 and 2004. For all state responsibility areas (SRA; Fig. 1), fire statistics are recorded by county and include numbers by size class, total area burned, vegetation type, and cause. Because the statistics did not include spatially explicit information on individual fires, we weighted the data by the area within the SRA in each county by calculating proportions to use as our dependent variables. These fire statistics were substantially more comprehensive than the readily available electronic Statewide Fire History Database, which excludes most fires $<$40 ha, which in many counties represents $>$90% of the fires. Although both anthropogenic and lightning ignitions would be important to consider for fully understanding fire patterns in other regions (e.g., Marsden 1982), humans were responsible for $\sim$95% of both the number of fires and area burned in California in the last century. We restricted our analysis to these anthropogenic fires because our focus was on human relationships with fire. Although the fire statistics were not spatially explicit, we developed GIS grids at 100-m resolution to derive data for all of the explanatory variables. The data for these explanatory variables were only extracted and averaged from within the SRA boundaries corresponding to the fire data.

Out of the 58 counties in California, we had fire statistics for 54 of them for the year 2000. Therefore, to assess the contemporary relationship between fire and human activities (hereafter referred to as the "contemporary analysis"), we analyzed the data from these counties using the annual number of fires and area burned as our dependent variables (Table 1).

Based on a preliminary exploration of the fire history data (averaged across all counties), we observed two distinct trends during the last 50 years. First, the number of fires substantially increased until 1980 and then decreased until 2000; and second, the average area burned changed inversely to the number of fires, but the differences over time were less dramatic and not statistically significant (Fig. 2). Considering these trends, we broke the historic analysis into two equal time periods (1960–1980 and 1980–2000) to compare the relative influence of the explanatory variables on both the increase (i.e., from 1960 to 1980) and decrease (from 1980 to 2000) in fire activity. The year 1980 is used to compute differences for both time periods because the census data that formed the basis for many of our explanatory variables were only available by decade. We averaged the number of fires and the area burned for 10-

TABLE 1. Variables analyzed in the regression models.

Variable	Source	Processing
2000 data		
Dependent variables		
Number of fires	CDF	proportion in SRA, square-root transformed
Area burned	CDF	proportion in SRA, square-root transformed
Explanatory variables		
Human		
Intermix WUI	SILVIS	proportion in SRA
Interface WUI	SILVIS	proportion in SRA
Low-density housing	SILVIS	proportion in SRA
Distance to intermix WUI	SILVIS	mean Euclidean distance in SRA
Distance to interface WUI	SILVIS	mean Euclidean distance in SRA
Population density	SILVIS	proportion in SRA
Road density	TIGER	mean km/km^2 in SRA
Distance to road	TIGER	mean Euclidean distance in SRA
Biophysical		
Ecoregion	CDF	discrete class
Vegetation type	CDF	area burned in vegetation type/area burned in SRA
Historic data, 1960–1980 and 1980–2000		
Dependent variables		
Change in number of fires	CDF	difference between decadal averages, proportion in SRA, square-root transformed
Change in area burned	CDF	difference between decadal averages, proportion in SRA, square-root transformed
Explanatory variables		
Human		
Change in housing density	SILVIS	difference between decades
Change in distance to low-density housing	SILVIS	difference between mean Euclidean distance in SRA
Initial housing density	SILVIS	mean housing density in either 1960 or 1980
Initial distance to low-density housing	SILVIS	mean Euclidean distance in SRA in either 1960 or 1980
Biophysical		
Ecoregion	CDF	discrete class
Vegetation type	CDF	mean area burned in vegetation type/area burned in SRA over time period

Notes: Key to abbreviations: WUI, wildland–urban interface; SRA, state responsibility area. Sources are as follows: CDF, California Department of Forestry and Fire Protection, Sacramento, California, USA, *unpublished data*; SILVIS, Radeloff et al. (2005); TIGER, U.S. Census Bureau (2000).

year time periods that bracketed the dates of the census data (e.g., 1955–1964 [1960], 1975–1984 [1980], 1995–2004 [2000]) and then calculated the difference in averages from the 1960–1980 and 1980–2000 periods for our dependent variables (Table 1). By averaging the fire data, we smoothed some of the annual variability that may have occurred due to stochastic factors such as weather.

Explanatory variables: housing data.—Data for most of the anthropogenic variables were available through a nationwide mapping project that produced maps of the WUI in the conterminous United States using housing density data from the 1990 and 2000 U.S. Census (U.S. Census Bureau 2002) and land cover data from the USGS National Land Cover Dataset (Radeloff et al. 2005). The maps were produced at the finest demographic spatial scale possible, the 2000 decennial census blocks. The vegetation data were produced at 30-m resolution. These maps delineated two types of WUI in accordance with the Federal Register definition (USDA and USDI 2001). "Intermix WUI" is defined as the intermingling of development with wildland vegetation; the vegetation is continuous and occupies >50% of the area. "Interface WUI" is defined as the situation in which development abuts wildland vegetation; there is <50% vegetation in the WUI, but it is within 2.4 km of an area that has >75% vegetation. In both types of WUI communities, housing must meet or exceed a density of more than one structure per 16 ha (6.17 housing units/km^2). Interface WUI tends to occur in buffers surrounding higher-density housing, whereas intermix WUI is more dispersed across the landscape (Fig. 3A, B).

The WUI data were only produced for 1990 and 2000 due to the lack of historic land cover data, but housing density data were available from 1960 to 2000. Historic housing density distribution was estimated using back-casting methods to allocate historic county-level housing unit counts into partial block groups (as described in Hammer et al. 2004). We used both intermix and interface WUI as explanatory variables (proportions within the county SRAs) in the current analysis to evaluate how these different patterns of vegetation and housing density affected fire activity. We also used low-density housing (housing density $\geq$6.17 housing units/km^2 and <49.42 housing units/km^2) to determine whether it could act as a substitute for WUI as an explanatory variable in the historic analysis (Table 1).

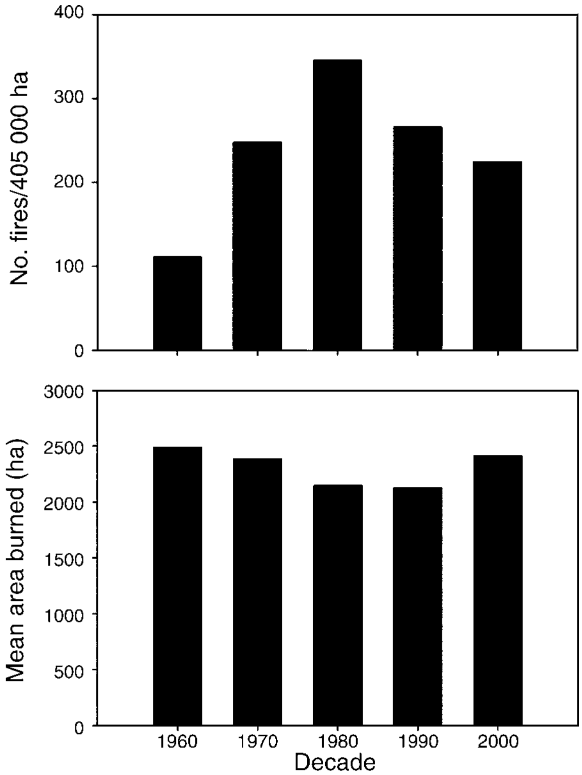

FIG. 2. Trends in number of fires and area burned for all land in the state responsibility areas (SRAs) in California from 1960 to 2000.

Looking at an overlay of fire perimeters from the electronic Statewide Fire History Database (from the last 25 years; *available online*)[7] on the WUI data, it was apparent that many fires occurred close to the WUI, but not necessarily within the WUI (Fig. 3C, D). Therefore, we calculated the mean distance to intermix and interface WUI to evaluate as explanatory variables (Table 1). These means were calculated by iteratively determining the Euclidean distances from every grid cell in the county SRA boundaries and then averaging the distances across all cells to determine means for the counties. We also included population density data from the 2000 Census.

For the historic analysis, we calculated changes in mean housing density and mean distance to low-density housing between the 1960–1980 and 1980–2000 periods to relate to change in the dependent variables. We excluded the proportion of low-density housing from our analysis because it was highly correlated with mean housing density ($r = 0.84$). Unlike the historical fire data that switched in their direction of change over time, housing density continued to increase while the mean distance to low-density housing continued to decline (Fig. 4). We included the initial values of these data (e.g., 1960 and 1980) to account for the fact that the same magnitude of change may have different effects on the dependent variables depending on the starting value of the explanatory variables (Table 1).

Explanatory variables: road data.—The quality of road data can vary according to data source (Hawbaker and Radeloff 2004), so we compared the U.S. Geological Survey digital line graph (DLG; U.S. Geological Survey 2002) and the US TIGER 2000 GIS (U.S. Census Bureau 2000) layers of roads to determine whether there were substantial differences that could affect the interpretation of the results. After calculating and summarizing road density by county, we found a strong positive correlation ($r = 0.97$). Therefore, we used the TIGER data because they were produced in 2000, the same year as the contemporary analysis. The more current TIGER data generally capture new development that might not be included in the DLG data. We evaluated mean road density and mean distance to roads in the current analysis (Table 1), but road data were unavailable for the historic analysis.

Explanatory variables: environmental.—In the absence of human influence, fire behavior is primarily a function of biophysical variables (Pyne et al. 1996, Rollins et al. 2002). These can vary widely across a county, but ecoregions capture broad differences by stratifying landscapes into unique combinations of physical and biological variables (ECOMAP 1993). Our ecoregion data were the geographic subdivisions of California defined for The Jepson Manual (Hickman 1993), designated through broadly defined vegetation types and geologic, topographic, and climatic variation (Fig. 5).

Because vegetation type influences the ignitability of fuel and the rate of fire spread (Bond and van Wilgen 1996, Pyne et al. 1996), we also evaluated the proportion of area burned within three broad vegetation types: shrubland, grassland, and woodland (Fig. 5). Differences in fire regimes between broadly defined vegetation types can be striking, particularly between shrubland and woodland in southern California (Wells et al. 2004). The CDF fire statistics included information on the proportion of area burned in these vegetation types. For the historic analysis, we averaged the proportion of fires burned within different vegetation types over the entire decade (Table 1).

Analytical methods

Diagnostics and data exploration.—Before developing regression models, we examined scatter plots for each variable. Nonlinear trends were apparent (e.g., Fig. 6), suggesting that we needed to include quadratic terms for the explanatory variables in the regressions. Unequal variances in the residual plots prompted us to apply a square-root transformation to the dependent variables. We also plotted semivariograms of the models' residuals (using centroids from the SRA boundaries) and found no evidence of spatial autocorrelation. To check for

[7] ⟨http://frap.cdf.ca.gov/data/frapgisdata/select.asp⟩

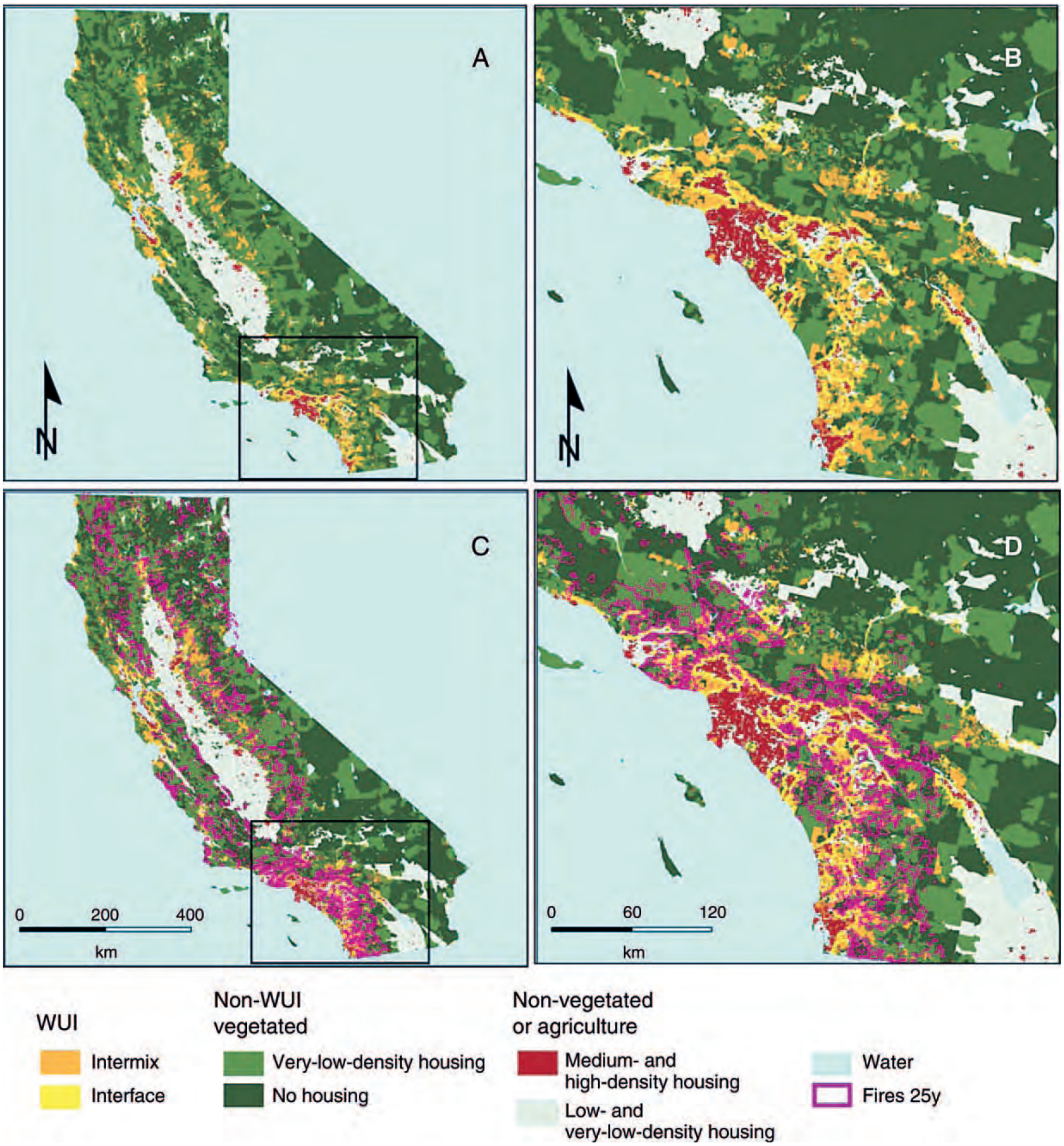

FIG. 3. The wildland–urban interface (WUI) in 2000 with and without fire perimeter overlays (from 1979 to 2004) in (A, C) California and (B, D) southern California. Housing density is defined as follows: very low, >0–6.17 housing units/km^2; low, 6.17–49.42 housing units/km^2; medium, 49.42–741.31 housing units/km^2; and high, >741.31 housing units/km^2 (USDA and USDI 2001). "Fires 25y" refers to 25 years of fire perimeters, from 1980 to 2005.

multicollinearity, we calculated the correlation coefficients between all of the explanatory variables and only included noncorrelated variables ($r \leq 0.7$) in the multiple regression models.

The areas of CDF jurisdiction for each county varied slightly over time. Therefore, we compared separate regressions from the full historic data set ($n = 37$) to a subset of the data excluding counties that experienced a greater than 20% change in area over time ($n = 23$). For both the 1960–1980 regressions and the 1980–2000 regressions, every one of the explanatory variables that was significant in the subset was also significant in the full data set, with very similar R^2 values; therefore, we felt confident proceeding with the full data set for the historic analysis because we had greater power with the larger sample size.

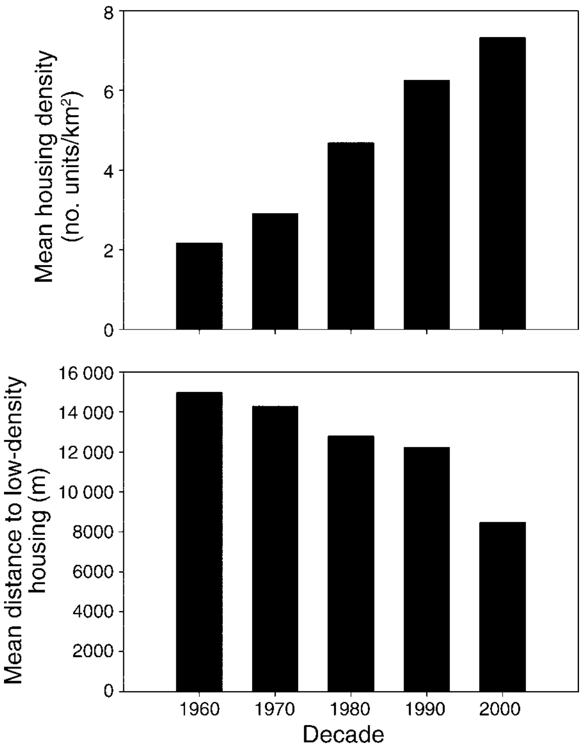

FIG. 4. Trends in housing density and distance to low-density housing (6.17–49.42 housing units/km^2) for all land in the state responsibility areas (SRAs) in California from 1960 to 2000.

Statistical analysis

We used the same regression modeling approach for both the current and historic analyses. First, we developed bivariate regression models for all of the explanatory variables and their quadratic terms so that we could evaluate their independent influence on fire frequency and area burned. To account for the interactions between variables (and their quadratic terms), we also built multiple regression models using the R statistical package (R Development Core Team 2005). For all models, we first conducted a full stepwise selection analysis (both directions) using Akaike Information Criteria to identify the best combination of predictor variables (Burnham and Anderson 2002). Some of the models retained a quadratic term without including the lower-order variable. In these models, we added the lower-order term, rebuilt the model, and then proceeded with a backwards elimination process until all predictor variables in the model were significant with P values ≤ 0.05.

RESULTS

Current analysis

Bivariate regressions.—Many of the anthropogenic variables were highly significant in explaining the number of fires in 2000. The quadratic term for each of these variables was also significant, and the direction of influence was both positive and negative (Fig. 7). Compared to the other variables, population density explained the greatest amount of variability. The proportion of intermix WUI and low-density housing in the counties also explained significant variation in the number of fires; but the proportion of interface WUI was insignificant. The number of fires was significantly related to the mean distance to both types of WUI, but neither of the road variables was significant. All three vegetation types, particularly shrubland, significantly influenced the number of fires, but ecoregion was insignificant.

For the anthropogenic variables, the number of fires was highest at intermediate levels of population density (from ~35 to 45 people/km^2; Fig. 6), proportion of intermix WUI (~20–30% in the county), and proportion of low-density housing (~25–35% in the county). It was also highest at the shortest distances to intermix and interface WUI, but started to level off at ~9–10 km for intermix (Fig. 6) and 14–15 km for interface WUI.

Unlike the number of fires, none of the anthropogenic variables were significantly associated with the area burned in 2000. In fact, shrubland was the only variable that explained significant variation in area burned.

Multiple regression.—When all of the variables were modeled in the multiple regressions, the resulting model for number of fires in 2000 included population density, the proportion of intermix WUI and its quadratic term, grassland and its quadratic term, and shrubland (Table 2). The model was highly significant with an adjusted R^2 value of 0.72.

The multiple regression model for area burned in 2000 included distance to road, shrubland, and woodland, and all three variables had significant positive relationships (no quadratic terms were retained). This model was also highly significant with an adjusted R^2 of 0.50.

Historical analysis 1960–1980

Bivariate regressions.—Change in the number of fires (net increase) from 1960 to 1980 was significantly explained by each of the human-related variables except for change in the mean distance to low-density housing (Fig. 8). The quadratic term was also significant in the separate models, except for the initial distance to low-density housing (in 1960), which had a negative influence on the change in number of fires. Change in number of fires was also significantly related to ecoregion and shrubland vegetation.

The only three variables with significant influence on the change in area burned (net decrease) were the three vegetation types.

Multiple regression.—The explanatory variables that were retained in the multiple regression model for change in the number of fires from 1960 to 1980 included mean housing density in 1960 and its quadratic term, grassland vegetation, and ecoregion (Table 2). The adjusted R^2 value was highly significant at 0.72.

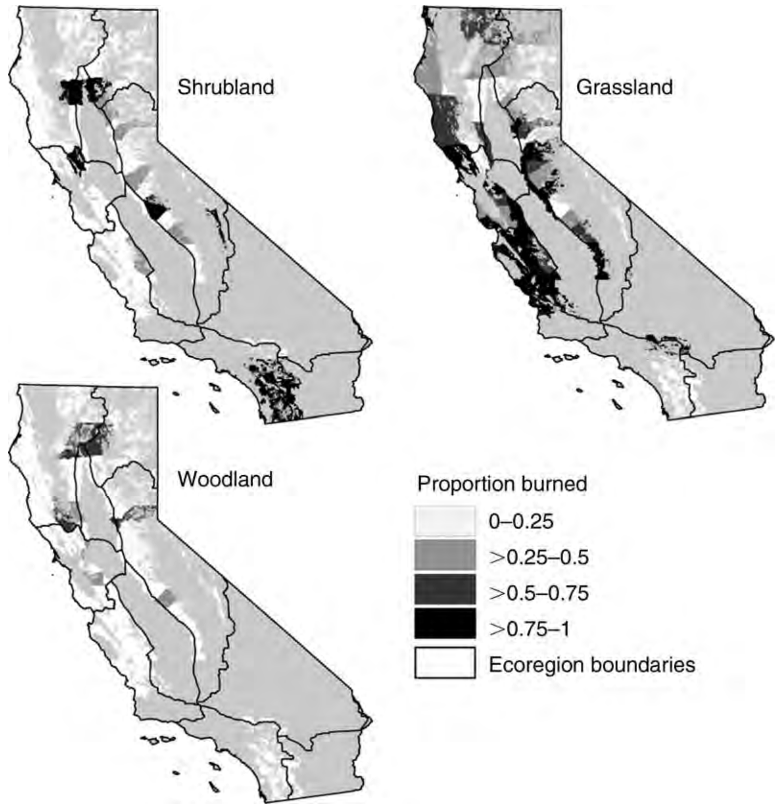

FIG. 5. Maps showing ecoregion boundaries and the proportion of area burned in shrubland, grassland, and woodland in 2000.

Mean housing density in 1960 was positively associated with change in area burned from 1960 to 1980, and the distance to low-density housing had first a positive, then a negative influence because the quadratic term was included. Other variables retained in the multiple regression model included shrubland and its quadratic term, grassland, woodland, and ecoregion.

Historical analysis 1980–2000

Bivariate regressions.—Initial housing density (in 1980) was the only significant explanatory variable explaining change in number of fires (net decrease) from 1980 to 2000 (Fig. 9). Woodland vegetation was the only significant variable out of the separate models explaining change in area burned from 1980 to 2000 (net increase). The quadratic terms were significant for both of these models.

Multiple regression.—The multiple regression model explaining change in number of fires from 1980 to 2000 included change in housing density, initial housing density (in 1980), and woodland vegetation; the quadratic term was also significant for these three variables (Table 2). Although the model was significant, the R^2 was substantially lower than the 1960–1980 model, at 0.26.

The multiple regression model explaining change in area burned included initial housing density (in 1980) and its quadratic term, initial distance to low-density

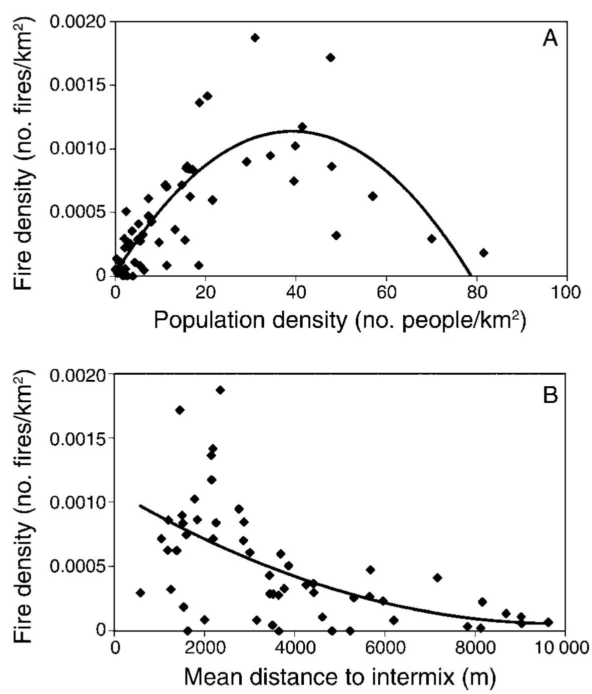

FIG. 6. The relationships between (A) the proportion of the number of fires and population density and (B) the proportion of the number of fires and mean distance to intermix wildland–urban interface (WUI).

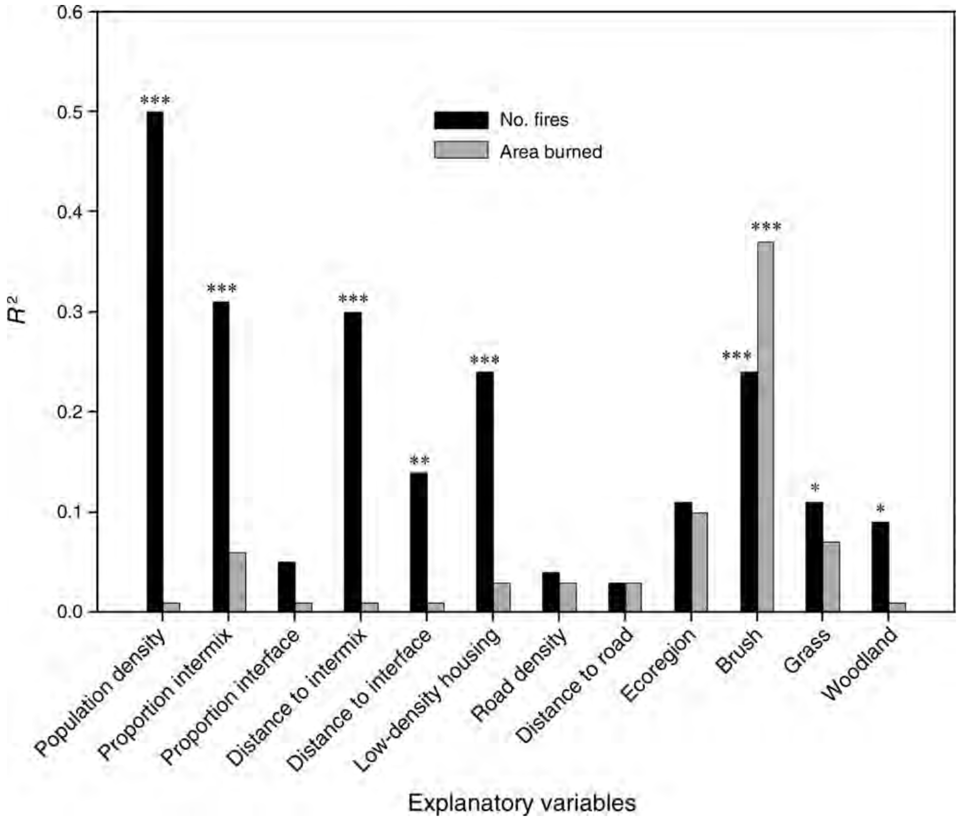

FIG. 7. R^2 values and significance levels for the explanatory variables in the bivariate regression models for number of fires and area burned in 2000.
* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

housing, woodland vegetation and its quadratic, and ecoregion. This model had better explanatory power than the number of fires model, with an R^2 of 0.41.

DISCUSSION

The expression of fire on a landscape is influenced by a combination of factors that vary across spatial and temporal scales and involve both physical and biological characteristics. Fire behavior has long been viewed as a largely physical phenomenon illustrated by the classic fire environment triangle that places fire as a function of weather, fuels, and topography (Countryman 1972), but clearly the human influence on modern fire regimes must also be understood to meet fire management needs (DellaSalla et al. 2004). We first asked what the current relationship is between human activities and fire in California and found that humans and their spatial distribution explained a tremendous proportion of the variability in the number of fires, but that area burned was more a function of vegetation type. Anthropogenic ignitions are the primary cause of fire in California and were the focus of our analysis, so we were not surprised by the strong human influence. Nevertheless, the high explanatory power of the models underscores the importance of using locally relevant anthropogenic factors as well as biophysical factors in fire risk assessments and mapping. The models also identify which indicators of human activity are most strongly associated with fire in California. For number of fires, the proportion of intermix WUI explained more variation than any other variable except for population density, suggesting that the spatial pattern of housing development and fuel are important risk factors for fire starts.

Human-caused ignitions frequently occur along transportation corridors (Keeley and Fotheringham 2003, Stephens 2005), so it was surprising that neither road density nor average distance to road were significant in explaining fire frequency. Although roads are important in local-scale ignition modeling, detecting their influence on fire ignitions may be difficult at an aggregated, county level since they are narrow, linear features. On the other hand, distance to roads was the only anthropogenic variable associated with area burned, having a positive influence when grassland and shrubland were also accounted for in the multiple regression model, which may reflect the difficulty of fire suppression access contributing to fire size.

Humans influence fire frequency more than area burned because anthropogenic ignitions are responsible

TABLE 2. Variables retained in the multiple regression models for the current and historic analyses.

Analysis and explanatory variable	Coefficient and intercept	P
Current		
2000		
No. fires		
Population density	0.0006	<0.01
Proportion intermix	0.0702	<0.01
(Proportion intermix)^2	−0.2629	<0.01
Grassland	0.0496	<0.01
(Grassland)^2	−0.0441	<0.01
Shrubland	0.0093	0.02
Overall model (adjusted R^2: 0.72)	0.0001	<0.01
Area burned		
Distance to road	0.00004	<0.01
Shrubland	0.0833	<0.01
Woodland	0.0559	<0.01
Overall model (adjusted R^2: 0.50)	−0.0052	<0.01
Historic		
1960–1980		
No. fires		
Initial housing	2.7649	<0.01
(Initial housing)^2	−0.1523	<0.01
Grassland	4.6311	0.05
Ecoregion	. . .†	<0.01
Overall model (adjusted R^2: 0.72)	0.6443	<0.01
Area burned		
Initial housing	0.0188	<0.01
Initial distance	0.00002	<0.01
(Initial distance)^2	-2×10^{-10}	<0.01
Shrubland	−0.3641	0.12
(Shrubland)^2	0.8778	0.01
Grassland	0.0371	<0.01
Woodland	0.0449	0.01
Ecoregion	. . .†	0.03
Overall model (adjusted R^2: 0.51)	−0.373	<0.01
1980–2000		
No. fires		
Change housing	3.0666	0.01
(Change housing)^2	−0.2661	0.01
Initial housing	−1.8269	0.01
(Initial housing)^2	0.0505	0.03
Woodland	38.1957	0.03
(Woodland)^2	−107.0112	0.02
Overall model (adjusted R^2: 0.26)	−1.894	0.01
Area burned		
Initial housing	−0.0114	0.01
(Initial housing)^2	0.0003	0.05
Initial distance	−0.000003	<0.01
Woodland	0.0292	0.18
(Woodland)^2	−1.2831	0.02
Ecoregion	. . .†	0.05
Overall model (adjusted R^2: 0.41)	0.0409	<0.01

† Coefficients are not listed for categorical variables.

for fire initiation, but fire spread and behavior is ultimately more a function of fuel availability and type (Bond and van Wilgen 1996, Pyne et al. 1996). Yet humans do have some control over fire size through suppression and, indirectly, through fuel connectivity (Sturtevant et al. 2004), although fires are extremely difficult to suppress in California shrublands under high-wind conditions that typify the most destructive fires (Keeley and Fotheringham 2003). Therefore, human effects on area burned may cancel one another out to some extent because fire suppression can minimize the increase in area burned that would result from increased ignitions, at least at the WUI. Fire suppression resources are more likely to be concentrated on structural protection in developed areas (Calkin et al. 2005), which would explain the positive relationship between area burned and distance to road. Roads can serve as firebreaks and can also provide access routes for firefighters.

The inclusion of vegetation type in the multiple regression models illustrates that, despite the strong influence of humans, fire occurrence remains a function

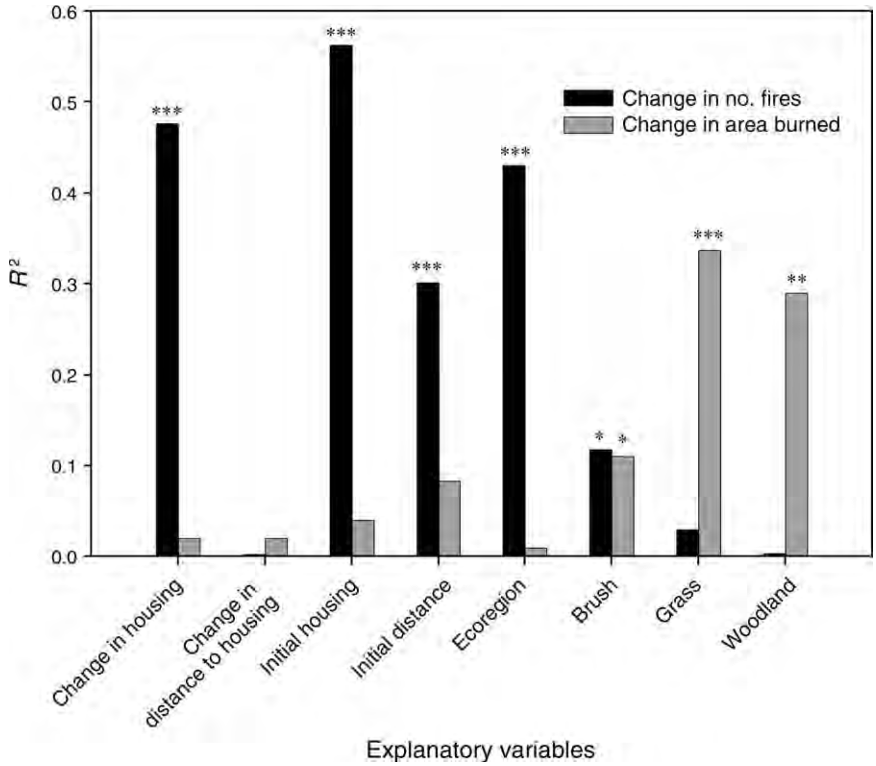

FIG. 8. R^2 values and significance levels for the explanatory variables in the bivariate regression models for number of fires and area burned from 1960 to 1980.
* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

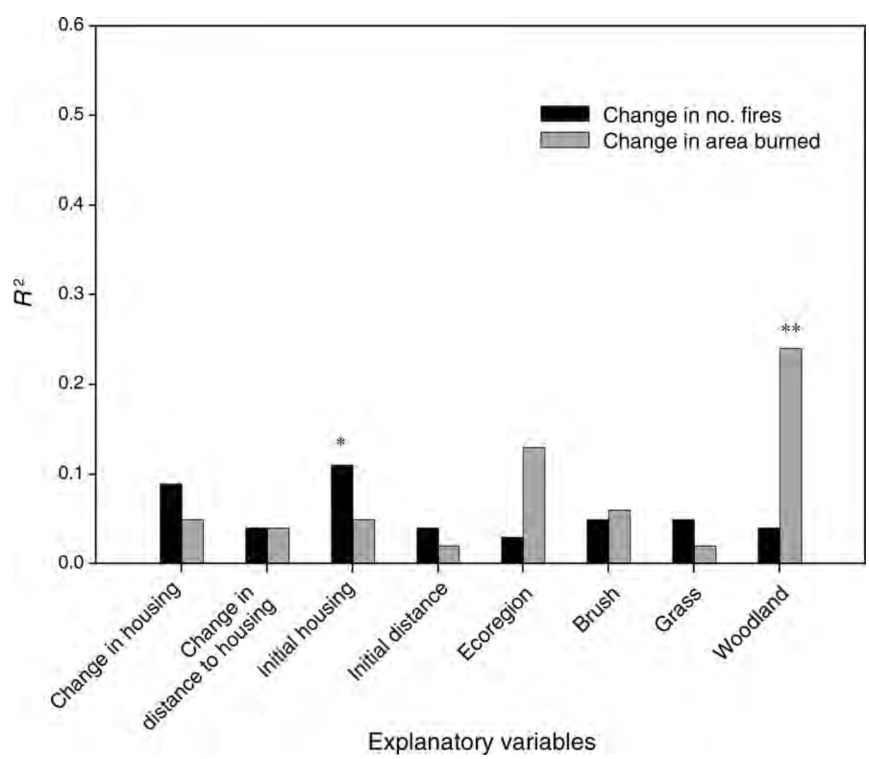

FIG. 9. R^2 values and significance levels for the explanatory variables in the bivariate regression models for number of fires and area burned from 1980 to 2000.
* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

PLATE 1. (Left) Wildland–urban interface (WUI) and (right) burned-over fuel break, both at the eastern end of Scripps Ranch (San Diego County, California, USA) after the autumn 2003 Cedar Fire (largest fire in California since the beginning of the 20th century). Photo credits: J. E. Keeley.

of multiple interacting social and environmental variables. For number of fires and area burned, shrubland had the strongest explanatory power of the vegetation types. Chaparral and coastal sage scrub are both extremely fire-prone vegetation types and high human population density tends to be distributed in these types; other studies have shown that they have experienced a higher rate of burning than other vegetation types in the southern part of the state in the last century (Keeley et al. 1999, Keeley 2000, Wells et al. 2004). Increased ignitions in highly flammable vegetation types can lead to very hazardous conditions (Halsey 2005).

The second question we asked was "How do human activities relate to change in fire?" In the last 40 years, the most substantial change was the increase in number of fires from 1960 to 1980. The decrease in number of fires was less dramatic between 1980 and 2000; and the change in area burned was relatively small in both time periods. Housing development patterns were most influential when change was greatest, from 1960 to 1980, and for trends in fire frequency (vs. area burned).

Although anthropogenic influence was partially responsible for the change in area burned, the apparent inverse relationship between change in fire frequency and change in area burned may be spurious. In other words, the explanation for a decrease in number of fires may be independent of the concurrent increase in area burned. Trends in area burned are naturally cyclic due to broad-scale factors such as climate. Recent research has shown that change in climate was a major factor driving fire activity in the western United States in the last several decades (Westerling et al. 2006); however, that research was restricted to large montane fire events on federally owned land above 1370 m. Therefore, while climate change may have played some role in our observed change in area burned, we cannot extend those results to our analysis because we included fires of all sizes under multiple land ownership classes, and historical fire patterns in the lower elevations do not correspond to patterns in montane forests (Halsey 2005).

Fire both constrains and is constrained by the fuel patterns it creates, resulting in cycles of fire activity and temporal autocorrelation in area burned, in part because young fuels are often less likely to burn (Malamud et al. 2005). Temporal autocorrelation effects vary with ecosystem, fuel type, and the area of analysis; but in all vegetation types, temporal dependence diminishes over time due to post-fire recovery. Therefore, we assumed that the effects would be low in our study because we were looking at change over 20-year time periods. Furthermore, the chaparral vegetation that dominates much of California recovers very quickly following fire, meaning that the effect of temporal autocorrelation in this vegetation type would last for only brief periods of time. Also, under extreme weather conditions, young age classes are capable of carrying fires in the southern portions of California (Moritz 1997, Moritz et al. 2004).

In general, the anthropogenic influence on fire frequency and extent was complicated through the combination of positive and negative effects, which helps to answer our third question: "Do fire frequency and area burned vary nonlinearly in response to human influence?" Nonlinear effects were evident in the scatter plots and confirmed by the significance of quadratic terms in most of the models. The regression models indicate that humans were responsible for first increasing and then decreasing fire frequency and area burned. These dual influences may explain why prior studies presented conflicting results, because a positive or negative response was dependent on the level of human presence. Aside from the fact that we intentionally tested hypotheses regarding nonlinear relationships, our data also contained a wide range of human presence due to the large extent and diversity of the state of California.

The scatter plots illustrate how these human–fire relationships occurred. For both the number of fires and area burned, and in the current and historic analyses, the maximum fire values occurred at intermediate levels of human presence (as in Fig. 6A); and when human activity was either lower or higher, fire activity was lower. Initial increase in fire occurrence with increasing population is reasonable since human presence results in more ignitions. However, it appears that when human population density and development reach a certain threshold density, ignitions decline, and this is likely the result of diminished and highly fragmented open space with fuels insufficient to sustain fire. In addition, above a certain population threshold, fire suppression resources are likely to be more concentrated in the WUI. Inverse relationships were evident in the scatter plots of distance (Fig. 6B). In these, fire frequency and area burned were greatest at short distances to WUI; and at longer distances, the trend lines leveled off. These distance relationships indicate that more fires would be expected in close proximity to settled areas where ignitions are likely to occur.

The inclusion of quadratic terms in the multiple regression models supports the concept that fire frequency and area burned were dependent on the level of human activity. Initial housing density was important in all four historic multiple regression models, and initial distance to low-density housing was important in both of the historic area-burned models. The change in number of fires for both periods was also related to change in housing density, in bivariate regression models for the earlier period and in the multiple regression model for the later period (1980–2000). These results further emphasize that fire activity was a function of a certain level of human presence. In addition to the strong influence of human presence, ecoregion and vegetation types were also highly significant in the multiple regression models, suggesting that the particular level of human activity that was most influential in explaining fire activity was dependent upon biophysical context.

The primary value of the multiple regression models was to identify the most influential variables and their direction of influence when accounting for other factors. While they explained how fire activity varied according to context-dependent interactions, their purpose was not to provide a formula for determining fire risk at a landscape scale. Environmental and social conditions differ from region to region, and processes such as fire and succession are controlled by a hierarchy of factors, with different variables important at different scales (Turner et al. 1997). Nevertheless, these models provide strong evidence about the strength and nature of human–fire relationships. That these relationships are significant across a state as diverse as California suggests that human influence is increasingly overriding the biophysical template; yet, managers must account for the interactions with ecoregion and vegetation type when making management decisions. Determining the conditions (e.g., thresholds) for nonlinear anthropogenic relationships will be important to understand how fire risk is distributed across the landscape.

At the coarse scale of our analysis, we can estimate these thresholds based on the nonlinear relationships in our scatter plots (as in Fig. 6) and suggest that fire frequency is likely to be highest when population density is between 35 and 45 people/km^2, proportion of intermix WUI is ~20–30%, proportion of low-density housing is ~25–35%, the mean distance to intermix WUI is <9 km, and the mean distance to interface WUI is <14 km. Our next step is to more precisely define these relationships at scales finer than the county level (where management decisions often occur) and to understand the conditions under which human activities positively or negatively influence fire.

These results imply that fire managers must consider human influence, together with biophysical characteristics such as those represented in the LANDFIRE database, when making decisions regarding the allocation of suppression and hazard mitigation resources. If human presence is not explicitly included in decision making, inefficiencies may result, because fire occurrence is related to human presence on the landscape. In particular, we identify an intermediate level of housing density and distance from the WUI at which the effects of human presence seem to be especially damaging, i.e., a point at which enough people are present to ignite fires, but development has not yet removed or fragmented the wildland vegetation enough to disrupt fire spread. This intermediate level of development is one that large areas of the lower 48 states, particularly in the West and Southwest, will achieve in the coming decade. Hence, the WUI's location, extent, and dynamics will continue to be essential information for wildland fire management.

Conclusion

In addition to the risk to human lives and structures, changing fire regimes may have substantial ecological impacts, and the results in this analysis support the hypothesis that humans are altering both the spatial and temporal pattern of the fire regime. Although the overall area burned has not changed substantially, the distribution of fires across the landscape is shifting so that the majority of fires are burning closer to developed areas, and more remote forests are no longer burning at their historic range of variability (Pyne 2001). In either case, the ecological impacts may be devastating. Due to lack of dendrochronological information, historic reference conditions are difficult to determine in stand-replacing chaparral shrublands. Although chaparral is adapted to periodic wildfire, there is substantial evidence that fires are burning at unprecedented frequencies, and this repeated burning (at intervals closer than 15–20 years apart) exceeds many species' resilience and has already resulted in numerous extirpations (Zedler et al. 1983, Haidinger and Keeley 1993, Halsey 2005).

If present trends continue in California, the population may increase to 90×10^6 residents in the next 100 years. Recent trends in housing development patterns also indicate that growth in area and number of houses in intermix WUI has far outpaced the growth in interface WUI (Radeloff et al. 2005; Hammer et al., *in press*). Our results showing that fire frequency and area burned tend to be highest at intermediate levels of development (more typical of intermix than interface) suggest that fire risk is a function of the spatial arrangement of housing development and fuels. Therefore, in addition to more people in the region that could ignite fires, future conditions that include continued growth of intermix WUI may also contribute to greater fire risk. Land use planning that encourages compact development has been advocated to lessen the general impacts of growth on natural resources (Landis and Reilly 2004), and we suggest that reducing sprawling development patterns will also be important to the control of wildfires in California.

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Housing Arrangement and Location Determine the Likelihood of Housing Loss Due to Wildfire

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Abstract

Surging wildfires across the globe are contributing to escalating residential losses and have major social, economic, and ecological consequences. The highest losses in the U.S. occur in southern California, where nearly 1000 homes per year have been destroyed by wildfires since 2000. Wildfire risk reduction efforts focus primarily on fuel reduction and, to a lesser degree, on house characteristics and homeowner responsibility. However, the extent to which land use planning could alleviate wildfire risk has been largely missing from the debate despite large numbers of homes being placed in the most hazardous parts of the landscape. Our goal was to examine how housing location and arrangement affects the likelihood that a home will be lost when a wildfire occurs. We developed an extensive geographic dataset of structure locations, including more than 5500 structures that were destroyed or damaged by wildfire since 2001, and identified the main contributors to property loss in two extensive, fire-prone regions in southern California. The arrangement and location of structures strongly affected their susceptibility to wildfire, with property loss most likely at low to intermediate structure densities and in areas with a history of frequent fire. Rates of structure loss were higher when structures were surrounded by wildland vegetation, but were generally higher in herbaceous fuel types than in higher fuel-volume woody types. Empirically based maps developed using housing pattern and location performed better in distinguishing hazardous from non-hazardous areas than maps based on fuel distribution. The strong importance of housing arrangement and location indicate that land use planning may be a critical tool for reducing fire risk, but it will require reliable delineations of the most hazardous locations.

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Introduction

As the frequency, extent, and severity of wildfires are surging across the world [1,2], so too are the ecological, social, and economic consequences. Residential losses associated with wildland fire have escalated globally [3–5], and recent fire events have resulted in billions of dollars of damage per event [6]. The problem is particularly critical in Mediterranean-climate regions of the world, where major metropolitan centers are juxtaposed with highly flammable ecosystems [7]. Since the 1950s, southern California has experienced the highest losses in property and life in the U.S., averaging 500 homes per year [8]. Here we show that the arrangement and location of structures strongly affects their susceptibility to being destroyed in a wildfire, and that empirically based maps developed using housing density and location can better identify hazardous locations than fuel-based maps.

The escalation of wildland fire losses is typically attributed to housing development within or adjacent to wildland vegetation (i.e., the "wildland-urban interface") [6,9], changing climate conditions [1], or an accumulation of hazardous wildland fuels [10]. The primary preventive strategy used for reducing fire impacts has been the manipulation of wildland vegetation to reduce hazardous fuels. The U.S. federal government has strongly promoted and funded fuel reduction treatments to mitigate fire hazard, and federal land management agencies spent billions of dollars (e.g., $2.7 billion from 2001–2006) to treat millions of hectares within the last decade [10]. Yet, while costs for suppression and treatment have nearly tripled since 1996 [11], the fire problem has only gotten worse.

With the growing realization that wildland fuel manipulations can alter fire outcomes only to a limited extent, the need for alternatives has risen. For example, a structure's survival during a wildfire depends largely on its building materials and the characteristics of fuels in its immediate surroundings [3], suggesting that fire hazard can be reduced by homeowner actions to protect the structure [12].

However, what remains unclear is to what extent property loss depends on the role of land planning and the placement and arrangement of homes relative to the spatial patterns of wildland fire hazards. Past land-use decision-making has allowed homes to be constructed in highly flammable areas, and this may be one of the roots of the fire problem [13]. Although it is not feasible to change current housing patterns, homes in the most hazardous locations could be identified and prioritized for fire protection efforts, and land use planning and regulation may potentially be a powerful tool for reducing future property loss [14], especially in areas such as southern California where substantial future housing growth is expected [15], and across the western US, where further development is expected in a substantial proportion of the wildland-urban interface [16].

If land use regulation and planning are to effectively reduce wildland fire loss, they have to be based on solid understanding of what landscape factors most significantly contribute to wildfire danger and where to locate and arrange homes to reduce fire hazard. Currently, most fire hazard maps are based on expert knowledge of how fuel and fire history determine threats to a given community e.g., [17–19]. Similar fire hazard maps have been created for the state of California that identify communities at risk and areas of substantial fire threat to people. These maps are readily available [20] and widely used. Fire hazard maps, however, are only effective if they accurately delineate areas where property loss is most likely to occur. Whether this is the case or not is unknown since most have never been evaluated against empirical data.

We constructed a complete database of structure locations in two extensive, fire-prone regions of southern California and identified which structures were destroyed or damaged by wildfires since 2001 (Fig. 1). These two regions were the Santa Monica Mountains, one of the largest wildland open space areas adjacent to the Los Angeles metropolitan area and San Diego County, site of major wildfire losses in both 2003 and 2007 [20]. Based on these data, we used logistic regression and maximum entropy analysis to answer three questions: 1) What is the relative importance of housing arrangement (i.e., the spatial pattern of residential structures), location, and environment in explaining property loss from fire? 2) How well do currently available statewide fuel-based maps of fire hazard correspond to actual wildfire impacts? 3) Can fire hazard maps based on empirical data and an expanded set of explanatory variables successfully predict local-scale housing losses?

Results

In the Santa Monica Mountains, 3% of 36,399 structures were located within the boundaries of 10 large fires that occurred from 2001 to 2009. In these fires, 173 homes, guest houses, or outbuildings were destroyed and an additional 140 were damaged. For the second study region in San Diego County, 4% of 687,869 structures were located within one of 40 fire perimeters. In these fires, 4315 structures were completely destroyed and an additional 935 were damaged.

In both study regions, the spatial arrangement of structures (Table 1) significantly influenced the likelihood of property loss (i.e., destruction or damage) (Figs. 2 and 3). Property loss was more likely in smaller, more isolated housing clusters with low- to intermediate housing density and fewer roads, although road density was insignificant after accounting for spatial autocorrelation in the Santa Monica Mountains (Table 2). Structures located near the edges of developments, or in housing clusters on steep slopes, were also more susceptible. Many relationships were nonlinear, with the highest property loss occurring when structures were at intermediate distances to other structures or housing clusters.

In addition to spatial arrangement, a structure's location on the landscape was also a highly significant predictor of property loss (Fig. 2). In both study regions, property loss was significantly related to a structure's distance from the coastline, but the relative effect varied. In the Santa Monica Mountains, property loss occurred disproportionately closer to the coast, whereas structures farther from the coast were most susceptible in San Diego County (Tables 2 and 3).

The other significant location-dependent variable affecting property loss was historical fire frequency (Fig. 2). In the Santa Monica Mountains, this was the single most important predictive variable. Here, property loss was most likely in areas of historical high fire frequency, which corresponded with wind corridors. Fire frequency was also a significant variable in San Diego County, but here the relationship was nonlinear.

Property loss was more likely to occur when structures were surrounded by wildland vegetation rather than by urban or impervious areas (Fig. 4). However, property loss was also more (Santa Monica Mountains) or as likely (San Diego County) to

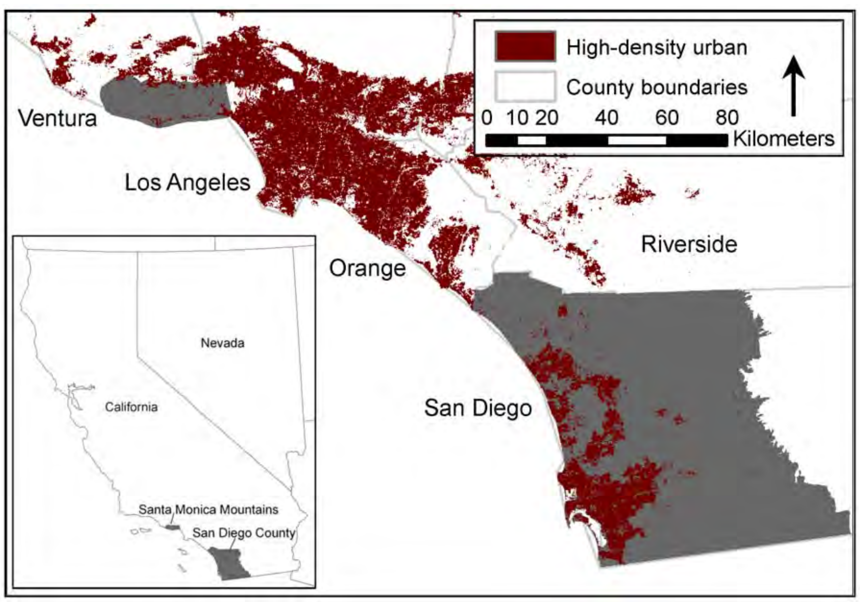

Figure 1. The Santa Monica Mountains and San Diego County, California, USA. Study areas in gray. The Santa Monica Mountains are located in Ventura and Los Angeles counties, and both study areas are located within the South Coast Ecoregion of California, USA. Study areas in gray.
doi:10.1371/journal.pone.0033954.g001

Table 1. Variables analyzed for explaining structure loss in the Santa Monica Mountains and San Diego County.

Variable	*Source*	*Description*
Fire frequency 2001	CDF* Fire perimeter overlays	Number of fires (2001–2010)
Distance to coast	Derived from coastline of county	Continuous distance in meters
Fire threat	CDF*	Ranking from 1 to 5
Fire threat to people	CDF*	Ranking from 1 to 5
Communities at risk	CDF*	Binary, at risk or not at risk
Housing density	Derived from digitized structures	Structures per hectare
Distance nearest housing cluster	Derived from 100 m buffer of structures	Continuous distance in meters
Housing dispersion	Derived from 100 m buffer of structures	Standard deviation/mean distance between structures in housing cluster
Distance to nearest structure	Derived from digitized structures	Continuous distance in meters
Distance to edge of housing cluster	Derived from digitized structures	Continuous distance in meters
Area of housing cluster	Derived from 100 m buffer of structures	Squared meters
Elevation	US Geological Survey digital elevation model (DEM	30 meters
Slope	Derived from the DEM	Percent slope
Southwestness	Derived from the DEM	SW = con(aspect(<dem>) = = −12, 201,(cos(((aspect(<dem>)−255) div deg)+1) * 100)))
Road length	US Census Bureau TIGER/Line files	Meters

*California Department of Forestry Fire and Resource Assessment Program.
doi:10.1371/journal.pone.0033954.t001

occur within herbaceous fuel types than within the higher fuel-volume woody types that are typically considered as the most hazardous fuels.

Variables with correlation coefficients greater or equal to 0.7 in the Santa Monica Mountains included road length and area of housing cluster (0.95) and elevation and distance to coast (0.72). In San Diego County, pairs of correlated variables also included road length and area of housing cluster (0.99), distance to nearest structure and distance to nearest housing cluster (0.71). Distance to coast was correlated with housing density (−.71) and elevation (0.89). To develop multiple-regression models, we removed elevation and road length from consideration in the Santa Monica Mountains, because they explained less variation than the variable with which they were correlated. For the San Diego County analyses, we removed distance to coast, road length, and distance to nearest housing cluster.

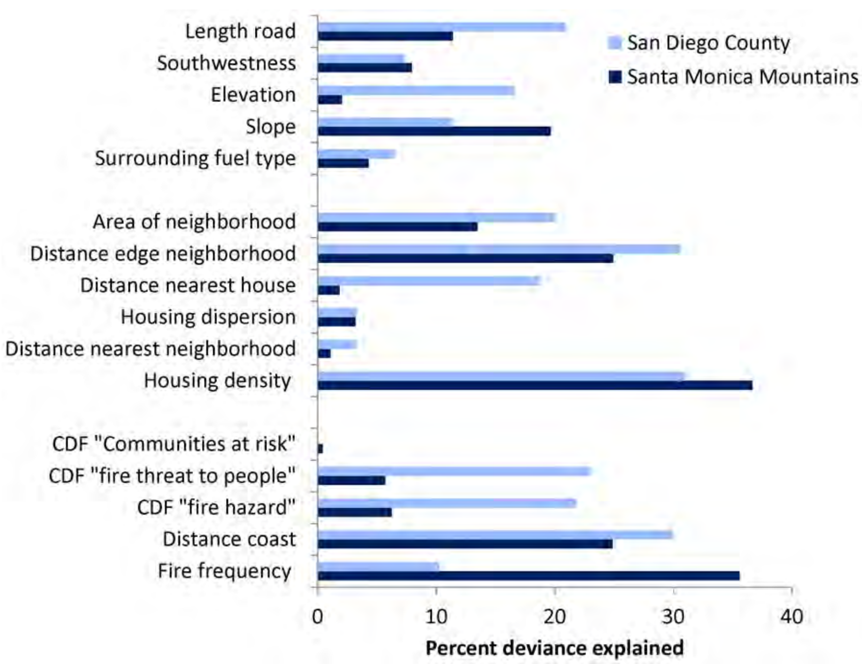

Figure 2. Percent deviance explained for generalized additive models (GAMs). GAMs explain the influence of firefighter access, biophysical variables, structure arrangement, and structure location on burned structures from fires during 2001–2010 in the Santa Monica Mountains, CA and San Diego County, CA. CDF – California Department of Forestry and Fire Protection.
doi:10.1371/journal.pone.0033954.g002

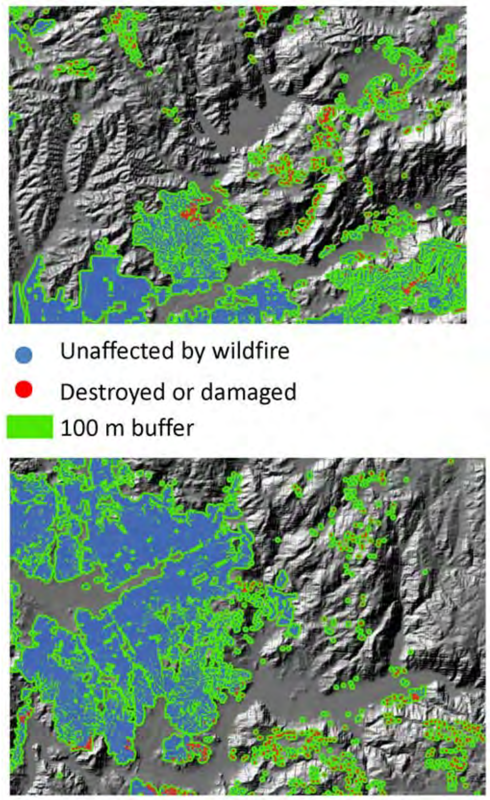

Figure 3. Maps from portions of San Diego County illustrating how housing arrangement influences the likelihood that a house will be lost from wildfire. Structures most likely to be burned by fires (in red) were: in areas with low to intermediate structure density; in small, dispersed housing clusters, close to the edge of the housing cluster, at intermediate distance to the nearest structure or housing cluster than structures that were unaffected (in blue).
doi:10.1371/journal.pone.0033954.g003

The multiple-regression GAM model for the Santa Monica Mountains included fire frequency, housing density, distance to edge of housing cluster, distance to coast, slope, area of housing cluster, southwestness, fuel type, housing dispersion, distance to nearest structure and housing cluster. Only nonparametric terms were selected, except fuel type, which was categorical. The deviance explained for the model was 65.7%, and the area under the curve (AUC) of receiver operating characteristic (ROC) plots, indicating the ability of the model to discriminate between burned and unburned structures on test data (20%), was 0.82.

The multiple-regression GAM model for San Diego County included housing density, distance to edge of housing cluster, area of housing cluster, elevation, fire frequency, fuel type, and housing dispersion. All terms included in the model were nonparametric except for distance to edge of neighborhood, which was linear, and fuel type. The deviance explained for the model was 45.5%, and the AUC was 0.87.

Our fire-hazard maps developed with the Maxent model using empirical data and multiple explanatory variables (Figs. 5 and 6) performed well. The AUC of receiver operating characteristic (ROC) plots on test data (15% withheld) was 0.987 for the Santa Monica Mountains and 0.923 for San Diego County.

In contrast, statewide fire-hazard maps developed using fuel rank and fire rotation were unable to predict which structures were burned by fire (Fig. 7). This poor performance of the statewide maps was also evident through visual comparison with maps of actual property loss (Figs. 5 and 6). Similarly, property loss was not substantially higher in the highest hazard or communities-at-risk areas of the statewide maps. In most cases, property loss was evenly divided among hazard levels (Fig. 8A and 8B), and even where a substantial proportion of burned structures were located in areas mapped as high fire hazard, most of the unaffected structures were also distributed in these high-hazard areas, suggesting high commission error (Fig. 8C and 8D). The most worrisome finding was that the majority of property loss occurred in areas not designated as at-risk (Fig. 8E and 8F).

The results of all sensitivity analyses indicated that the results were robust: the importance and ranking of variables remained essentially the same for all data sets at different buffer distances and certainty classifications (Table 3). Differences in results were slightly larger using different buffer distances than using all burned structures across a range of certainty levels versus all destroyed structures classified at the highest level of certainty. The main difference between the 200 and 100-m buffer analysis was that housing density was somewhat less important while distance to nearest housing cluster and southwestness were somewhat more important using the 200-m buffer in the Santa Monica Mountains. In San Diego County, housing dispersion and distance to the edge of housing cluster were somewhat more important using the 200-m buffer. We also found no substantial difference in results for the Maxent models.

After adding a spatial term, spatial autocorrelation was no longer present in the residuals of any of the models (Table 2). Also, although there were small differences in the coefficients between spatial and non-spatial models, the direction of influence consistently remained the same. The only variables that were no longer significant after accounting for spatial autocorrelation included the CDF communities at risk map, the distance to the nearest housing cluster, southwestness, and road length for the Santa Monica Mountains, and southwestness for San Diego County.

Discussion

Wildfire is a key process that interacts with all major components of the earth system, but fire frequency, extent, and/or severity are on the rise [1,2,21,22]. Residential losses to wildfire have also escalated despite enormous investments in wildland fuel manipulation, improvements in fire-safe codes and building regulations, and advanced fire suppression tactics. Therefore, our finding that housing arrangement and location were the most important contributors to property loss supports the notion that patterns of land use may be partly responsible for property loss in the wildland-urban interface [13].

One reason that property loss is related to the arrangement of housing across the landscape may be that the amount and arrangement of human infrastructure also strongly and non-linearly influence wildfire ignitions and frequency [7,23,24]. Therefore, the places where homes are most likely to burn may also be the places where fires are most likely occur, which is partly a function of the distribution of people. Thus, there may be spatial interactions and feedbacks between fire and housing patterns.

In southern California, as in many regions, humans cause most fires [7,23–25]. Thus, population growth and housing development increase fire frequency. Yet, although urban expansion increases fire frequency in general, the highest hazard tends to be in low-density housing areas, where structures are interspersed with wildland vegetation [9]. Scattered, isolated structures are more difficult for firefighters to defend, and poor firefighter access may explain why housing clusters with fewer roads were more vulnerable in San

Table 2. Model coefficients for generalized linear models (GLMs) estimated with and without autocovariate terms in the Santa Monica Mountains and San Diego County.

	Linear	*Autocovariate linear*	*Quadratic*	*Autocovariate quadratic*	*P-value*
Santa Monica Mountains					
Fire frequency 2001	0.860	0.440			<0.001
Distance coast	0.004	0.002	−7.0E-07	−4.0E-07	<0.001
CDF Fire threat	5.900	2.880	−8.5E-01	−3.9E-01	<0.001
CDF Fire threat people	3.070	1.540			<0.01
CDF Communities risk	−0.540	−0.280			NS
Housing density	1.010	1.130	−3.9E-01	−4.0E-01	<0.001
Distance housing cluster	0.006	0.004	−1.0E-05	−7.0E-06	NS
Housing dispersion	2.280	2.670			<0.001
Distance structure	0.020	0.020	−3.0E-05	−2.0E-05	<0.001
Distance edge	−0.021	−0.017			<0.001
Area housing cluster	−2.0E-07	−8.0E-08			<0.001
Slope	0.033	0.016			<0.001
Elevation	−0.001	−0.001			0.01
Southwestness	−0.002	0.002			NS
Road length	−2.0E-05	−2.0E-05			NS
San Diego County					
Fire frequency 2001	1.53	1.05	−0.33	−0.22	<0.001
Distance to coast	3.0E-04	3.0E-09	2.0E-04	2.0E-09	<0.001
CDF Fire threat	−0.54	−0.68	0.189	0.17	<0.001
CDF Fire threat people	2.27	1.69			<0.001
CDF Communities risk	−0.93	−0.51			<0.001
Housing density	−0.99	−0.47			<0.001
Distance housing cluster	0.005	0.004	−4.0E-06	−1.0E-06	<0.001
Housing dispersion	−3.08	−1.68	0.865	0.542	<0.001
Distance structure	0.007	0.004	−5.0E-06	−2.0E-06	<0.001
Distance edge	−0.02	−0.01			<0.001
Area of housing cluster	−2.0E-08	−7.0E-09			<0.001
Slope	0.17	0.12			<0.001
Elevation	0.001	0.003			<0.001
Southwestness	−0.005	−0.003			NS
Road length	−1.0E-06	−7.0E-07			<0.001

Quadratic terms were evaluated for all models, and coefficients are only provided for those models in which the quadratic term was significant in the non-spatial model.
doi:10.1371/journal.pone.0033954.t002

Diego County. However, there can also be situations in which high housing density contributes to structure-to-structure fire spread e.g., [26], depending on their flammability [27].

The importance of a structure's location on the landscape relative to the coast and historical patterns of fire frequency shows that certain places are more fire-prone than others, which in turn reflects how biophysical and human variables together create conditions that are particularly conducive to wildfire occurrence [2]. In our study areas, these relationships are also likely a function of a structure's location relative to predominant wind patterns and direction [28]. In the Santa Monica Mountains, certain fire corridors tend to burn repeatedly, and winds funnel down these corridors toward vulnerable structures located directly in their path. Here, the high-density coastal strip is narrow, and homes are closer to continuous vegetation than in San Diego County, where high-density development extends inland for much greater distances. This may be why houses were more likely to burn at a closer distance to the coast in the Santa Monica Mountains than in San Diego County. The low-density, high-risk areas in San Diego County are located farther inland where, if an ignition occurs there under extreme wind conditions, the fire is in its initial stages. Santa Ana winds blow from west toward the coast, and they are particularly dangerous in the beginning because they are usually most explosive and fast-moving right after they start, and it takes time to mobilize firefighting resources. Thus, the significance of distance to coast may be a proxy for other variables, such as the juxtaposition of housing density, contiguous fuels, and location relative to predominant wind patterns.

The importance of historical fire frequency suggests that, at least in non-forested ecosystems, fuel age may not be an important predictor of home loss [25], despite the fact that fuel age and time-since-fire maps are often used to delineate fire hazard. In fact, substantial property loss occurred when the primary surrounding fuel type was low fuel-volume grasslands. Although this result may seem counter-

Table 3. Percent deviance explained in generalized additive models (GAMs) for structures that were destroyed or damaged (Burned) and destroyed with the highest certainty (Destroyed); and for burned structures analyzed using a 200 m buffer distance (200 m).

	Burned	*Destroyed*	*200 m*	*Relationship*
Santa Monica Mountains				
Fire frequency 2001	35.59	31.63	NA	Positive
Distance coast	24.86	22.85	NA	Intermediate
CDF fire threat	6.23	4.37	NA	Intermediate
CDF fire threat people	5.69	5.01	NA	Positive
CDF Communities at risk	0.42	0.81	NA	Negative
Housing density	36.68	33.19	14.04	Intermediate
Distance housing cluster	1.08	1.46	14.23	Intermediate
Housing dispersion	3.18	2.23	4.24	Positive
Distance structure	1.85	2.17	NA	Intermediate
Distance edge	24.92	33	16	Negative
Area of housing cluster	13.47	12.88	18.06	Negative
Surrounding fuel type	4.3	3.18	NA	NA
Slope	19.66	17.79	18.31	Positive
Elevation	2.04	0.78	1.62	Negative
Southwestness	7.93	8.91	16.1	NA
Road length	11.4	11.2	13.98	Negative
San Diego County				
Fire frequency 2001	10.2	10.6	NA	Intermediate
Distance coast	30.0	28.19	NA	Intermediate
CDF fire threat	21.8	20.4	NA	Intermediate
CDF fire threat to people	23.9	24.1	NA	Positive
CDF Communities at risk	0.0	0.02	NA	Negative
Housing density	31.0	28.16	21.59	Negative
Distance housing cluster	3.2	2.92	0.97	Intermediate
Housing dispersion	3.3	2.85	8.62	Parabolic
Distance structure	18.7	15.73	NA	Intermediate
Distance edge	30.5	28.74	54.76	Negative
Area of housing cluster	20.1	16.41	10.63	Negative
Surrounding fuel type	6.5	4.90	NA	NA
Slope	11.4	13.94	10.61	Positive
Elevation	16.6	25.5	19.75	Positive
Southwestness	7.3	6.98	4.17	NA
Road length	20.9	19.6	15.4	Negative

The buffer distance used in all other analysis was 100 m. Relationship describes the shape of the response curve for all models. Ïntermediate signifies a nonlinear relationship in which values were highest at intermediate levels of the variable. Values listed as NA in 200 m were for variables that were only analyzed at the level of the individual house.
doi:10.1371/journal.pone.0033954.t003

intuitive, herbaceous fuels tend to have low fuel moisture, facilitate high wind speeds and fire spread, and have low heat requirements for ignition, thus promoting longer fire seasons and high fire frequency [29,30]. Grasslands also tend to ignite quickly, then carry fires into shrublands or woodlands [31]. These results suggest a need to reexamine the assumptions used in existing hazard maps and the management practice of converting shrublands to grasslands.

Fire hazard in the CDF statewide maps, as with most hazard maps [17–19,32], depends largely on the assumption that fuel properties are the primary contributors to fire danger. However, our empirical data indicate that, at least at the local scale considered here, fuel was not as significant as measurable factors related to the arrangement and location of structures. This is likely because the influence of fuel is complex and interacts with other risk factors [33]. Therefore, our empirical maps developed using a more comprehensive set of predictor variables, including fuel type, housing arrangement and location, and other environmental variables, performed better in distinguishing hazardous from non-hazardous areas.

Another reason for the discrepancy in map performance may be related to differences in mapping approach: while our approach used empirical data on actual structure loss, the statewide maps were developed based on a priori assumptions of where hazard is expected to be highest. At larger scales, such as the state level, the CDF fuel-based maps would likely perform better at picking out where homes are most vulnerable to fires. We also did not evaluate the CDF maps developed for local responsibility areas, which may better capture finer-scale patterns of hazard in local jurisdictions.

The fact that unburned structures in our analysis were more likely to be located in "communities at risk," whereas burned structures were more likely to be located outside of high-risk areas is potentially due to two reasons. At the most basic level, this may simply be caused by an incorrect identification of communities at risk. However, we caution that the discrepancy may also be due to scale effects and the definition of "community at risk." At a broad scale, "communities at risk" are likely located within areas that generally have the potential for hazardous fires, and places with more houses in such a danger zone are more likely to be identified as a "community at risk." However, at the structure level, low-housing density significantly increases the chance a house will burn – while it decreases the likelihood that at home will be included in a "community at risk." In summary, our results support the notion that property loss is a function of many physical and biological factors, in addition to characteristics of home construction and maintenance that we did not consider, such as roofing, construction materials, and home landscaping.

The effects of housing arrangement and location on the likelihood that a house will be destroyed or damaged by wildfire suggest that land use planning may be a critical tool for reducing fire hazard. Restricting development from hazardous locations has been effective for other hazards, such as flooding and the prevention of building on floodplains [34]. In the case of fire, new structures should be located and arranged in ways that not only minimize their exposure to hazard, but may also limit the increase in fire occurrence that often accompanies urban development. For example, our results suggest that in both study areas, new development would have a lower likelihood of burning if it were located away from fire-prone areas, such as wind corridors or steep slopes, and if new structures were arranged in intermediate-to high-density neighborhoods designed to minimize the amount of interface between homes and wildland vegetation. New development within large, existing urban areas, which typically also have better firefighter access, would also lower the likelihood of burning, compared to new development in more isolated, remote settings. Land use planning that considers minimizing future structure loss and prioritizing other fire prevention actions would be more informed with maps that reliably differentiate the most hazardous locations than with maps currently used for this purpose. Although the direction of influence was the same for most variables in the two study regions, the relative importance varied, and the distance from coast and elevation had opposite effects. This supports the notion that hazard is place-specific [35], and fire hazard mapping should therefore be individualized for specific landscapes.

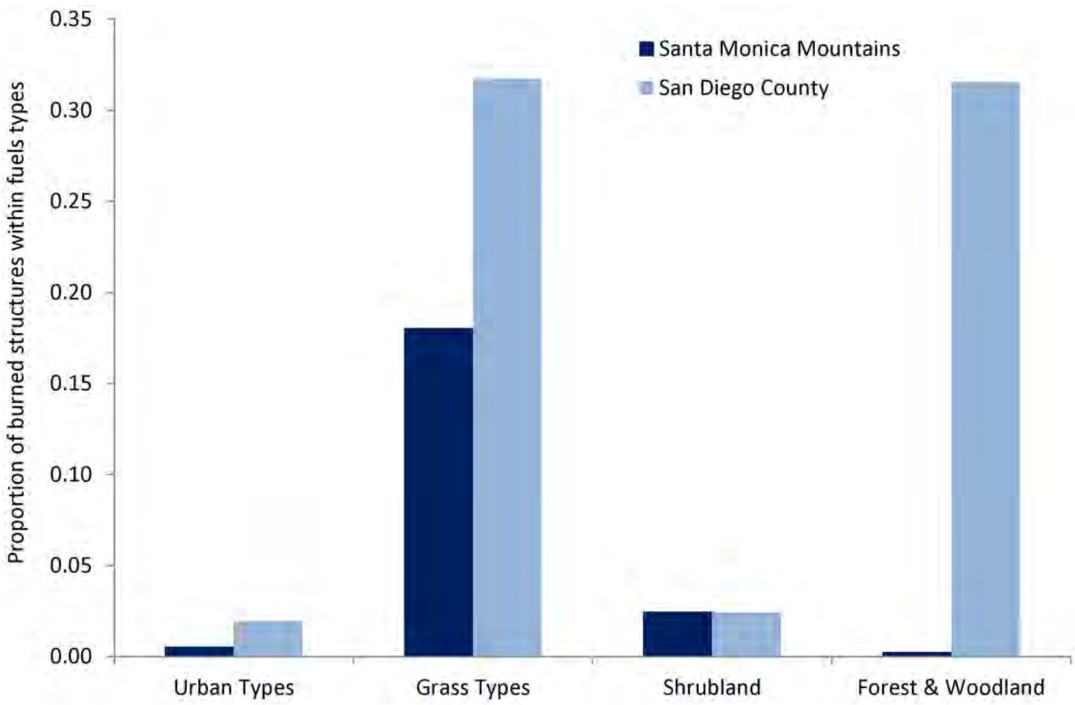

Figure 4. Proportion of burned structures within broad fuels types in the Santa Monica Mountains and San Diego County.
doi:10.1371/journal.pone.0033954.g004

Materials and Methods

Data and digitizing structures

We explained property loss by comparing structures that were burned (i.e., destroyed or damaged) by wildfires to those structures that were unaffected. The likelihood of a house burning in a fire has two major components: the first is the likelihood that there will be a fire, and the second is the likelihood that a structure will burn if there is a fire. That 'total' likelihood required us to include both structures inside and outside of fire perimeters in the model. We

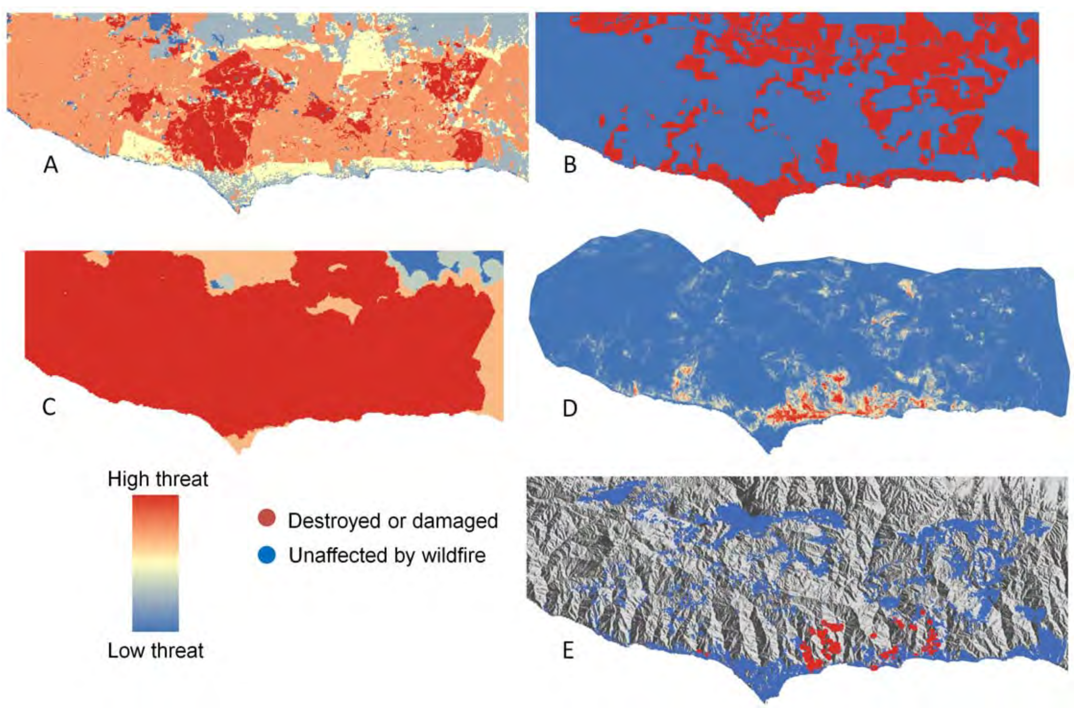

Figure 5. Fire hazard maps versus actual burned structures in the Santa Monica Mountains. (A) CDF "Fire threat" (B) CDF "Communities at risk" (C) CDF "Fire threat to people (D) Empirically based map showing probability of structure being burned by fire (E) Structures that were destroyed or damaged (red) and unaffected (blue) by wildfire from 2001–2010. CDF – California Department of Forestry and Fire Protection.
doi:10.1371/journal.pone.0033954.g005

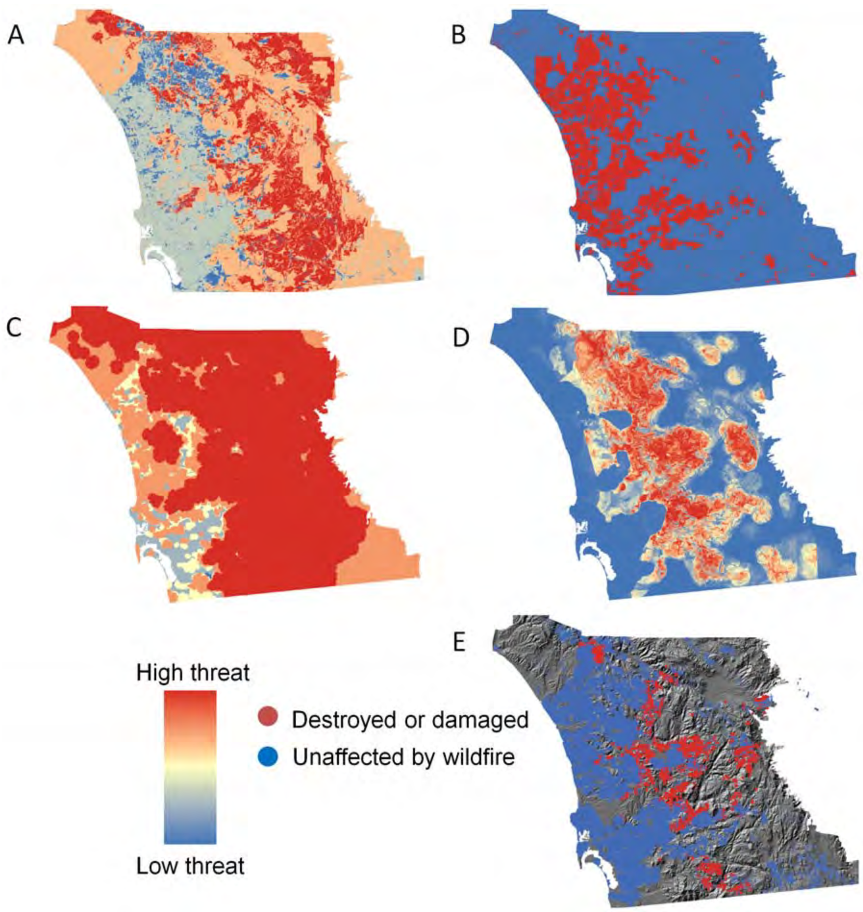

Figure 6. Fire hazard maps versus actual burned structures in San Diego County. (A) CDF "Fire threat" (B) CDF "Communities at risk" (C) CDF "Fire threat to people (D) Empirically based map showing probability of structure being burned by fire (E) Structures that were destroyed or damaged (red) and unaffected (blue) by wildfire from 2001–2010. CDF – California Department of Forestry and Fire Protection.
doi:10.1371/journal.pone.0033954.g006

also wanted to account for the full range of variation for the explanatory variables because planning decisions occur at a landscape scale, not just for a subset of structures within fire perimeters. Therefore, we digitized and analyzed all residential structures within the Santa Monica Mountains National Recreation Area in Ventura and Los Angeles counties, California as well as the portion of San Diego County that falls within the South Coast Ecoregion. Using onscreen digitizing, we carefully scanned the most recent aerial imagery available in Google Earth for each study area and placed a point over every visible structure. We digitized all structures, including homes, outbuildings, and guest houses, because we assumed that the factors explaining which homes burned were similar to those explaining the burning of other structures. Because most of the vegetation in our study areas is non-forested, there were very few occasions in which vegetation canopy obscured structures in the imagery. Structures were in all cases at least partly visible, even if they were covered by vegetation, and we looked at earlier images available in Google Earth to confirm where structures were located. The canopy cover was generally lower farther back in time.

Due to the large number of structures in San Diego County, many of which are located in high-density urban core areas, we used a parcel map to facilitate the digitizing process. For small parcels (area <900 m^2, equivalent to one 30×30 m pixel of the environmental data, see below), we placed the point representing the structure in the centroid of the polygon instead of digitizing the exact location of the structure within the parcel boundary. We assumed the location of the structure within the boundary of small parcels would not significantly alter the overall calculations of spatial pattern among structures. However, for large parcels, the location of the structure within the parcel boundary may be important because the parcel may include more than one pixel, and thus, the environmental data are associated with the structure may depend on structure location. Distance calculations to other structures could also be more substantially influenced by the location of structures in large parcels, which is why we analyzed the Google Earth imagery to place those structures accurately. We did not digitize houses under construction at the date the remote sensing imagery was recorded.

To identify burned structures, we developed an initial address list and spatial database of structures destroyed or damaged by fires from a variety of records, including official incident reports, county assessors' offices, public works departments, city records, and newspaper reports. Because these records were incomplete, we also used Google Earth imagery for a systematic visual analysis to correct geocoded locations and to identify additional structures that had not been documented. For this analysis, we identified burned structures by comparing pre-fire to post-fire images that are available in Google Earth. To develop a data set of houses to inspect for property loss, we selected all structures that fell within and up to 80 m outside any perimeter of a fire that occurred since 2001 in both study areas. We used 80 m because it is twice the distance beyond which flame fronts are not expected to ignite

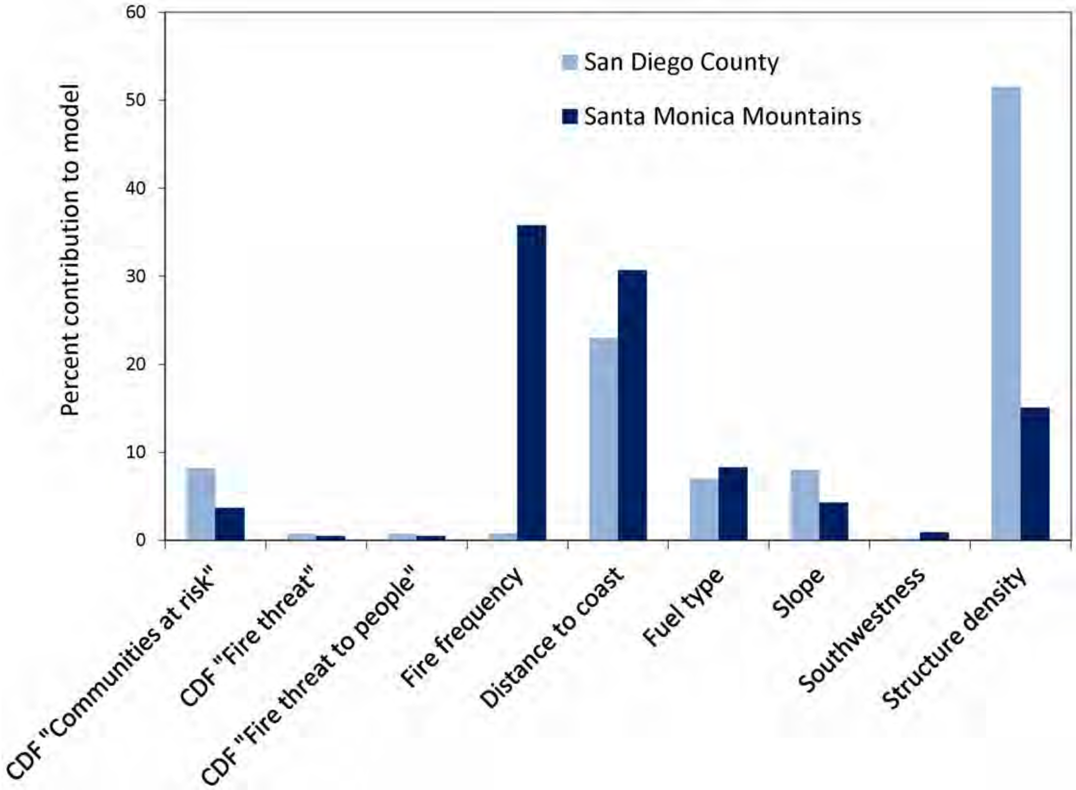

Figure 7. The percent contribution of explanatory variables in Maxent empirical fire hazard model. CDF – California Department of Forestry and Fire Protection.
doi:10.1371/journal.pone.0033954.g007

wood [36].The determination of destroyed or damaged structures was based on data collected from official records combined with visual inspection of imagery. Destroyed structures were those in which the house had completely burned to the ground, whereas damaged structures where those that had partially burned. Because damaged structures were more difficult to identify in the imagery, we ruled that if a fire had clearly burned into the property (i.e., if vegetation had visibly been burned), the structure was classified as damaged.

For both the destroyed and damaged structures, we assigned an estimate of certainty for the classification and conducted sensitivity analyses to test if results were similar for destroyed structures that were classified with the highest level of certainty versus a complete dataset with all destroyed and damaged homes at all certainty levels. In our classification, we indicated "1" for uncertain if the house was damaged or destroyed; "2" for fairly certain; "3" for absolutely certain. Since the results were similar (Table 3), we used the full dataset in our analyses to obtain the largest sample size. Although rare, if two buildings burned on a parcel, we only included one in our analysis. For those structures that burned in more than one fire, which only occurred in San Diego, we only used the data for the first fire to avoid double counting of structures in the spatial analysis.

Explanatory variables

To fully explore the influence of housing arrangement and pattern, we analyzed both the spatial relationships among individual structure locations and the arrangement of structures within housing clusters. Housing clusters were defined as groups of houses with a maximum distance of 100 m from each house to any other house [24]. We calculated these housing clusters by creating a 100 m buffer around each structure and dissolving overlapping boundaries. Thus, areas with many homes within 100 m of each other constituted one large housing cluster, while smaller housing clusters contained fewer or more isolated homes. This allowed spatial analysis based on the spatial and biophysical properties of the structure locations as well as spatial and biophysical properties of the housing clusters within which structures were located. Thus, some variables were calculated for the housing cluster in which the structure was located and the values for that housing cluster were assigned back to the structure. Other variables were calculated only for the location in which the structure was located.

Because our objective was to better understand the landscape factors that significantly contribute to the likelihood that a house will burn in a wildfire, particularly focusing on those factors that are relevant to land use planning, we only assessed variables affecting exposure of structures to wildfires (i.e., fires spreading into the property and reaching the structure, or embers landing on a structure). We did not consider factors such as urban landscaping or housing construction materials within the home ignition zone that determine whether the house survived the exposure. To evaluate the influence of housing arrangement and location on susceptibility to wildfire, we considered a suite of variables representing different spatial configurations and locations of structures as well as additional environmental variables that may affect property loss due to their potential control over fire spread behavior, fuel moisture, or flammability [23,37] (Table 1).

Housing arrangement variables. We evaluated the area of the housing cluster to test the hypothesis that small, isolated groups of structures are more susceptible to wildfire than large groups of structures. Housing density was calculated as the number of structures divided by the area of the housing cluster. For every

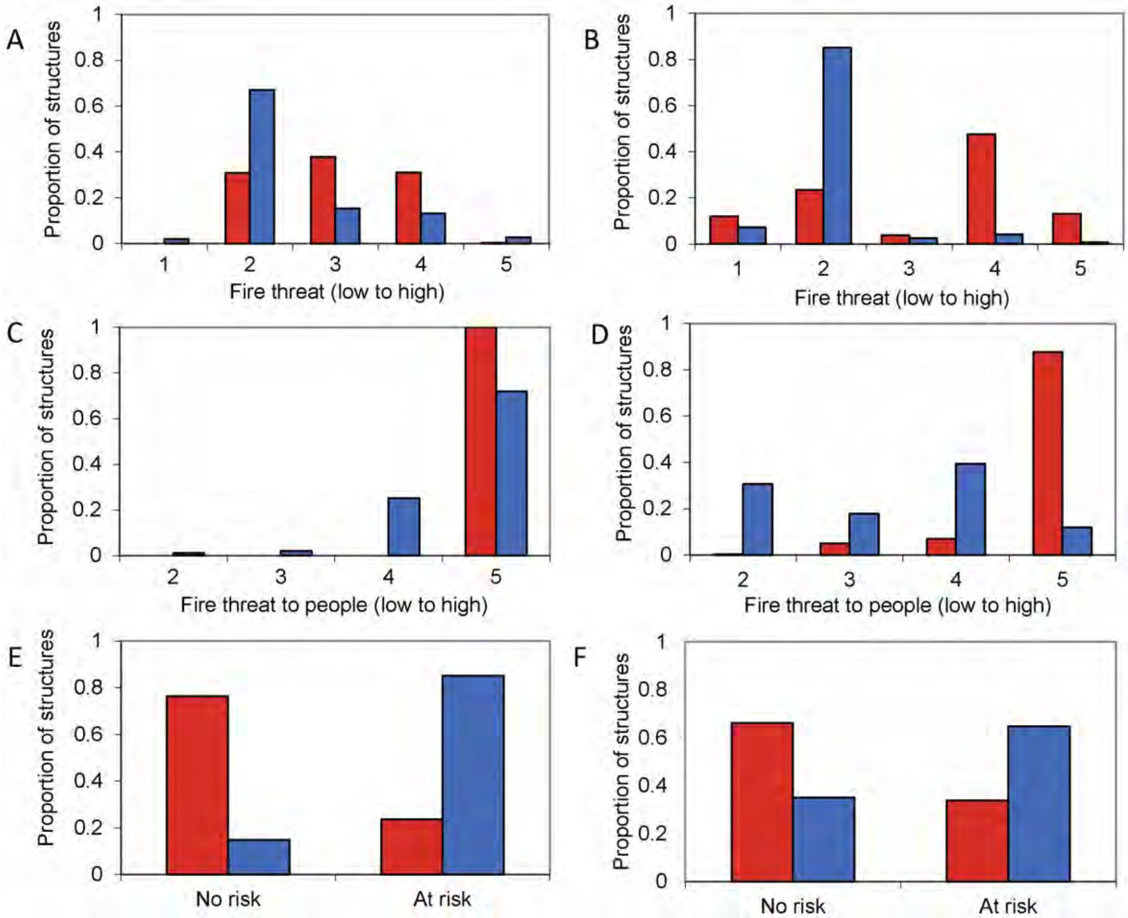

Figure 8. Distribution of actual burned structures in classes of statewide fire hazard maps. Proportion of structures burned (in red) or unaffected (in blue) distributed within map classes of: (A) CDF "Fire threat" in Santa Monica Mountains. (B) CDF "Fire threa" in San Diego County. (C) CDF "Fire threat to people" in Santa Monica Mountains (D) CDF "Fire threat to people" in San Diego County (E) CDF "Communities at risk" in Santa Monica Mountains (F) CDF "Communities at risk" in San Diego County. CDF – California Department of Forestry and Fire Protection.
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structure, we calculated the distance to the edge of the housing cluster to evaluate whether structures in the interior of housing clusters were less susceptible to wildfire than structures at the edge. To assess local spatial patterns, we calculated the distance from each structure to its nearest neighbor, and for overall landscape configuration of structures, we calculated the distance from each housing cluster to the next nearest housing cluster. Finally, we calculated the coefficient of variation, or, the standard deviation of distance among structures in a housing cluster divided by the mean to assess housing dispersion, or, regularity of housing pattern.

Housing location variables. To test whether structures located in fire-prone parts of the landscape were more likely to be burned, we overlaid fire perimeter polygons compiled by the California Department of Forestry (CDF)-Fire and Resource Assessment Program and created a continuous raster map representing the number of times an area had burned from the beginning of record-keeping, 1878, until 2001. We did not include any fires that occurred after 2001 to ensure that our count of fire frequency was independent of those fires that burned the structures in our analysis. We calculated the distance from the coast for every structure as another way to test whether a structure's location influences its likelihood to be burned. In southern California, a number of variables that influence fire patterns, including climate, terrain, and vegetation distribution, are correlated with the distance to the coast. Distance to the coast is also correlated with housing patterns, and may influence how a house is arranged relative to the major wind corridors in the region [38]. Although the inclusion of weather data at the time of fires would be more directly related to fire behavior and danger, the high variability of weather over space and time limits the ability to relate specific weather data to the place and time that fires burn structures. First, we did not know the exact time that fires burned structures, and thus could not retrieve the temporally matching weather data. Second, weather stations are generally located too far away from where fires burned homes to reflect local variability in weather conditions.

Biophysical variables. Terrain-derived variables included the average elevation and percent slope of the housing cluster as well as a cosine-transformation of aspect to create an index of 'southwestness,' which could account for the influence of solar radiation and aspect on fuel properties and fire behavior. For each structure, we also determined fuel type in the surrounding by identifying the most common fuel model within a 1 km buffer of the structure. This buffer allowed us to identify the vegetation types fires spread through before reaching the property. Our objective for this analysis was to determine which broad-based fuel classes were most closely associated with structure loss. If more than one fuel type occurred in the buffer, we used the fuel type present in the majority of the area. We obtained spatial fuel model data, developed for fire behavior modeling, from statewide maps developed by the U.S. Forest Service (N. Amboy) at 30 m resolution. The fuel models provided in the USFS maps were created through remote sensing and classified according to Scott and Burgan [39]. From this map, we grouped together the fuel models from broad fuel types (representing grassland, shrubland, and timber). We also grouped agriculture, barren land, and urban land into one type representing mostly urban landscaping and impervious surface (i.e., with little wildland vegetation).

Firefighter access. As a way of indirectly assessing firefighter access to the structure, we calculated the length of road within each housing cluster using the 2000 US Topologically Integrated Geographic Encoding and Referencing system TIGER/line files from the US Census.

Statewide fire hazard maps

Statewide fire hazard maps were available online from the California Department of Forestry and Fire Protection (CDF) [20].We downloaded the Wildland Urban Interface (WUI) "fire threat" data product that includes a series of maps that rank the wildland fire threat to human development. The term "fire threat" in these maps is used analogously to the way we use the term fire "hazard" or, a phenomenon or place where harm is likely to occur.

The "fire threat" map is based on the hazard ranking of different fuels types combined with the fire rotation period, or, the average area burned during the period of record for different vegetation types. Fuels types with higher fuel loads and vegetation types that burned most frequently were considered most hazardous. The "fire threat to people" map is based on a cost-distance calculation that estimates distances from areas of high fire hazard. As an example, the highest "fire threat to people" is calculated as a maximum of 2400 m from "extreme threat" in the fire threat map. Finally, the "communities at risk" map depicts U.S. Census communities with more than 1 house per 8.09 ha (20 acres) that are located in areas with "high fire threat to people."

The CDF provides additional fire hazard severity maps developed separately for state and local responsibility areas. The finer-scale maps for local responsibility areas, which include incorporated cities, cultivated agricultural lands, and portions of the desert, are limited in extent and only overlap a small portion of our study areas. Due to the limited extent of the local responsibility area maps, and the fact that the state responsibility maps were still being refined, we did include these in our analysis. Their proposed modeling approach will be based upon the existing fire threat and communities at risk maps and will be refined to include additional methods that characterize brand production from vegetative fuels.

To evaluate how well the CDF statewide fire hazard maps corresponded to actual burned structures, we included the three maps as predictor variables in our statistical analyses and quantified the distribution of burned and unaffected structures within the different classes of each map.

Analysis

To identify the variables that best explain property loss and to estimate the relative contribution of each variable, we developed generalized additive models (GAMs) using a binary response (i.e., house burned or unaffected by fire) and logit link. We used three target degrees of freedom for smoothing splines for our continuous explanatory variables. Because we wanted to compare the independent relative variance explained for all explanatory variables, we estimated separate regression models for each variable. However, we also calculated the correlation coefficients among all variables and developed multiple-regression models with non-correlated variables for each study area. We used a stepwise selection procedure, entering variables according to amount of deviance explained and exploring both forward and backwards directions. We used AIC as the selection criterion for variable selection. To develop the models, we split the data for training and testing (withholding 20% of the data for testing) so we could calculate the area under the curve (AUC) of receiver operating characteristic (ROC) plots on an independent dataset to quantify model performance.

We used GAMs because prior studies reported nonlinear relationships between fire patterns and many of our predictor variables [7,23,24]. Unlike parametric statistical methods, such as generalized linear models (GLMs), in which nonlinear relationships are specified *a priori* (e.g., through polynomial terms) in the model, GAMs allow the structure of the data to determine the shape of the response curves. Thus, GAMs provide a more flexible and automated approach for identifying and describing nonlinear relationships [40,41]. We used the GAMs to estimate the shape of response curves and to calculate deviance explained (D^2, analogous to R-squared in linear regression) for all explanatory variables.

Although non-parametric methods, such as GAMs, tend to be less sensitive to the effects of spatial autocorrelation than other model approaches [42], we wanted to ensure that spatial autocorrelation did not significantly influence the results of our analysis. The main concerns about spatial autocorrelation in regression models are inflated significance values and biased coefficients [42,43]. GAMs do not estimate regression coefficients, which are replaced with smoothing functions. This is why we also fit GLMs to our data because they are parametric models similar to GAMs, but they estimate coefficients. Therefore, the GLMs allowed us tocheck the influence of autocorrelation on both coefficients and the significance of variables. The GLMs also allowed us to test whether our results were robust by comparing two modeling methods. We first developed non-spatial GLMs, and fit linear and quadratic terms for all variables (except for fuel type, which was categorical). After detecting residual autocorrelation in these nonspatial models using Moran's I [43], we calculated an autocovariate term to account for the influence of neighboring values on predictions, and included as the term as an additional explanatory variable in models. To calculate the autocovariate term, we specified a neighborhood radius of 1, which finds the minimum distance for which all observations (i.e., structure locations) are linked to at least one neighbor. The influence of structures located within any neighborhood radius was weighted by inverse distance. . After fitting these autocovariate models, we used Moran's I to recheck for spatial autocorrelation of model residuals, compared the coefficients to the nonspatial models, and checked variable significance after incorporating the autocovariate term..All model fitting and evaluation were accomplished using the gam, spdep, vegan, and ROCR packages for R [44].

Empirical fire mapping

To develop empirical fire hazard models and maps, we selected Maxent [45], a machine-learning method that is best recognized for creating species distribution models and maps. We selected Maxent because it outperforms other presence-only and presence-background species distribution modeling methods [41] and has been applied successfully to map the distribution of fire [46]. Maxent assumes that the best approximation of an unknown distribution (e.g., fire hazard) is the one with maximum entropy. The model iteratively evaluates contrasts between values of explanatory variables at locations of the response variable (i.e., burned structures) and for averages of the explanatory variables across the entire study area. The output is an exponential function that assigns a hazard probability (i.e., probability of structure being burned) to each site or cell of a map. In the output map, areas of predicted high risk that do not have structures on them represent environmental conditions similar to those in which structures have actually burned.

Because mapped predictor variables were required for the modeling, so that conditions similar to those where structures were burned could be delineated continuously across the landscape, we created maps representing a subset of the variables that we explored with the regression analysis. These variables represented a combination of structure arrangement, location, and biophysical variables, including: interpolated structure density, distance to coast, fuel type, slope, historical fire frequency, and southwestness. We developed models that included CDF fire hazard maps as predictors to test their importance relative to the other predictor variables. However, for generating maps and quantifying model performance, we only used models that did not include CDF predictor variables.

Sensitivity tests

The results of our analysis may have been affected by the size of the buffer that we used around structures to create housing clusters, the degree of impact of fire on the structure (i.e., destroyed or damaged), and certainty of the classification (i.e., 1–3). Therefore, to evaluate how sensitive our results were to these variables, we created housing clusters around structures using a 200 m buffer and compared the regression results for which housing cluster was relevant in the to those obtained when using a 100 m buffer. We also performed separate regressions using only those structures that had been destroyed with complete certainty (a "3") and compared those to the regressions of all burned structures at all certainty levels. For the Maxent analysis, we also compared models using only structures that were destroyed with the highest level of certainty to models using all burned structures at all certainty levels.

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Author Contributions

Conceived and designed the experiments: ADS JEK ABM TJB VCR. Performed the experiments: ADS ABM TJB. Analyzed the data: ADS JEK ABM. Wrote the paper: ADS JEK ABM TJB VCR.

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The relative influence of climate and housing development on current and projected future fire patterns and structure loss across three California landscapes

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ABSTRACT

Climate and land use patterns are expected to change dramatically in the coming century, raising concern about their effects on wildfire patterns and subsequent impacts to human communities. The relative influence of climate versus land use on fires and their impacts, however, remains unclear, particularly given the substantial geographical variability in fire-prone places like California. We developed a modeling framework to compare the importance of climatic and human variables for explaining fire patterns and structure loss for three diverse California landscapes, then projected future large fire and structure loss probability under two different climate (hot-dry or warm-wet) and two different land use (rural or urban residential growth) scenarios. The relative importance of climate and housing pattern varied across regions and according to fire size or whether the model was for large fires or structure loss. The differing strengths of these relationships, in addition to differences in the nature and magnitude of projected climate or land use change, dictated the extent to which large fires or structure loss were projected to change in the future. Despite this variability, housing and human infrastructure were consistently more responsible for explaining fire ignitions and structure loss probability, whereas climate, topography, and fuel variables were more important for explaining large fire patterns. For all study areas, most structure loss occurred in areas with low housing density (from 0.08 to 2.01 units/ha), and expansion of rural residential land use increased structure loss probability in the future. Regardless of future climate scenario, large fire probability was only projected to increase in the northern and interior parts of the state, whereas climate change had no projected impact on fire probability in southern California. Given the variation in fire-climate relationships and land use effects, policy and management decision-making should be customized for specific geographical regions.

1. Introduction

As one of the most fire-prone places in the world, California is globally recognized for its long history of wildfire-related losses of homes and human lives. Wildfire is also important for shaping ecological structure and function (van Wagtendonk, 2018), but many of California's diverse fire regimes, as those across the world, are changing in response to past fire management (e.g., Steel et al., 2015), invasive species (e.g., Syphard et al., 2017a), land use change (e.g., Mann et al., 2016), and climate change (e.g., Westerling and Bryant, 2008). Climate and land use patterns, in particular, are expected to change dramatically in the coming century, raising concern about their effects on fire regimes and subsequent impacts to human communities across the world. California is expected to embody a wide range of these changes and their impacts, and the risk to human communities is complex because it requires predicting how and where climate or land use change will alter fire patterns, i.e., the long-term spatial and temporal characteristics of fire events on a landscape. Manifestation of change will depend upon both the nature and

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strength of the drivers and their relative impacts in different regions.

There is evidence from historical patterns and modeling studies that climate change will lead to large changes in fire extent and severity (e.g., Westerling et al., 2006; Jolly et al., 2015; Abatzoglou and Williams, 2016; Restaino and Safford, 2018). However, the relationships between climate and fire are nuanced and complex (Krawchuk et al., 2009; Bradstock, 2010; Doerr and Santín, 2016) and vary in nature and strength geographically (Littell et al., 2009; Hessl, 2011; Keeley and Syphard, 2017). One of the clearest factors that determines whether a fire becomes large is wind speed (Abatzoglou et al., 2018). Large, wind-driven fire events have been responsible for the vast majority of structures lost in California wildfires (Keeley et al., 2009), including the recent fires in 2017 and 2018. Beyond weather, climate controls fire size directly via temperature, and also via its short and long-term effects on fuel volume and moisture content, which are important controls on fire behavior (Keeley and Syphard, 2016). Thus, given that hot, dry conditions are generally associated with fire, and that temperatures and moisture deficit are projected to increase globally, there is widespread concern that climate change will lead to greater fire activity. However, feedbacks between climate, vegetation, and fire are likely to mediate these effects (Bowman et al., 2014; Parks et al., 2016; Syphard et al., 2018).

Adding to the complexity, changes in human land use and population are also expected to alter spatial and temporal characteristics of future wildfires, and these effects may also interact with climate-driven effects. Humans affect fire patterns in a variety of ways, including deliberate or accidental ignitions, prescribed burning and mechanical vegetation treatments, and suppression activities; humans also change fire behavior and extent through landscape fragmentation, cultivation practices, landscaping, and flammability of buildings. Given the diversity of these effects, recent studies highlight that one of the main problems for prediction of fire patterns and related human impact is that human presence may dampen or override the influence of climate in driving fire activity (Higuera et al., 2015; Ruffault and Mouillot, 2015; Mann et al., 2016; Syphard et al., 2017b). Another complexity is that the anthropogenic and biophysical factors that influence patterns of small fires have been shown to differ from the factors that drive large fires, particularly in areas where most fires are caused by humans (Syphard et al., 2008, 2017, Barros and Pereira, 2014). This is likely due to inherent geographical and biophysical differences between those fires that are easily suppressed and those that escape control (Moritz, 1997; Hantson et al., 2015).

In California, the vast majority of fires are human-caused (Syphard et al., 2007; Balch et al., 2017), but the spatial and temporal pattern of ignition causes and patterns varies widely across the state (Keeley and Syphard, 2018). Contrary to what might be expected, fire activity is not highest where population is highest. Instead fire frequency, and to a lesser extent, area burned, tend to peak at low- to intermediate population and housing density (Syphard et al., 2007; Westerling and Bryant, 2008; Mann et al., 2016); this relationship has also been observed in other areas across the globe (Syphard et al., 2009; Aldersley et al., 2011; Bistinas et al., 2013). This hump-shaped relationship reflects, in part the increased ignitions in rural and residential areas (compared to wildlands), balanced against lower potential for fire spread and/or greater suppression in urban areas (Butsic et al., 2015).

Beyond housing density's effect on fire patterns, studies have shown that structure loss in southern California is significantly correlated with low-to-intermediate housing density (Syphard et al., 2012, 2013, 2016). Other work in southern California and Colorado (Alexandre et al., 2016a), and a national analysis across the U.S. (Alexandre et al., 2016b), identified the spatial arrangement of housing development, in addition to topographic conditions, as consistently more important than vegetation-related variables in explaining structure loss to wildfire. Although small, isolated clusters of development were consistently associated with structure loss, in some cases, high housing density in those clusters contributed to higher structure loss. In addition, high-density development has been implicated in structure loss in some fires due to fire spread among structures (Cohen and Stratton, 2008; Price and Bradstock, 2013), as seen recently in the Coffey Park neighborhood in Sonoma County, CA in 2017 (Nauslar et al., 2018). House-to-house spread is also suspected for contributing to massive structure loss in the Camp Fire in Butte County in 2018. The role of building codes and ignition resistance has yet to be examined in such loss patterns, however.

Despite clear evidence of a nonlinear relationship between housing density and patterns of fire, and subsequently on patterns of structure loss, much is unknown regarding the scale and potential thresholds that define the relationship between housing density and fire. For example, Bistinas et al. (2013) reported regionally varying thresholds determining the shape of the nonlinear relationship between population density and area burned across the globe. Much more work is needed to identify the relative roles of climate and human presence in determining fire and structure loss patterns, and to determine the extent to which these relationships vary regionally. This is particularly critical considering there have already been rapid changes in both climate patterns (Swain et al. (2018)) and land use patterns in flammable landscapes (Radeloff et al. (2018)).

To better understand the relative importance of climatic and land use factors on long-term spatial and temporal patterns of fire and structure loss and how these patterns vary from region to region, we developed an integrated modeling framework to quantify variable importance and to map the distribution of current and future projected probability of fires and structure loss in three California study areas. These regions vary biophysically but have all experienced substantial residential losses from wildfire. We first developed statistical models and maps based on the association of climate, biophysical, and anthropogenic variables with small and large fire patterns, and then we modeled structure loss as a function of those variables and the projected probabilities of large fires. After quantifying and mapping current relationships, we projected future large fire and structure loss probability under different climate and housing growth scenarios. We address the following questions:

1) How do fire patterns vary by housing density and climate?
2) How do structure loss patterns vary by housing density and climate?
3) Do these relationships vary from region to region?
4) Which is likely to be the most influential driver of future change, climate or housing development, across our study regions?

2. Methods

2.1. Study areas

The northern coastal study area (NC) includes more than 1.4 million ha of land spanning all of Lake, Sonoma, and Napa Counties, in addition to small parts of Mendocino, Glenn, Colusa, Yolo, and Solano Counties (Fig. 1). The vegetation is characterized by a mosaic of oak woodlands, grassland, chaparral, and Douglas fir/hardwood ("mixed evergreen") forests, with montane conifer forests at higher elevations. Extensive exurban development has occurred in recent decades, and numerous homes have been destroyed by fire here; in particular, the 2017 'wine country' wildfires in this region resulted in 44 lost lives and nearly 9000 destroyed buildings.

The Butte and Plumas Counties study area (BP) included the full counties, plus a 20 km buffer to incorporate a larger urban-wildland gradient (2.2 million ha). Across this gradient spanning from the Central Valley to the northern cismontane Sierra Nevada, the vegetation transitions from grassland and chaparral to mixed evergreen and then pine- and fir-dominated forests, with a very small component of subalpine forest on the highest peaks (Fig. 1). Although the higher-elevation forests are mostly protected by the U.S. Forest Service and National Park Service, substantial residential development has been

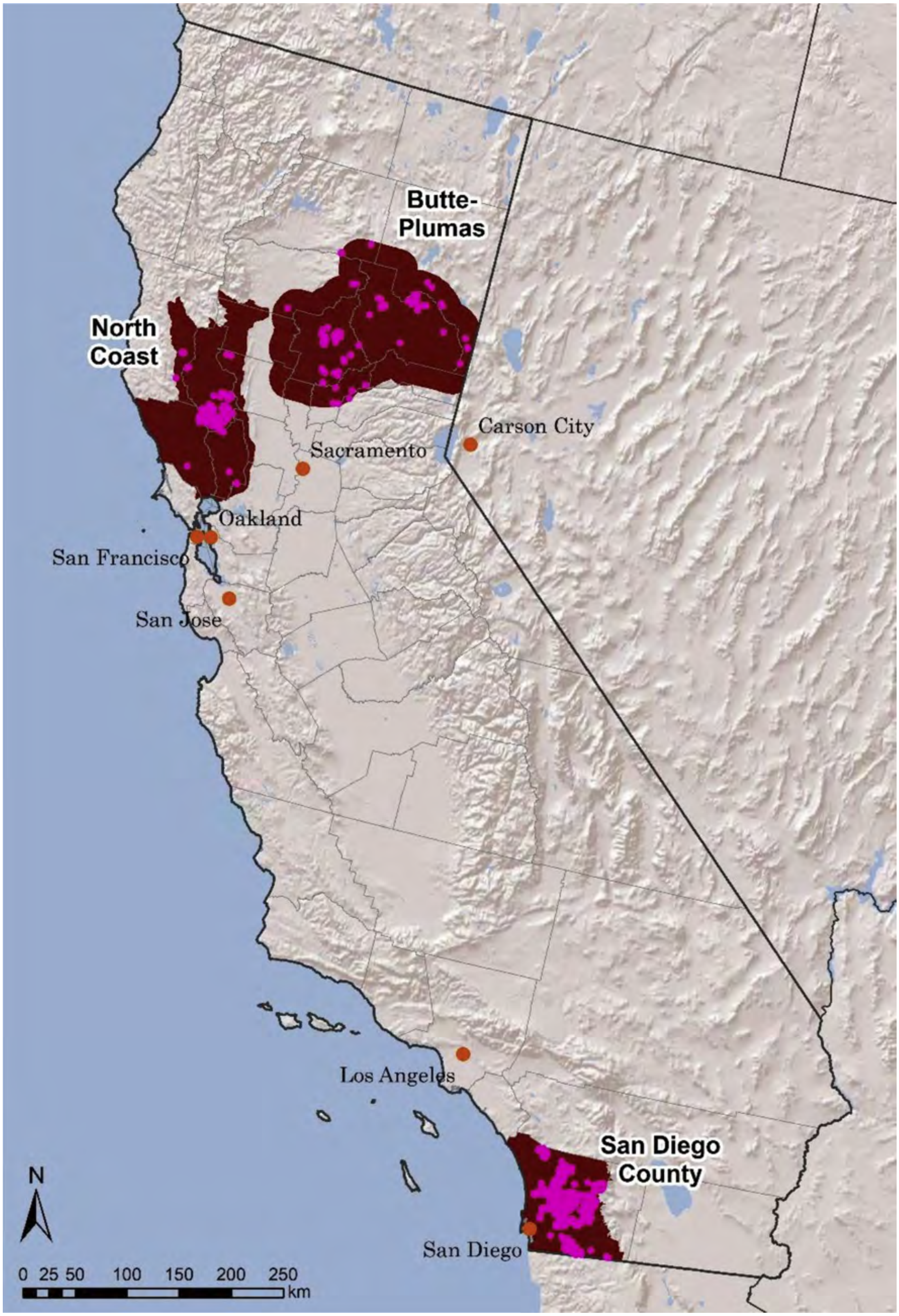

Fig. 1. Boundaries of three California study areas, with destroyed structure locations (2000–2015) in pink (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

occurring in the foothills. Wildfires destroyed more than 1000 structures here between 2000 and 2015 (the period we used for modeling); in 2018, the Camp Fire alone resulted in 86 fatalities and more than 18,000 destroyed structures. While all three study areas are characterized by Mediterranean climates, with warm to hot, dry summers and wet winters, BP is the only study area to receive substantial precipitation in the form of snowfall.

The third study area, coastal San Diego County (SD), is a rapidly developing, highly fire-prone region with an extensive wildland-urban interface. The majority of the study area is dominated by coastal sage and chaparral shrublands intermixed with grasslands and mixed oak woodlands, and some montane conifer forests at the highest elevations. Native shrubs are threatened by too-frequent fire, typically human-caused, which could lead to extensive replacement with more fire-prone herbaceous vegetation (Syphard et al., 2018b). Thousands of structures have been destroyed during large, Santa Ana wind-driven fire events (Keeley et al., 2009).

2.2. Data

For all dependent and independent variables (Table 1), we first assembled consistent statewide spatial data coverage, which we then clipped to the boundaries of the three study areas. We also rasterized all vector data, or resampled all grid data, to match the resolution of the climate variables (270 x 270 m).

2.2.1. Fire data

To determine whether different factors influence fire ignitions and large fire patterns across the study areas, we created statistical models based on two sources of data (Table 1). The first dataset included the location of origin for all fires of any size from the most recent decade of data available, 2003–2013 and was available via spatial coordinates indicating the point location of fire ignition. The data, from the National Interagency Fire Program Analysis, Fire-Occurrence Database (FPA FOD), include fire size and date as attributes and are publicly available for the whole country (Short 2014). Spatial clustering of points has the potential to lead to autocorrelation, which can inflate the accuracy of statistical distribution models (Veloz, 2009). Although we were less interested in model accuracy than we were in variable importance and maintaining comparability of model results, we nevertheless spatially filtered the presence data to ensure no duplicate points within a 500-m radius, as spatial filtering can reduce the effect of sample bias (Veloz, 2009). While this distance was not systematically determined, this was the radius used in Syphard et al. (2018) that best attained the appropriate number of samples per fire, using the method described in Davis et al. (2017).

We developed a second dataset for large fire locations using a separate comprehensive statewide fire perimeter database, provided by the State of California Fire and Resource Assessment Program (FRAP, http://frap.fire.ca.gov/data/frapgisdata-subset). We only considered large fires from these data (> =40 ha), and, based on the method developed by Davis et al. (2017), we generated a random sample of points within all fire perimeters from a baseline period of 1985–2015, the most recent 30 years available. That is, to calculate the number of random points to generate for each fire in the database, we took the square root of the ratio of the given fire's area to the area of the smallest fire in the study area as recorded in this dataset. Because a filter distance of 500 m resulted in too-small sample sizes for many of the fires, we reduced the filter distance to 400 m.

We considered the two fire datasets to capture two different processes, where each process potentially has its own set of drivers. The 'fire ignitions' dataset reflects the spatial patterns of ignitions (which is an outcome of fire initiation processes), whereas the 'large fires' dataset reflects a discrete sample of burnt locations (which is an outcome of fire spread processes).

2.2.2. Structure loss data

The dependent variable for the structure loss models was the location of any structure that had been destroyed in a fire from 2000 to 2015 (Table 1). The baseline data were developed by Alexandre et al. (2016), and included all destroyed structure locations across fires in the U.S. from 2000 – 2010. These data were created by examining, for all wildfires recorded in the Monitoring Trends and Burn Severity dataset (MTBS, https://mtbs.gov), Google Earth historical imagery from the closest dates before and after the fires. Within each fire perimeter, Alexandre et al. digitized all buildings before the wildfire; then, any building that had been completely removed in the post-fire image was considered destroyed. To update and extend these data, we followed the same methods using pre- and post-fire Google Earth imagery and digitized buildings in all three study areas that were present through 2015. Additionally, we selected all fires from the most recent Cal Fire historical perimeter database (2015 at the time of completion) and added new structures that may have been missed by Alexandre et al. (e.g., due to small fire size) or had occurred after 2010.

2.2.3. Topographic data

Terrain-related variables are typically included in fire behavior and distribution models due to their direct influence on fire behavior and indirect influence on fuel characteristics and flammability (Bond and van Wilgen 1996, Pyne 1996); and they have also been significantly associated with structure loss to wildfire due to exposure (Syphard et al., 2012, Alexandre et al. 2016). Therefore, we considered a range of topographic variables in both the fire and structure loss models, including slope, topographic variability, and topographic position (Table 1).

2.2.4. Climate data

We considered a range of historical and projected future climate variables, which were developed by Flint and Flint (2012) and updated through 2017 using the California Basin Characterization Model (https://ca.water.usgs.gov/projects/reg_hydro/basin-characterization-model.html (Table 1). The data were available annually at 270 m resolution. We processed the annual data to create 30-year baseline statistical summaries from 1981 to 2010 as well as decadal future projections from 2020 to 2050. To ensure consistency with state recommendations (Kravitz, 2017), we compared two scenarios of future climate conditions from complementary CMIP-5 General Circulation Model projections regarded as relevant for California. The scenarios were CNRM-CM5 and MIROC5, which represent "warm/wet" and "hot/dry" conditions, respectively. Despite this characterization both scenarios have substantial spatial and temporal variation in projected conditions, but should still provide meaningful bookends for representative climate spaces. For both scenarios, we used the RCP 8.5 "business as usual" emissions scenario (RCP scenarios are generally similar through 2050 and only diverge in the second half of the century).

For the fire models, we considered a combination of temperature and moisture-related climate variables that have had significant associations with fire patterns in other studies due to their effects on energy and moisture gradients that influence wildland fuel condition and abundance (e.g., Whitman et al., 2015; Parisien et al., 2016; Davis et al., 2017). We also included actual evapotranspiration (AET) and climatic water deficit (CWD) in all models, as these variables have been used to account for changes in fuel abundance (AET) and moisture (CWD) (Krawchuk et al., 2014, Parks et al., 2016, Mann et al., 2016). We did not include temperature and precipitation in the structure loss models because we assumed their influence on structure loss would be indirect, via their effects on large fire probability. On the other hand, given that AET and CWD served as proxies for vegetation, and that vegetation adjacent to structures could be influential beyond the effect on large fire probability, we did include these variables.

Table 1
Dependent and explanatory variables used to model fire and structure loss distribution in three California study areas.

Category	Fire models	Structure loss model	Data layer	Description and source	Time Variant
Dependent variable	x		Fire ignitions	Fire occurrence locations delineating point of ignition from 2003 - 2013 (Short 2014)	NA
	x		Large fires	Cal Fire fire perimeter database 1985 – 2015 (Department of Forestry and Fire Protection	NA
		x	Structure loss	Digitizing, Alexandre et al. (2016)	NA
Terrain					
	x	x	Slope	LANDFIRE, 30-m native resolution, aggregated by mean to 270m	No
	x	x	Topographic roughness	Range of slope values within 810-m radius from center cell (Derived from 30-m digital elevation model)	No
	x	x	Topographic position index	Index of slope position and landform, Jenness 2006 (Derived from 30-m digital elevation model)	No
	x	x	Topographic heterogeneity	Range of elevation values within 810-m radius from center cell (Derived from 30-m digital elevation model)	No
Climate					
	x		Temperature seasonality	Coefficient of variation across calendar year of temperatures (Derived from Flint and Flint, 2014)	Yes
	x		Annual precipitation	Sum over calendar year (mm) (Flint and Flint, 2014)	Yes
	x		Summer precipitation	Sum over June, July, August (mm) (Flint and Flint, 2014)	Yes
	x		Annual minimum temperature	Mean low temperature of coldest month (degrees C) (Flint and Flint, 2014)	Yes
	x	x	Actual evapotranspiration	Total annual water evaporated from surface and transpired by plants (Flint and Flint, 2014)	Yes
	x	x	Climatic water deficit	Annual evaporative demand exceeding water availability (Flint and Flint, 2014)	Yes
Land use					
	x	x	Housing density	Based on 2000 U.S. Census data using the baseline projection at 2009 (Mann et al., 2014)	Yes
		x	Housing cluster area	Boundaries around areas with housing density > = 0.02 units per ha (Derived)	Yes
		x	Distance to cluster edge	Mean Euclidean distance to boundary of housing clusters (Derived)	Yes
	x	x	Distance to populated places	Census populated places of at least 10,000 inhabitants in 2010 (Derived)	No
	x	x	Distance to roads	TIGER line files 2015, U.S. Department of Commerce, U.S. Census Bureau	No
	x	x	Distance to public land	Cal Fire land ownership database 2015 (Department of Forestry and Fire Protection)	No
Fire					
		x	Predicted large fire suitability	Output from large fire model (this paper)	Yes

2.2.5. Land use projections and anthropogenic data

Our primary source of land use data were maps of current and future projected housing density that were published in Mann et al. (2014). The historical data were collected from the U.S. Census long form with models trained using historical trends from 1940 to 2000 (the latest date that the long form was available). The predictions of housing density were provided in decadal time steps, and we used the 2009 forecast as our baseline here. Created using longitudinal census data, the model calculated the total number of new houses based on demographic forecasts at the national level, and then allocated them to split-block units based on a spatio-temporal estimate of housing density. We considered two scenarios, one with concentrated urban development ("urban scenario") and the other that favored rural expansion ("rural scenario"). In the "urban development" scenario, an additional 25% of all new housing was added into urban areas (density greater than 1 house per acre), while the "rural growth" scenario pushed the 25% into areas with less than 1 house per acre.

Housing density data were initially provided as vector data, with housing density listed as an attribute for each polygon. We converted these data into 270 m raster layers using housing density as the value to grid. In previous studies of structure loss to wildfire, two additional variables, the size of the housing cluster and the distance from each structure to the edge of development, were found to be highly significant (Syphard et al., 2012; Alexandre et al., 2016a, 2016b). Given that those data had been created using point locations of all structures, we developed an approach to devise similar housing clusters by thresholding and creating borders around polygons with at least 0.01 housing units per ha, which was the value that resulted in the best fit to the data created for San Diego County (Syphard et al., 2012). The housing density variables were available for the same time periods as the climate data, with 2009 representing current conditions, and decadal projections until 2050 for the two growth scenarios. Thus, for models using baseline climate data for 1981–2010, we used housing data from 2009; and for models using climate projections from 2019 to 2029, we used the housing projection for 2029, etc.

In addition to the housing projections, we included three other variables that have been significantly associated with fire occurrence patterns in other studies (e.g., Mann et al., 2016; Syphard et al., 2018). These included proximity to primary and secondary roads, which are often associated with human-caused ignitions (Syphard and Keeley, 2015); proximity to public land, which typically consists of large uninterrupted swaths of wildland vegetation; and distance to census populated places where the city includes at least 10,000 residences (Mann et al., 2016). These maps remained static for future projections.

2.3. Statistical modeling

We used Maxent 3.3.3k to estimate variable importance and project mapped probabilities of current and future fires and structures loss (Phillips and Dudik, 2008; Elith et al., 2011). A statistical machine learning method, MaxEnt estimates the best approximation of a distribution via iterative comparisons between values of the environmental predictor variables at the location of presence locations (i.e., all fires, large fires, destroyed structures) versus the values of the same variables at 10,000 randomly located background points. The best distribution is identified as the one with maximum entropy, and the model outputs a continuous grid with each cell assigned a relative suitability of occurrence from an exponential function. Recognized as one of the top-performing species distribution models (Elith et al., 2006), MaxEnt has also been successfully used in a range of wildfire analyses and mapping applications (e.g., Bar-Massada et al., 2012; Batllori et al., 2013; Parisien et al., 2016; Davis et al., 2017; Tracy et al., 2018).

We developed separate models for all fires and large fires to investigate potential differences in variable importance. We also tested the output of both models as potential predictors for the structure loss model, but we found significant correlation between the output of the small fire model and distance to roads. Given that most homes are destroyed in large fires, we decided to only use the output of the large fire probability model as a predictor variable for the structure loss model.

We initially developed all models with the full range of climatic, topographic, and anthropogenic explanatory variables to compare variable importance. For projecting future conditions, we employed a variable selection and model tuning process separately for each of the three study regions to ensure the best model fit. We first used ENMTools (Warren et al., 2010) to calculate Pearson correlation coefficients for all explanatory variables using current conditions (baseline) in each study area. For any pair of variables with a correlation coefficient of $r >= 0.8$, we retained the one that had a higher mean cross-validated receiver operating characteristic curve (AUC, Fielding and Bell, 1997), based on univariate models.

We used most of the default parameters for the MaxEnt modeling, except that we used only linear, quadratic, and product features for all models, and selected regularization multipliers, that avoid overfitting by penalizing complex solutions, by running models in 0.5 increments from 0.5 to 5. The final model was chosen by selecting the multiplier that resulted in the lowest Bayesian Information Criterion (BIC). For the baseline models of all and large fires, and structure loss, we ran five cross-validated model replicates to obtain mean permutation importance values and mean out-of-sample AUCs. We averaged the predicted values from the five replicate output maps to produce the baseline maps, which are interpreted as grids of mean predicted probability of large fires or structure loss given the environment in each study area.

After conditioning the models on the baseline time period, we then projected the averaged baseline models of large fires and structure loss onto maps representing future conditions at each time step for all combinations of future climate (two scenarios) and land use (two scenarios) projections. For each future time step, we first projected large fires, and then used those projections as input to the structure loss models.

2.4. Analysis

We averaged large fire probability and structure loss probability for all maps generated as model output by first summarizing the predicted probabilities across all grid cells in every map, then dividing this sum by the total number of cells in the maps of the three study areas. We calculated these numbers for all model replicates in all time periods and for all climate/land use scenario combinations. The probability averages for current conditions served as a baseline to compare with the probability averages of future scenarios, which allowed an overall estimate of whether fire or structure loss probability went up or down across the region.

To identify the housing density where most structure loss occurs in each study area, we extracted the housing density of destroyed structures from the baseline housing density maps generated by Mann et al. (2014). We then compared the mean housing density of destroyed structures in each study area with the underlying housing density in each region (i.e., all burned and unburned structures), which we determined by multiplying the area of each polygon in the study area by its housing density as indicated in the attribute table. This calculation assumed housing density was evenly distributed across polygons. For polygons that overlapped the study area boundary, we calculated the number of units in the entire polygon, then prorated by the percentage of the polygon within the study area. For both destroyed and the total structures in each study area, we plotted and compared their mean and distribution across housing density classes.

To compare the mean housing density data in our study areas to the recent destructive fire events of 2017 and 2018, we additionally acquired point locations for the destroyed structures in the 2017 Tubbs, Nunn, Atlas, and Pocket Fires in Sonoma and Napa Counties (number destroyed = 8022; http://sonomamap.maps.arcgis.com/apps/webappviewer/index.html?id=5af1dd01cb9b446db928abe51a259763), the 2018 Camp Fire in Butte County (number destroyed = 18,804; https://calfire.app.box.com/s/z03vd6hoikxa94ey25m0kuq2fsq2ln5e/folder/64813192070), the 2018 Carr Fire in Shasta County (number destroyed = 1614; https://www.arcgis.com/home/item.html?id=17d44552e0ea4c6ab2c43e80246e05b9), and the 2018 Woolsey Fire in Los Angeles and Ventura Counties (number destroyed = 1673; provided from Cal Fire to the National Park Service, Robert Taylor personal communication). All of these data were provided as part of the Cal Fire Damage Assessment and Fatality Totals (**DINS**) program. We used the same methods as above to calculate the mean housing density for destroyed and total number of structures. We calculated the total number of structures within the county boundaries where the fires were located.

To map geographical variation in structure loss probability by land use scenario, we subtracted the mapped probability of structure loss projected in the rural growth scenario models for year 2049 from the corresponding mapped probability of structure loss in the urban growth scenarios.

3. Results

3.1. Baseline statistics

From 2000–2015, there were 2081 structures destroyed in the NC study area. These destroyed structures were distributed across 17 out of a total of 202 fires during the same time period (based on the Cal Fire perimeter data). The mean size of fires where structures were destroyed (includes entire perimeters of those intersecting study area) was 5525 ha versus an overall mean fire size of 896 ha. In the BP study area, there were 451 destroyed structures that burned through 2015 in 39 out of 241 fires. The mean fire size with destroyed structures was 4018 ha versus a mean of 905 ha overall. In SD, 4338 structures were destroyed, across 20 fires out of a total 206 fires. The mean fire size when structures were destroyed was 150,647 ha versus a total mean of 1877 ha.

The mean density of destroyed structures was much lower than that of all structures in all study areas, by orders of magnitude (Fig. 2). This pattern was the same for density of destroyed structures versus all structures within counties in the recent fire events of 2017 and 2018 (Fig. 2), although the difference between destroyed and all structures was only about half for the Camp Fire and about a third for the 2017 North Coast fires. The distribution of housing density for both destroyed and all structures varied by study region, but destroyed structures were consistently located in low-density classes (Fig. 3).

Projected future trends in temperature and precipitation varied across regions for the two different climate scenarios, as did the overall housing density change. In the NC and BP study areas, the mean annual precipitation resulted in conditions with consistently more moisture in the CNRM scenario and consistently drier conditions in the MIROC scenario by 2049, with slight geographical variability (Fig S1a&b). Both GCMs projected decreased annual precipitation in the SD study area, but the drying was stronger for the MIROC scenario (Fig. S1c). The changes in summer precipitation showed much more geographical variability within study regions, but the differences in GCMs were flipped such that CNRM was projected to be drier in the summer than MIROC (Fig. S2a-c). Annual temperature was projected to increase much more substantially in the MIROC than the CNRM scenario for all three study areas by 2049, with substantially more geographical variation in the CNRM scenario (Fig. S3a-c). Decadal fluctuations, reflecting idiosyncrasies of the model run, were strongest in MIROC in the North Coast.

Changes in projected housing density patterns from 2009 to 2049 show substantial geographical variability across all three study regions (Fig. 4). For all regions, the rural scenario showed a larger areal increase of housing densities within the range where houses have been destroyed historically (Fig. 4); but the difference in rural versus urban scenarios was most substantial in NC, followed by SD, then BP. In the rural scenario, most of this increase in low-density housing occurred via growth (i.e., increased housing density) across more rural parts of the landscape, whereas in the urban scenario, a larger portion of exurban areas declined in housing density as there was a shift to more

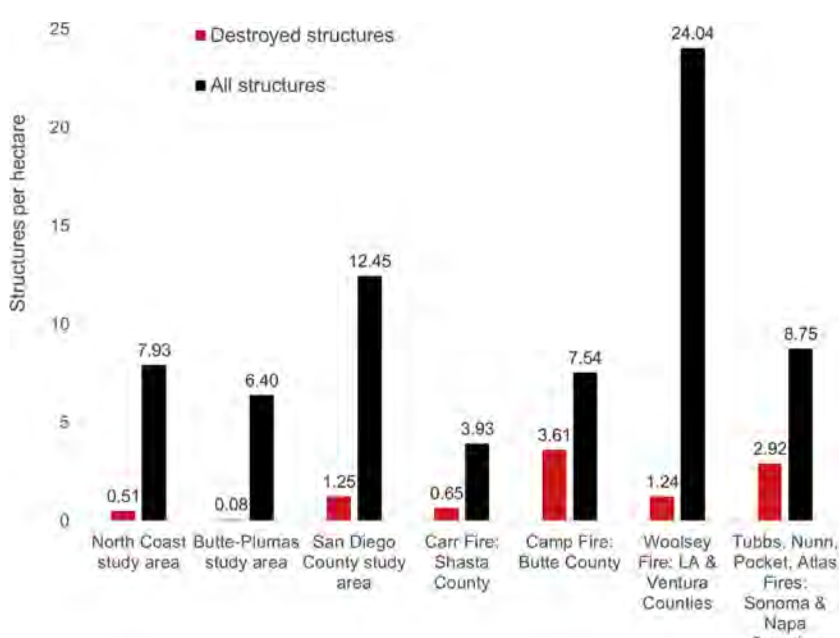

Fig. 2. Mean housing density for destroyed and all structures in three California study areas (using data through 2015) and for the four largest destructive fire events in 2017 and 2018.

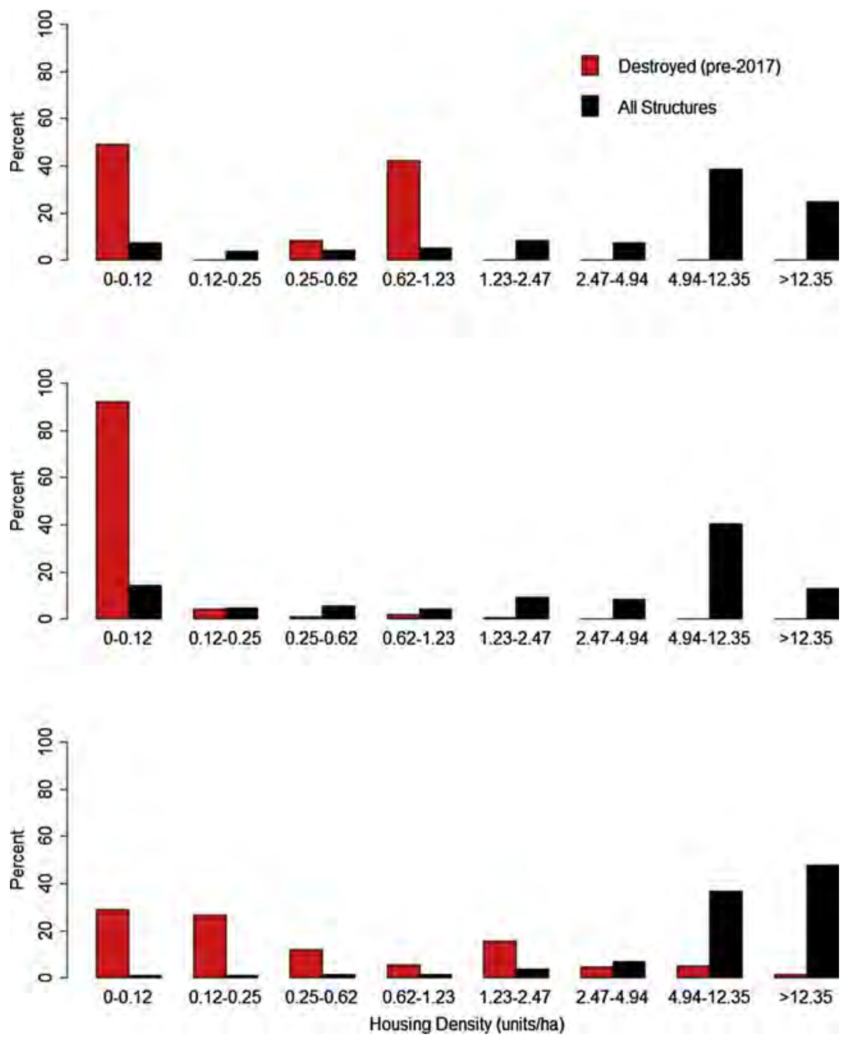

Fig. 3. Distribution of housing density classes (structures/ha) for destroyed and all structures in the a) North Coast, b) Butte-Plumas, and c) San Diego County study areas.

concentrated high-density housing near urban areas (Fig.4). One exception is the northern coastal portion of the SD study area, where there was some housing density decline in the rural scenario.

3.2. Variable importance

There were large differences in model variable importance for fire ignitions vs. large fires for all three study areas, and these were much larger than differences among regions (Table S1 – S2,Fig. 5). In particular, anthropogenic variables, particularly proximity to roads, dominated the patterns of fire ignitions, whereas topography and climate variables dominated the patterns of large fires, except in SD, where both housing density and distance to roads had about the same importance as topography and climate for large fires. In SD, housing density was almost equally as important as climate for explaining large fires. The directions of relationships differed such that fire ignitions tended to occur in close proximity to roads or populated places, but large fires occurred closer to public lands and farther from roads and populated places.

Whereas climate variables had a strong influence on fire ignitions and especially large fires, the vegetation productivity and moisture variables (AET and CWD) were not important for explaining structure loss patterns in NC or BP (Table S3 – S4, Fig. 5), and were less important than fire suitability for SD. Instead, housing variables and large fire suitability were the two most important factors explaining structure loss across all regions, with higher structure loss Univariate response curves showing the probability at low housing density (Fig. 6). SD was again different than NC or BP in that housing variables were more important than fire suitability.

3.3. Future projections

Overall, NC had a slightly lower baseline probability of large fires across the study area (Fig. 7a) than BP or SD, which had similar baselines (Fig. 7 b & c). Projections of future large fire probability were higher than the baseline for most time periods and climate scenarios for both the NC and BP study areas, except for MIROC in 2029 and 2049 in NC and CNRM 2019 in BP, and the results from these decades reflected oscillations that stemmed from decadal variability in the climate model projections. Large fire probability did not significantly change under either climate scenario in SD (Fig. 7c), but there was also slight decadal variability in the model run for CNRM. In all cases, differences in projected large fire suitability between the two land use scenarios were virtually absent due to the small relative importance of these variables to the model.

Compared to NC and BP (Fig. 8a & b respectively), SD had a relatively high baseline structure loss probability across the landscape (Fig. 8 c). Differences in structure loss probability for the two climate scenarios in NC and BP generally mimicked the large fire probability results in ranking and magnitude, and the decadal variability in fire

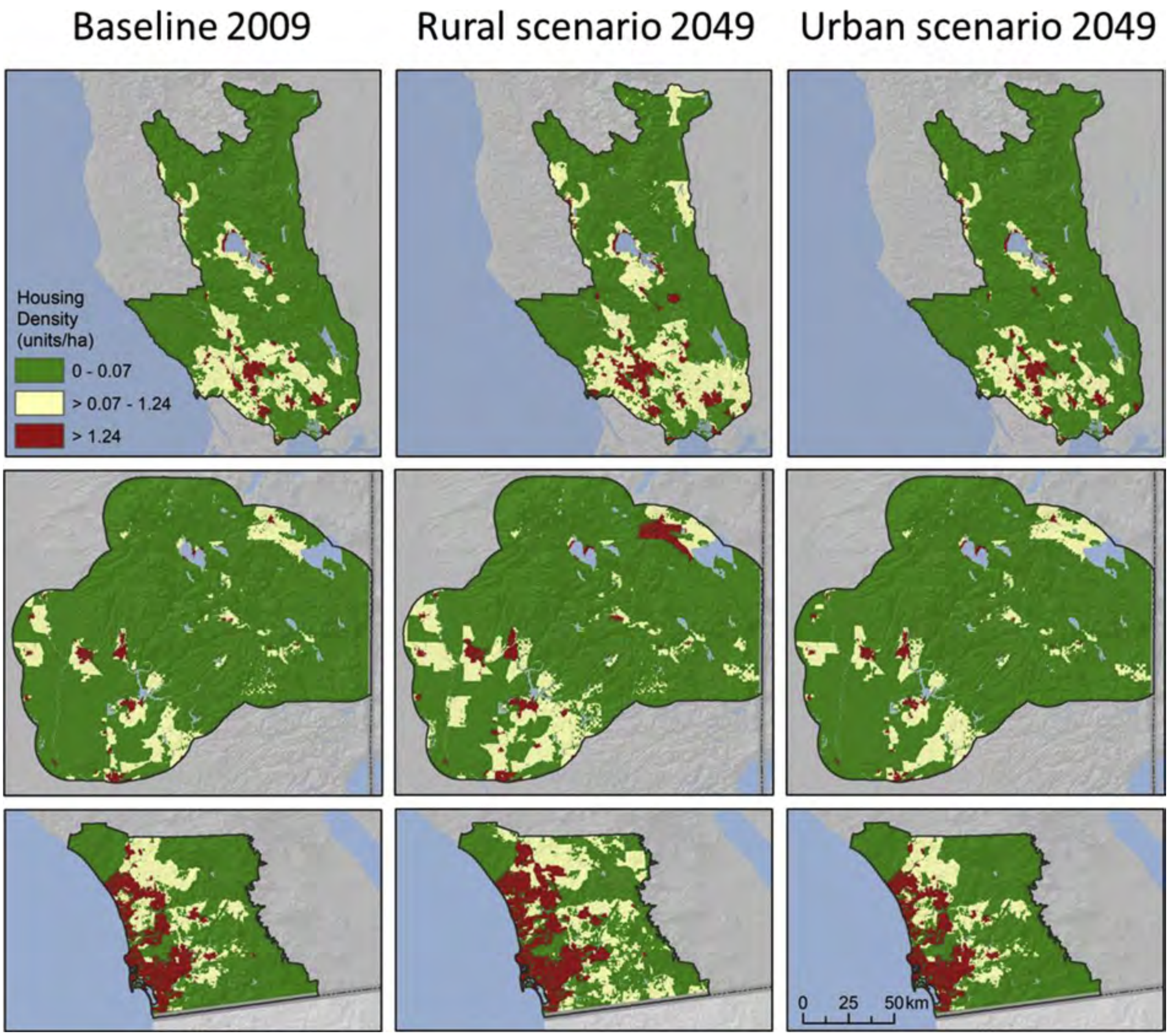

Fig. 4. Classified housing density in 2009, 2049 for the rural, and 2049 for the urban scenarios in the a) North Coast, b) Butte-Plumas, and c) San Diego County study areas. The middle (yellow) class represents the housing density range across the three study areas where structures have been destroyed in the past (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

probability for SD that came from climate model projections was reflected in the CNRM result. Compared to large fire probability, there was a much stronger effect of land use scenario on structure loss projections, and more variation in which scenarios exceeded baseline for NC (Fig. 8a) and SD (Fig. 8b). BP showed little variation in either climate or land use scenario probabilities. In NC, the rural land use scenario had a much larger probability of structure loss overall, and for CNRM, this difference generally determined whether probability would increase or decrease relative to the baseline. The rural scenario also resulted in higher overall structure loss probabilities in SD, but this was mostly apparent in 2049.

While structure loss was higher overall across regions and climate scenarios in the rural land use scenario (Fig. 8), there was considerable spatial heterogeneity in the effect of the land use scenario (Fig. 9). Comparing the rural land use scenario to the urban scenario in NC and SD, there were small changes to structure loss probabilities across most of the currently semi-urban and urban areas and large increases in structure loss probabilities in the currently rural areas (compare Fig. 9 to Fig. 4). In contrast, BP had locations of large increases and decreases in structure loss probabilities under the rural land use scenario compared to the urban land use scenario. However, all three regions had higher predicted structure loss in areas where there was an increase in low-density housing.

4. Discussion

Our projections suggest that both climate and land use will drive future changes in patterns of wildfire and subsequent likelihood of structure loss; but the relative importance and strength of different drivers will vary across and within different regions. Future changes will depend upon the nature and degree of change in both climate and land use relative to current conditions. For example, locations with increased low density rural housing are likely to see increased structure loss even in decades with lower large fire probabilities (compare decades 2029 and 2049 in Figs. 7a and 8a). Changes will also vary according to the strength and nature of regional relationships among climate, land use, fire patterns, and structure loss, with potential feedbacks among these drivers. Despite these complexities, which underscore the importance of customizing policy and management by geographical location (Keeley et al., 2009; Moritz et al., 2014), there were also key commonalities across regions. In particular, structure loss mostly occurred at fairly low housing densities. While more work needs to be done to create models that incorporate short-term weather conditions, such as wind, and feedbacks among drivers, we believe that the central importance of housing density to structure loss may be generally applicable to fire-prone landscapes.

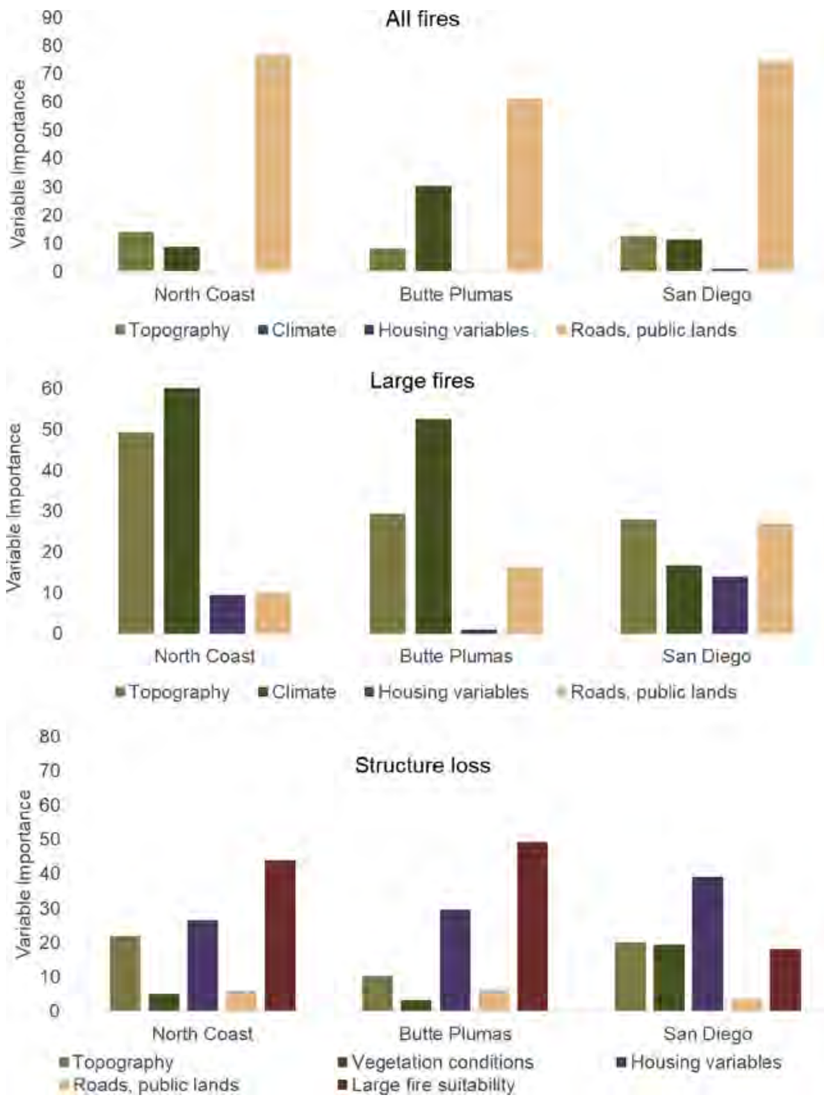

Fig. 5. MaxEnt variable permutation importance for fire and structure loss models in three California study areas, with variables grouped into categories. The fuel category for structure loss consisted of actual evapotranspiration and climatic water deficit.

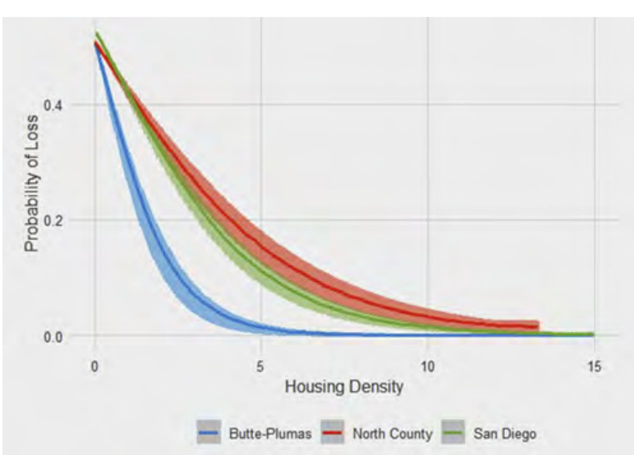

Fig. 6. Probability of structure loss relative to housing density (units/ha) for three California study areas, averaged across 5 model replicates.

4.1. *High anthropogenic variable importance for fire ignitions, but not large fires*

One commonality across regions was that anthropogenic variables were most important in explaining patterns of fire ignitions, whereas large fires were more related to topography, climate, and fuel (via AET and CWD). This finding is not surprising given that most fires in California are started by humans (Syphard et al., 2007; Balch et al., 2017), near human infrastructure (Syphard and Keeley, 2016). The finding is also consistent with other studies that have shown differences between the drivers of small and large fires (e.g., Syphard et al., 2008, 2016, Barros and Perreira, 2014; Abatzoglou et al., 2018) and that large fires are more likely to occur in remote areas where fuel continuity is greater, with severe winds better able to propagate fires via long-distance ember production, and access to suppression is lower (Gray et al., 2014). The consistency with other studies, and across divergent regions in this study, has important considerations for management. For example, ignition prevention efforts may be most effective if geographically concentrated near roads and development. Thus, land use change may generally be the biggest concern for preventing fires from starting; but climate change, in addition to weather and fuel patterns, may be more critical in the consideration of large fire behavior. One exception is that, unlike other human-caused fire sources, powerline-

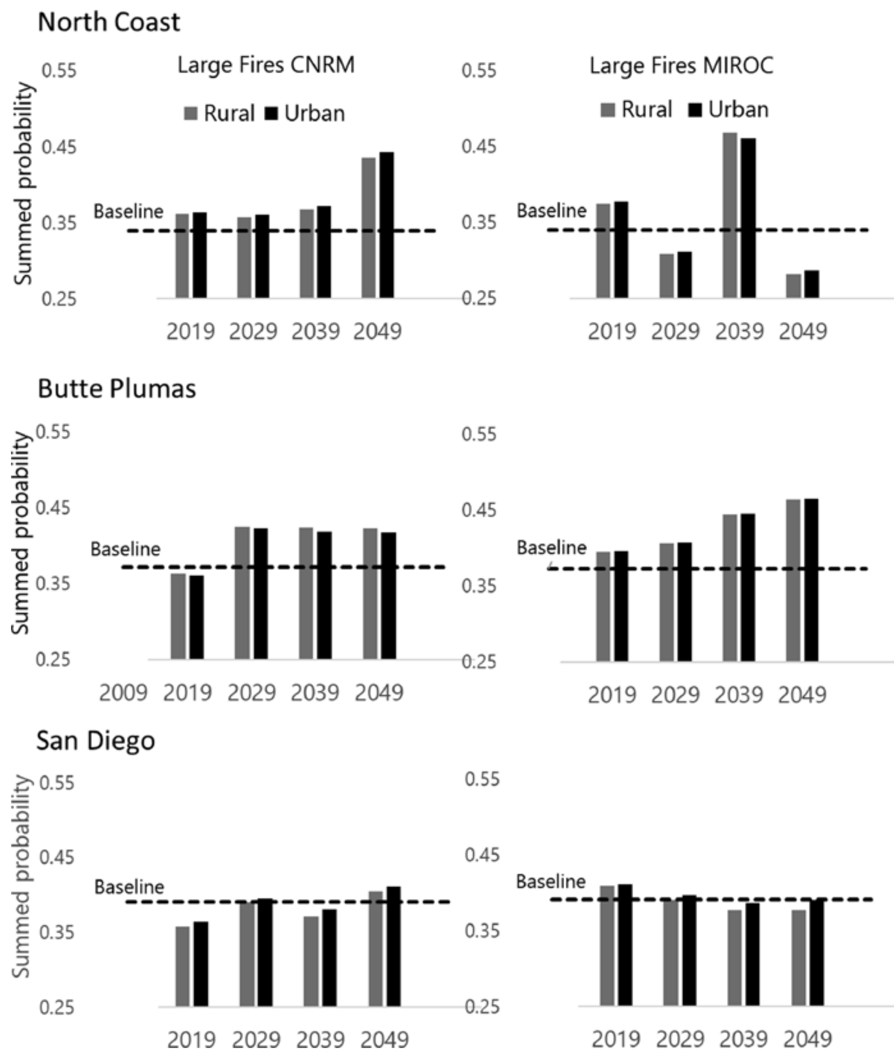

Fig. 7. Total projected probability of large fires under two climate and two land use scenarios for a) North Coast, b) Butte Plumas, and c) San Diego.

ignited fires tend to occur in more remote areas during severe weather, and these fires often result in large areas burned with substantial human losses (Keeley and Syphard, 2018). Understanding the relative importance of anthropogenic variables is critical given expected changes in human land use with resulting downstream impacts on deliberate or accidental ignitions, prescribed burning, mechanical vegetation treatments, and fire suppression.

The timing of ignitions, particularly corresponding with extreme fire weather, may be the most important variable to consider in determining whether fires become large and potentially destructive to human assets (Syphard et al., 2016; Abatzoglou et al., 2018). Historical analysis has also shown there to be an overall low correlation between fire frequency and area burned in California (Keeley and Syphard, 2018). Thus, small, frequent fires caused by human ignitions do not necessarily lead to highly destructive fires. Instead, the fires most likely to cause structure loss tend to be ignited in low-intermediate population or housing density (Syphard et al., 2007, 2009), adjacent to areas of high fuel loading.

Studies of historical fire-climate relationships in California (Keeley and Syphard, 2015, 2016) and across the U.S. (Littell et al., 2009; Parisien and Moritz, 2009; Syphard et al., 2017a; Littell et al., 2018) show differences in the strength and nature of climatic control over fire activity. In particular, those areas where fire is most strongly explained by climate in California are in northern, higher-elevation parts of the state, whereas in southern CA, fire-climate relationships have historically been weak (Keeley and Syphard, 2016). Other studies have shown fire-climate relationships to be weaker in areas with higher human presence (Higuera et al., 2015; Ruffault and Mouillot, 2015; Mann et al., 2016; Syphard et al., 2017b), and this is supported in our results, with the SD study area having both the highest overall housing density and the weakest link between climate and large fire suitability. SD was also the study area with the strongest relationship between anthropogenic variables and patterns of large fire suitability.

4.2. *Predicted future wildfire varied less across scenarios than structure loss*

Given the weak ties between climate and large fire suitability in SD, there were no major changes projected for large fires here, which is an important result given widespread concern that climate change will be responsible for increasing future fire activity across the western U.S. (Westerling et al., 2006; Barbero et al., 2015; Abatzoglou and Williams, 2016). Nevertheless, there could be other types of indirect climate change effects on fires in southern CA, such as long-term drought (Keeley and Zedler, 2009), vegetation type conversion facilitated by drier conditions (Jacobsen et al. (2007); Park et al., 2018; Syphard et al., 2018b), or changes in wind patterns (Guzman-Morales et al. (2016)). For the other two study areas, climate change was projected to increase large fire probability by the middle of the century, which corresponded to at least part of the increase in structure loss probability in these regions. In all regions, it is important to acknowledge that,

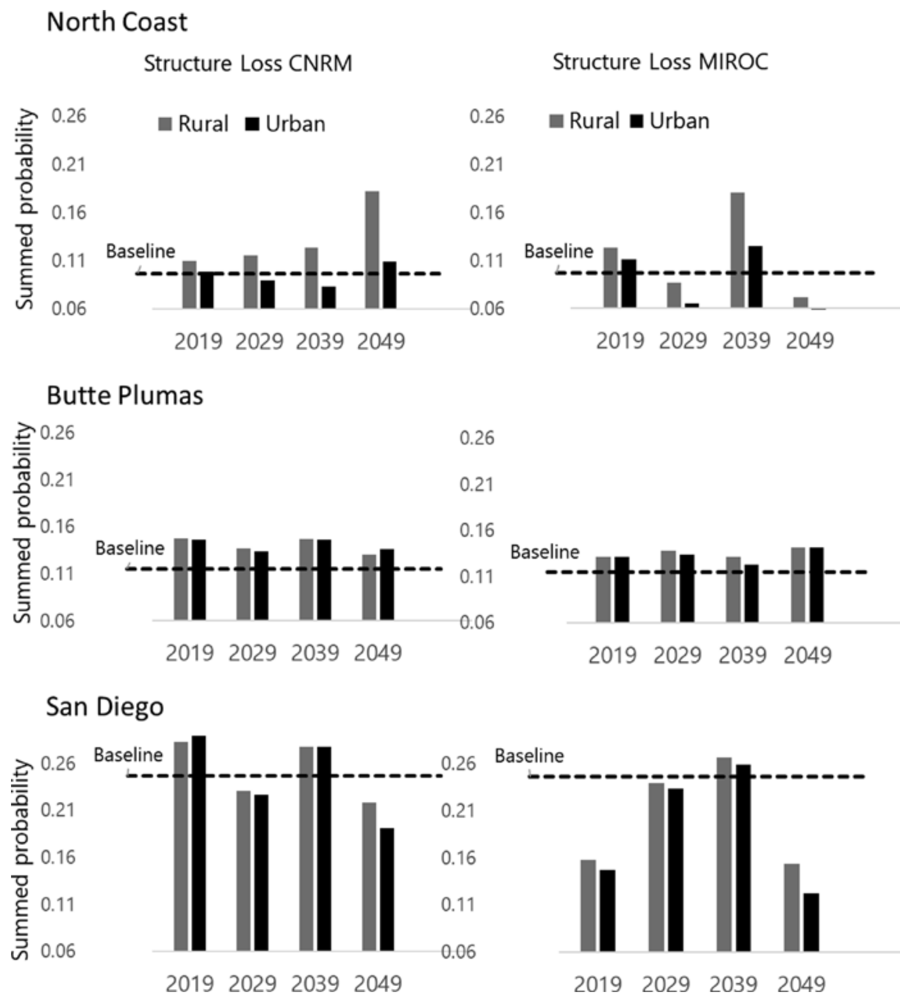

Fig. 8. Total projected probability of structure loss under two climate and two land use scenarios for a) North Coast, b) Butte Plumas, and c) San Diego.

despite inclusion of AET and CWD as proxies for fuel amount and condition, fire-vegetation feedbacks or vegetation type changes were not accounted for, and these could play an important, yet undetermined role in future fire activity (Syphard et al., 2018).

Particularly in the NC study area, land use change scenario played a major role in differences in structure loss probability, due to the significant relationships found in the baseline models as well as the nature of projected change in the rural versus urban scenarios. That is, there was substantially more expansion of low-density housing in the rural scenario versus the urban scenario in the NC study area, corresponding with the densities where most structures have been destroyed (i.e., the middle class in Fig. 4). This was true in BP and SD as well, but to a lesser extent. Also, for the urban scenario projections in all regions, and the rural projections for SD, there were both increases and decreases in housing density across the landscape; this patchwork of change may have dampened the apparent effect of land use on future projections of either fire or overall structure loss probability. Another important consideration is that structure loss probability may shift over time in response to changing density patterns. In other words, as some lower-density developments fill in with new homes, they may become less susceptible in the future; this is the likely reason that structure loss probability was projected to decline in some scenarios and time periods.

In modeling the decadal projections, we attempted to understand how different growth trajectories influenced model outcomes. For example, a region may initially experience low-density housing development in 2020–2030 that transitions to high density development by 2050. We hypothesized that either large fire or structure loss probability might thus vary through time as a function of the underlying housing density. However, given that land use was not one of the most important predictors of large fires, we did not observe a strong effect of oscillating housing density on fire projections. Instead, the up and down behavior in large fires, particularly in NC under MIROC, was due to idiosyncratic oscillations in climate projections that resulted from the climate model. For projections of structure loss, there was continued growth of low-density housing in the rural scenario for NC, which resulted in consistently higher structure loss probabilities over time. On the other hand, some areas of low-density development converted into high density development in San Diego County, which led to a net decline of structure loss probability by 2049. Overall, however, the biggest differences in effect of housing density was via the higher concentration of high-density development in the urban versus rural scenarios.

It is important to clarify that the land use scenarios were not meant to reflect precise changes but were designed to emphasize possible differences based on housing density and general trends towards urban or rural development. The land use change model tended to emphasize temporal and spatial spillovers; that is, any projection of housing density change in largely uninhabited areas first required either a history of growth or a spillover of growth from neighboring polygons, and this may have limited spatial expansion of housing in those areas. In other words, the model results, particularly for the rural growth scenario may understate the risks associated with low-density development. Further, we also assumed that road proximity, the distance to urban areas (areas with $\geq$10,000 residences), and the proximity to public land would remain unchanged over time, suggesting the results here are conservative.

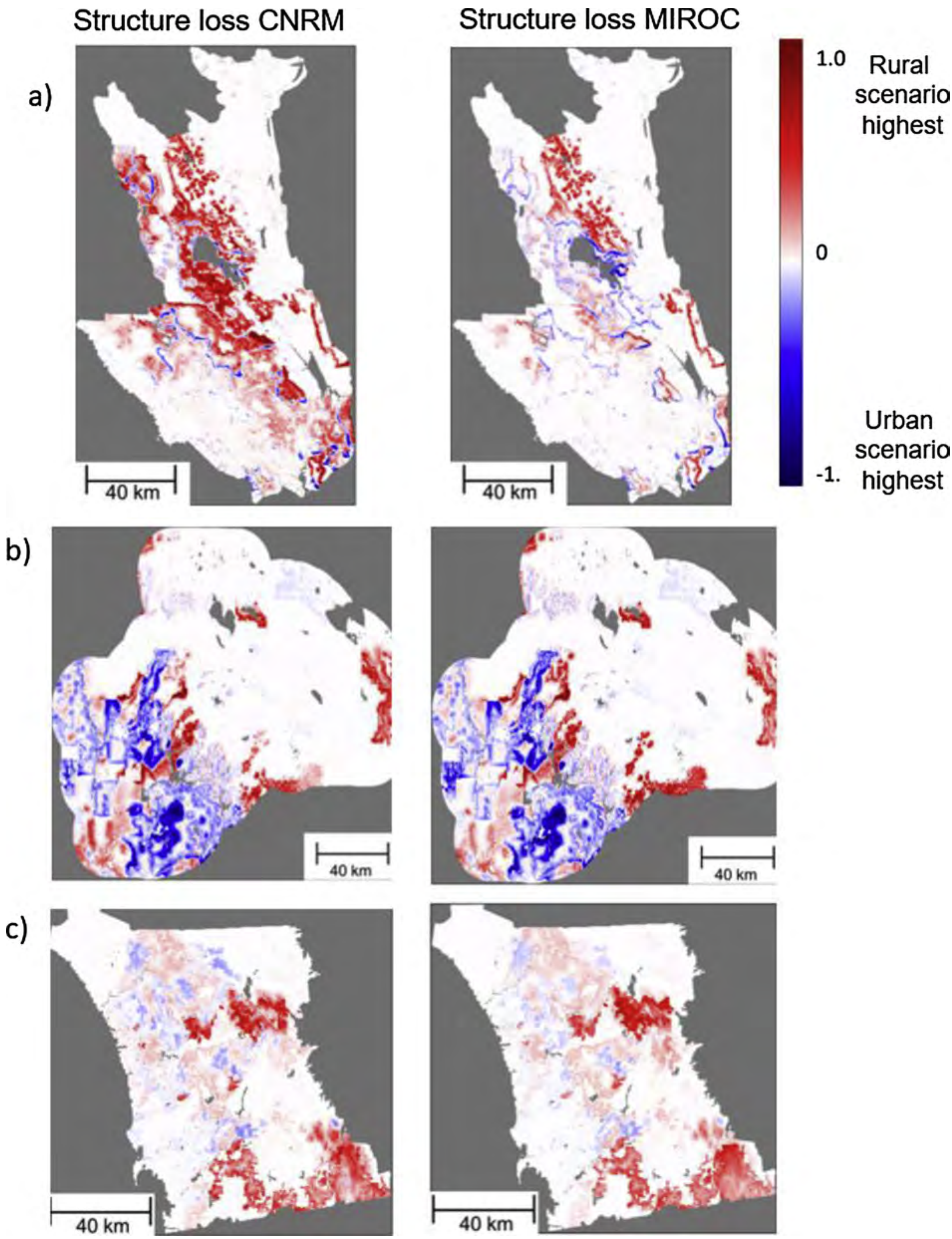

Fig. 9. Projected differences in structure loss probability at 2049 between the rural and urban density land use scenarios for CNRM and MIROC in the a) North Coast, b) Butte Plumas, and c) San Diego study areas.

4.3. Higher structure loss was seen in low density development

Regardless of future projections, one of the striking commonalities in the results was that observed structure loss occurred in larger fires and at lower housing densities than the averages for the regions. There are two different statistics related to housing density that are closely related but distinct. The first is the probability of structure loss for any house given its density (i.e., Fig. 6), and the other is the total number of structures lost at different housing densities (i.e., Fig. 3). Our results showed that probability of structure loss is negatively related to housing density in all regions, and while most destroyed structures were located in lower housing density classes, some structures were also destroyed at high densities. The association between structure loss and housing pattern has been documented in recent studies (Syphard et al., 2012, Alexandre et al. 2016, Kramer et al., 2018), and there has long been an assumption that fire risk is highest at the Wildland-Urban Interface (WUI), where houses meet or intermingle with wildland vegetation, both in the U.S. (e.g., Radeloff et al., 2018, Mell et al., 2010) and internationally (e.g., Lampin-Maillet et al., 2010; Montiel Molina and Galiana-Martín, 2016; Argañaraz et al. (2017)). However, the occurrence of several highly catastrophic wildfire events within high-density developments (e.g., Cohen and Stratton, 2008; Price and Bradstock, 2013; Nauslar et al., 2018), including recent California events, combined with previous lack of data associating changes in fire losses to changes in development patterns (McCaffrey et al. https://fireadaptednetwork.org/fire-narratives-accurate/) have led to questions and debate over which are the most dangerous development patterns.

Thus, one of the most important results of this study is that, even considering the massive numbers of structures that were destroyed in the last two years in wind-driven fire events, the overall mean housing density where houses are most likely to be destroyed (0.08 to 2.01 structures/ha pre-2015 and 1.24–3.61 in recent events) was more than an order of magnitude lower than the average housing density on the landscape for most cases (except the Camp Fire where the destroyed structure density was about 50% lower and the 2017 North Coast Fires, where the destroyed structure density was about 66% lower than total structures). The recent wildfires were uncharacteristic in the sheer number of structures and lives lost relative to historical numbers, in addition to the fact that wildfires did reach and enter parts of high-density urban areas in Coffey Park (Tubbs Fire), Paradise (Camp Fire), and the city of Malibu (Woolsey Fire). Thus, a lot more research is needed to understand how and why so many structures were lost. One clear factor were the wind speeds in these events, in addition to apparently substantial structure-to-structure spread and incendiary ember ignitions in which the houses themselves were more flammable than the nearby vegetation. Nevertheless, the losses in urban areas were still only a portion of the total number of structures destroyed in these fires, and thus they do not change the main conclusions of our study: overall, most structure loss tends to occur in areas of low-density development. One caveat is that we calculated housing density using data from the 2000 Census projected to 2009 as a baseline, and thus housing density has likely changed since then. However, the relative comparisons likely still hold because we consistently used the same housing data. Another recent study reported that the majority of threatened and destroyed structures from the last 30 years in the U.S. were located within the WUI; furthermore, when destroyed houses were not located in the WUI, the most common reason was that the housing density was lower than that in the WUI definition (Kramer et al., 2018).

The most likely explanation for this striking consistency is that housing patterns largely reflect exposure to wildfire. That is, wildfires typically burn through vegetation; and thus, those homes most interspersed with vegetation are most likely to encounter a wildfire in the first place, or be hit by incendiary embers. The reason for occasional catastrophic wildfire losses in high density areas is that, once exposed to a fire, a community with closely spaced homes made of flammable materials can lead to rapid house-to-house spread, particularly during severe weather conditions. In these cases, like the Tubbs fire in 2017 and Camp fire in 2018, the house itself becomes the fuel that propagates the fire.

Therefore, in terms of addressing conflicts between housing and wildfire in the future, the most effective mitigation may be land use and urban planning decisions that reduce the exposure of homes to wildfires (Syphard et al., 2013, 2016, Butsic et al., 2017). However, mitigation measures focused on defensible space and fire-safe construction materials, particularly when houses are closely spaced, are also critical for preventing future losses (Syphard et al., 2015, 2017c), as are other traditional fire management practices such as fire suppression and strategic location of fuel breaks to allow safe firefighter access to defend homes.

4.4. Conclusion

Looking at fire ignitions, large fires, and structures burned, we explored the importance of climatic and human variables for explaining fire and structure loss patterns across three diverse California landscapes, under current and future climate (hot-dry or warm-wet) and land use (rural or urban residential growth) scenarios. Across regions, we found that housing and human infrastructure were more responsible for explaining fire ignitions and structure loss probability. Large fires were better explained by climate, topography, and fuel variables. The differing strengths of these relationships interacted with the climate and land use scenarios, resulting in variability across regions in the relative importance of climate and housing patterns on fire and structures burnt. Focusing only on empirical housing density and structures burnt, we found that most structure loss occurred in areas with low housing density (from 0.08 to 2.01 units/ha), and as such, expansion of rural residential land use generally increased projected structure loss probability in the future. Both the historical results and the future projections highlight that future changes are likely to be complex and will result from a range of interacting factors. Climate change will be important to consider for managers and policy makers in some, but not all regions. In all areas, land use change merits increased attention, as local policy decisions can influence future patterns of development and exposure of structures to risk of loss in large wildfires.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gloenvcha.2019.03.007.

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Article

Factors Associated with Structure Loss in the 2013–2018 California Wildfires

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Abstract: Tens of thousands of structures and hundreds of human lives have been lost in recent fire events throughout California. Given the potential for these types of wildfires to continue, the need to understand why and how structures are being destroyed has taken on a new level of urgency. We compiled and analyzed an extensive dataset of building inspectors' reports documenting homeowner mitigation practices for more than 40,000 wildfire-exposed structures from 2013–2018. Comparing homes that survived fires to homes that were destroyed, we investigated the role of defensible space distance, defensive actions, and building structural characteristics, statewide and parsed into three broad regions. Overall, structural characteristics explained more of a difference between survived and destroyed structures than defensible space distance. The most consistently important structural characteristics—having enclosed eaves, vent screens, and multi-pane windows—were those that potentially prevented wind-born ember penetration into structures, although multi-pane windows are also known to protect against radiant heat. In the North-Interior part of the state, active firefighting was the most important reason for structure survival. Overall, the deviance explained for any given variable was relatively low, suggesting that other factors need to be accounted for to understand the full spectrum of structure loss contributors. Furthermore, while destroyed homes were preferentially included in the study, many "fire-safe" structures, having > 30 m defensible space or fire-resistant building materials, were destroyed. Thus, while mitigation may play an important role in structure survival, additional strategies should be considered to reduce future structure loss.

Keywords: defensible space; building construction; homeowner mitigation; firefighting; defensive actions; fire safety

1. Introduction

California has long been recognized for its fire-prone ecosystems and fire-related losses to human lives and property [1]. In the last several years, however, this recognition has turned into bewilderment and terror as tens of thousands of structures and hundreds of human lives have been lost in fire events throughout the state [2]. Deadly and destructive wildfires have been occurring in other regions across the globe as well, such as Portugal [3], Australia [4], and Southern Europe [5]. The increased frequency and magnitude of these fire events have contributed to the recent claim that we are entering a "new normal" phase of wildfires [6]. Most of these catastrophic fires are started by humans, so as populations steadily increase and people are pushed farther into hazardous wildlands, the problem could get even worse. Thus, the need to understand why and how structures are being destroyed during wildfires has taken on a new level of urgency.

Fully understanding why recent California wildfires were so destructive will likely require many years of research focusing on a range of factors at different scales, from fire behavior and climatology to fire management and land development. Answering questions pertaining to fire behavior will require different data and methodological approaches, compared to answering the questions related to why homes were destroyed, although the actual outcome will be a combination of the two.

In California, there has been a long-standing interest in understanding how local and regional responses are needed to reduce damage from wildfires [7,8]. In terms of understanding why homes are destroyed, there is an emerging literature that includes studies focused on local, property-level factors as well as studies on landscape-scale factors such as vegetation management and fuel characteristics, fire suppression, topography, and housing development patterns (e.g., [9,10]). These studies have significantly advanced our understanding of home safety, but the majority have been conducted through computer simulations and laboratory experiments, and thus, there remains a need for pre- and post-fire empirical data to document and validate what happens under actual wildfire conditions [11]. Recent fire events have generated more data on structure losses, and the number of empirical studies is increasing, particularly relative to understanding spatial patterns of structure loss at a landscape scale [12–15].

In terms of defensible space, the state of California requires fire-exposed homeowners to create a minimum of 30 m (100 ft) of defensible space around structures, and some localities are beginning to require at least 60 m (200 ft) in certain circumstances (e.g., [16]). Of the few studies that have empirically tested the relative benefits of defensible space, the authors demonstrated that up to 30 m (100 ft) of vegetation reduction around a structure can significantly increase the chance of structure survival (e.g., [17–20]). However, in these case studies, the most effective distance of defensible space was much less than regulations require (e.g., [19,21,22]), and other factors, such as housing density, landscape position, proximity of vegetation to the house, irrigation and water bodies, and building construction materials, were equally or more important [20,23,24].

Regarding fire safety in building construction materials, there have been many detailed studies conducted via carefully designed laboratory experiments [25–27]; and recent building codes in California have been designed to reflect these studies. Despite the solid laboratory evidence, few empirical studies have documented building characteristics associated with structure loss in real wildfire situations. In one study, Syphard et al. [23] found several significant relationships among building construction materials and structure loss in San Diego County, CA, USA, with window framing material and number of windowpanes being more protective than roofing or exterior siding material, and year of construction also being a significant proxy for building characteristics. The sample size in this study was somewhat limited, however, and other factors like structure density and vegetation characteristics were found to be equally or more important, depending on the location of the structure.

In addition to knowing whether certain mitigation actions can be statistically significantly associated with structure destruction, it is important to understand how often these homeowner 'best practices' actually translate into structure survival. Statistical significance is not a safety guarantee and does not necessarily translate into probability. While it is important for homeowners to have the best protection available, it is also important for them to understand the extent to which these actions tend to result in a positive outcome. Without large datasets of actual structure losses, it has until now been impossible to know the frequency at which best practices translate into structure survival, and whether those results are generalizable across different landscapes.

As of now, most guidance on homeowner 'best practices' is derived from limited empirical studies and assumptions based on fire behavior, and thus, the relative efficacy of these practices remains largely theoretical. Empirical studies on the effects of local homeowner mitigation practices, including defensible space or building materials, have been mostly in the form of case studies for a selection of wildfires on specific landscapes (e.g., [19,23,28,29]). Although these studies provide insights, we need a broader understanding across multiple fire events, and thus we need a database that captures characteristics of structures exposed to many fires across a variety of ecosystems.

The California Department of Forestry and Fire Protection (Cal Fire) began a statewide building inspection program in the late 1980s that has been continually upgraded and improved over time, and recent large catastrophic wildfires have added enormously to the amount of data available. The Cal Fire Damage INSpection Program (DINS) was founded with the goal to collect data on damaged, destroyed, and unburned structures during and immediately after fire events to assist in the recovery process, to validate defensible space regulations, and to provide local governments and scientists information for analyzing why some structures burned and why some survived [30]. For all fire events in the state that involve the damage or destruction of buildings worth $10,000 or more, a team of trained inspectors visit during and immediately after the wildfire to collect, for all structures exposed to the fire, a range of information including the extent of damage, defensible space before the fire, building characteristics, and other items.

Through a public records request, we acquired DINS data for more than 40,000 structures that survived, were damaged, or were destroyed across all California wildfires from 2013–2018, making this potentially the largest combined dataset of its sort. Our objective was to summarize these data statewide and across three broad California regions (San Francisco Bay Area, Northern Interior forests and foothills, and Southern California) to a develop a more generalized understanding of local-scale factors characterizing and differentiating destroyed or majorly damaged structures ("destroyed") from those that survived or only had minor damage ("survived") during wildfires. Although other studies have shown landscape-scale and other spatial factors such as topography, fuels, and housing arrangement to significantly affect structure loss probability, we focused here exclusively on the homeowner mitigation practices quantified by the building inspectors to answer:

1. How important was the extent of defensible space in distinguishing destroyed and survived structures?
2. What structural characteristics of homes were associated with increased susceptibility to destruction?
3. Did these patterns vary by region?

2. Materials and Methods

2.1. Data and Summary Statistics

The Cal Fire DINS data were collected for all wildfires, of any size, that resulted in structure damage or destruction. Once building inspection teams arrived at a fire, they recorded information on every exposed structure, including damaged, destroyed, and unburned homes, valued at a minimum of $10,000 or greater than 120 square feet (11 square meters), which is the size at which a permit is required for building. The inspection process occurred by dividing active wildfires into geographical zones as the fire was burning, then a designated number of two-person teams of trained inspectors were assigned to the zone and went to the field to record data. Data were collected for surviving structures in addition to damaged and destroyed structures, and the level of structural damage was recorded in different percentage classes.

Given that most recent structure losses in California have occurred in three distinct regions of the state [2], with most losses occurring within single fire events, we divided the dataset into three regions to compare potential regional differences. Thus, we assigned each county with structure loss to either the "Bay Area", which included counties surrounding the San Francisco Bay; the "North-Interior", which included primarily the northern Sierra Nevada but also other northern coastal and interior counties; and "Southern CA", including coastal counties south of San Luis Obispo County (Table 1).

Building inspectors grouped the structures into classes of damage corresponding to unburned; minor (cosmetic or nonstructural damage); moderate (partial to complete failure of structural building elements); and destroyed. The vast majority of structures were in either the minor or destroyed classes (94% in the Bay Area, 99% in the North-Interior, and 95% in Southern CA), so we lumped unburned with minor and called them "survived," and lumped moderate with destroyed and called those "destroyed."

The types of data collected included features of the property and vegetation, and inspectors also started to use pre-fire ancillary data, such as assessors' parcel information, to add details for badly damaged or destroyed structures. Most data fields were categorical to ensure consistency in recording, and the teams used phone applications and GPS data to enter information in the field. For this study, we summarized data for most categories in the inspection report, including distance of defensible space, roof type, exterior siding, eaves, windowpanes, vent screens, and deck or porch material.

The distance of defensible space around structures was recorded as one of several ordinal categories, including 0; 0–9 m (0–30 ft); 9–18 m (30–60 ft); 9–30 m (30–100 ft); 18–30 m (60–100 ft); and >30 m (100 ft). We therefore labeled defensible space into four classes in which 5 m (15 ft) were added to the lowest number of each class and used as the label. We merged the class 9–30 m (30–100 ft) with the 18–30 m (60–100 ft) class. Therefore, 0 or 0–9 m were labeled as "5 m", 9–18 m was labeled "14 m," 9–30 m or 18–30 m were labeled "22 m," and >30 m was labeled "35 m." We also used these numeric values to calculate average defensible space distances.

In the 2018 fires (including the Camp Fire and Woolsey Fire in the North-Interior and Southern CA regions, respectively), some new variables were added, including defensive action taken and home age. For defensive action, the inspectors recorded whether it was firefighters, civilians, or both who protected the structures during the wildfires, or, they recorded when the information was unknown. For all years, roof type was most frequently recorded as either "combustible" or "resistant" in the Bay Area, but it was broken into different material classes in the other two regions, so for each region we analyzed data according to the most commonly used classification for that variable. Vent screens were also characterized differently for different fires in which the "screened" class was broken into "fine" or "mesh > 1/8" in some cases, and "unscreened" was referred to as "no" or "none" in some cases. We lumped these together into "screened" and "unscreened".

Building data were collected for different occupancy types (e.g., single- and multi-family residences, outbuildings, commercial buildings, and barns), so we conducted an initial sensitivity analysis using the full dataset comparing rankings of proportions using all structures versus single-family residential structures only, and we found similar rankings for most variables. The variables in which the ranking between single-family residential and other buildings was different were those which would likely characterize non-residential structures (e.g., buildings having no windowpanes, vents, or eaves). Therefore, to preserve the integrity of these classes and for a more robust dataset we used all structures for our analyses in the different regions.

For all variables, there were a substantial number of blank fields where no data were recorded, so there are unequal numbers of data points in all data categories (Table S1). Therefore, we summarized and analyzed all data fields based only on the data that were available for those fields. For comparison purposes we calculated two types of proportions for different perspectives. First, we determined the proportion of the category in each burn class (i.e., for both survived and destroyed structures, what proportion belonged to each category of the variable); and second, we determined the proportion of burn class within each category (i.e., for each category in the variable, what proportion survived or were destroyed) (Figures S1–S8).

2.2. Analysis

To assess the relative importance of each variable, we developed simple generalized linear regression models (GLMs) [31] using defensible space or building characteristics as single predictor variables and survived versus destroyed structures as the bivariate dependent variable. For each model, we used a logit link and specified a binomial response, then calculated and compared the deviance explained (D^2), which is analogous to R-squared in linear regression for each variable. For the statewide analyses of defensive action and structure age, we used the combined data for the North-Interior and Southern CA regions only. We did not model roof type statewide (i.e., only ran models for individual regions) because the classification system varied from region to region. For these regions, we used data from whichever classification was most common in each region (roof type 1 for North-Interior and Southern CA and roof type 2 for the Bay Area, Table 1). Given the large amount of missing data in the different explanatory variables, we did not perform multiple regression, as our objective was to create a relative importance ranking of the variables using only the data available.

Table 1. Number of destroyed and survived structures from 2013–2018 by county and region in California. Dash marks indicate no structure outcomes recorded. The bold totals report the sums of destroyed and survived structures for each region.

Region	County	Number Destroyed	Number Survived
Bay Area	Contra Costa	1	–
	Lake	2588	89
	Mendocino	566	32
	Monterey	88	4
	Napa	1123	587
	Santa Clara	29	700
	Santa Cruz	6	19
	Solano	11	56
	Sonoma	6764	470
	Yolo	24	88
	Total	**11,200**	**2045**
North-Interior	Amador	1	
	Butte	19,061	740
	Calaveras	936	31
	Fresno	10	2
	Humboldt	5	–
	Inyo	2	–
	Lassen	4	1
	Madera	16	4
	Mariposa	142	20
	Mono	58	6
	Nevada	63	4
	Shasta	1889	260
	Siskiyou	339	18
	Tehama	26	4
	Trinity	142	7
	Tuolumne	1	–
	Yuba	274	8
	Total	**22,969**	**1105**
Southern	Kern	398	21
	Kings	1	–
	Los Angeles	1667	339
	Orange	38	43
	Riverside	53	10
	San Diego	246	67
	San Luis Obispo	81	7
	Santa Barbara	110	42
	Ventura	1075	200
	Total	**3669**	**729**

Because defensible space distance classes can be hypothetically considered as progressively protective against harm (i.e., that more defensible space is more protective), we used a calculation common in medical research, the relative risk [32], to compare adjacent pairs of shorter and longer distance classes of defensible space in addition to comparing the protective effect of the shortest versus longest distance classes (0–30 ft vs. >100 ft). Relative risk is a ratio between proportions of classes having a good outcome (here, structure survived wildfire) versus proportions of classes having a bad outcome (here, structure was destroyed) and indicates whether there is either no relationship (a value of 1) or if the exposed group (structures with shorter distances of defensible space) has either a significantly higher (values >1) or significantly lower (with values <1) risk of surviving the fire given the data available.

We also calculated the relative risk for most of the building inspection variables. For those with more than one independent category, we calculated the relative risk based on the proportion of survived structures in each category relative to the combined proportion of survived structures in all other categories. For variables with binary classes of "combustible" or "resistant", (Table 1), we calculated the relative risk using the combustible class as the exposure group.

3. Results

From 2013 to 2018, building inspectors examined 41,717 structures, with 37,838 (~90%) damaged or destroyed by fires in 36 California counties, with the largest number destroyed in Butte County in the North-Interior Region, followed by the Bay Area, then Southern California (Table 1). Of the total number of structures inspected, 18% (n = 2045) in the Bay Area, 5% (n = 1105) in the North-Interior, and 20% (n = 729) in Southern CA survived the fires.

3.1. Defensible Space and Defensive Actions

The relative importance of defensible space, as quantified by deviance explained in the regression models, was virtually nil statewide, and the only region in which defensible space had a deviance explained of at least 1% was the Bay Area (Figure 1). Statewide, home survival was associated with slightly longer average distances of defensible space, and this distinction was more pronounced for the Bay Area (Figure 2). On the other hand, when averaging mean values of defensible space classes across survived and destroyed homes, there was a slightly higher mean defensible space distance for destroyed structures in the North-Interior, and virtually no difference in Southern CA (Figure 2).

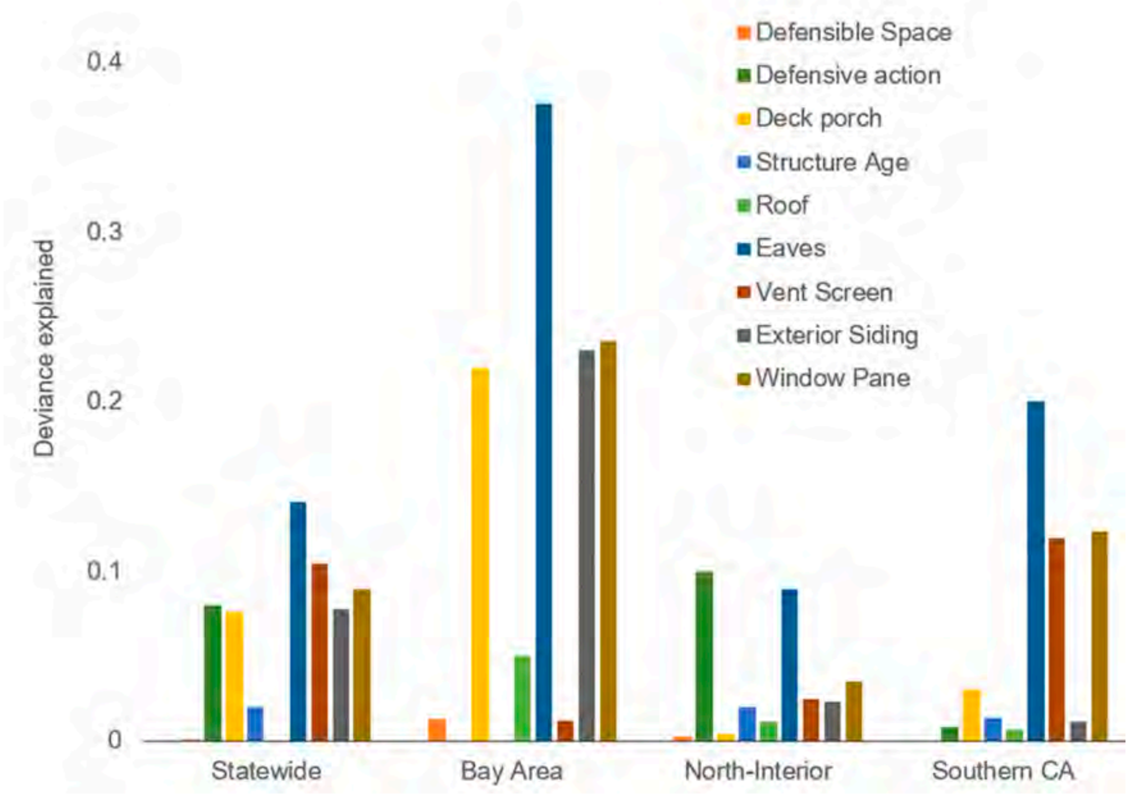

Figure 1. Deviance explained for building inspection variables statewide in three California regions. Defensive action and structure age were only available for North-Interior and Southern CA.

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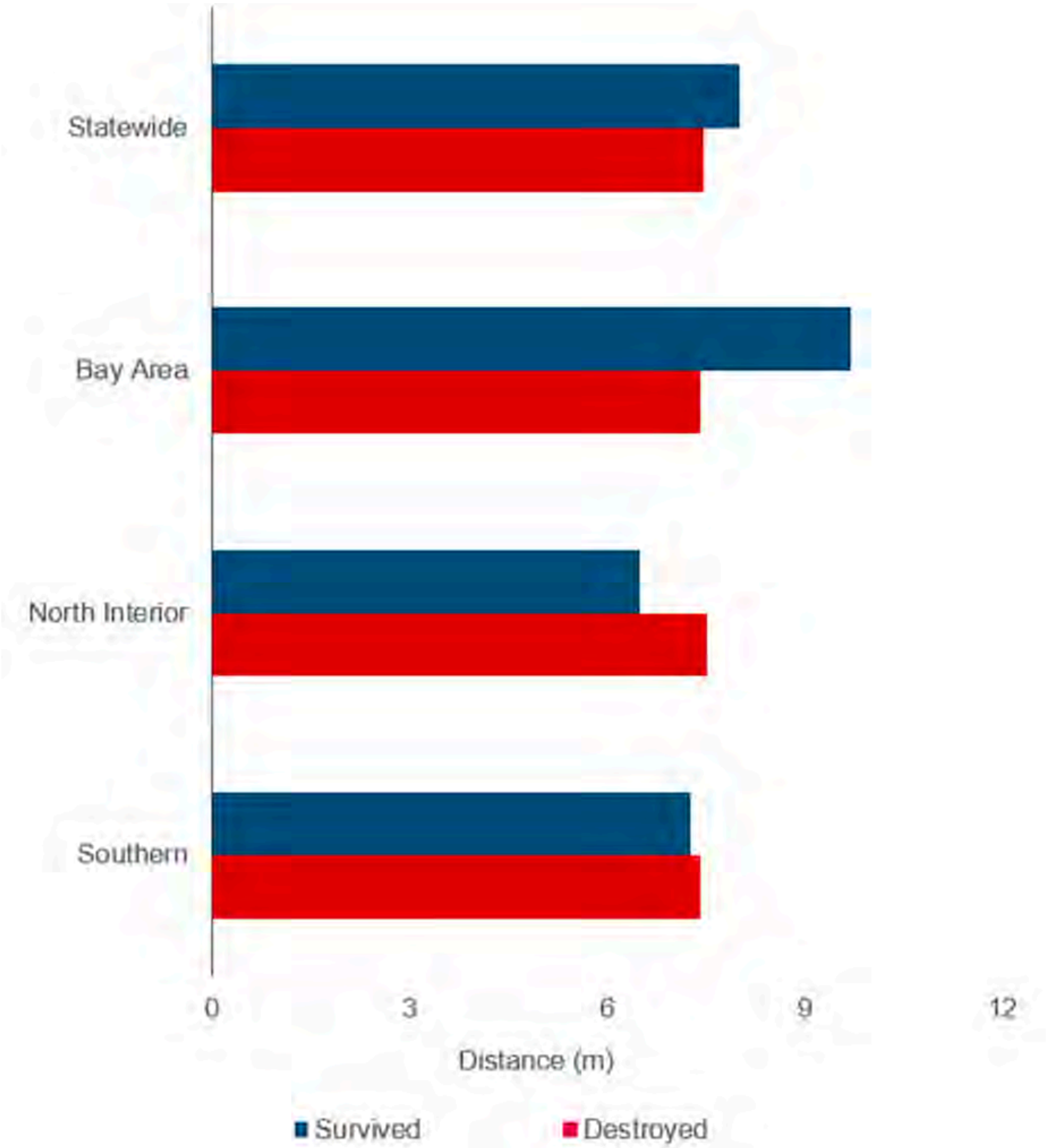

Figure 2. Average distance of defensible space for survived and destroyed structures statewide and in three California regions.

Figure 2. Average distance of defensible space for survived and destroyed structures statewide and in three California regions.

Except for the comparison between 22 m (75 f) vs. 14 m (45 ft) of defensible space statewide, the relative risk ratios for the statewide and Bay Area data showed consistently lower relative risk when comparing classes of longer distance intervals with shorter distance intervals (Table 2). In the North-Interior, there was a higher relative risk of destruction with more defensible space when comparing 22 m (75 f) vs. 14 m (45 ft), but there was a significantly lower relative risk when comparing 35 m (115 ft) vs. 22 m (75 ft) (Table 2). There were no significant differences in relative risk among any defensible space distance classes in Southern California (Table 2).

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Although defensive action was only recorded in the 2018 fires in the North-Interior and Southern CA regions, it was more important than any other variable for North-Interior, and it was less important in the Southern California data (Figure 1). Statewide (using these two regions and comparing the importance to other variables), it had a medium-high relative importance (Figure 1). The relative risk

Table 2. Relative risk (RR) among building inspection variables statewide and for three California regions. A relative risk of 1 indicates no difference between classes; > 1 means the relative risk of destruction is higher in the first category listed; < 1 means the relative risk of destruction is lower than in the other classes. Dashes indicate where no data were available for certain categories.

ratios for both regions showed that civilian, fire department, and both types of defensive actions were significantly more protective than unknown action (Table 2). In the North-Interior, the fire department providing defensive action provided better protection than civilian actions, but either both or civilian defensive actions provided a slightly better relative risk ratio for Southern CA.

Table 2. Relative risk (RR) among building inspection variables statewide and for three California regions. A relative risk of 1 indicates no difference between classes; >1 means the relative risk of destruction is higher in the first category listed; <1 means the relative risk of destruction is lower than in the other classes. Dashes indicate where no data were available for certain categories.

Variable	Statewide		Bay Area		North-Interior		Southern	
Defensible Space	**RR**	***p*-Value**	**RR**	***p*-Value**	**RR**	***p*-Value**	**RR**	***p*-Value**
14 m (45 ft) vs. 5 m (15 ft)	0.95	0.0001	0.98	0.06	0.97	0.09	0.97	0.24
22 m (75 ft) vs. 14 m (45 ft)	1.08	0.0001	0.98	0.19	1.07	0.003	1.07	0.06
35 m (15 ft) vs. 22 m (75 ft)	0.88	0.0001	0.79	0.0001	0.95	0.0001	0.98	0.61
35 m (15 ft) vs. 5 m (15 ft)	0.91	0.0001	0.76	0.0001	0.98	0.09	1	0.89
Defensive Action								
Both vs. others	0.95	0.0001	–	–	0.68	0.004	0.69	0.04
Civilian vs. others	1.08	0.0001	–	–	0.81	0.0001	0.68	0.04
Fire Department vs. others	0.88	0.0001	–	–	0.44	0.0001	0.81	0.03
Unknown vs. defensive action	0.91	0.0001	–	–	1.02	0.0001	1.01	0.39
Deck, Porch Material								
Composite vs. others	0.85	0.0001	0.93	0.007	0.92	0.03	0.78	0.04
Masonry vs. others	1.002	0.48	1.17	0.0001	0.99	0.03	1	0.78
Wood vs. others	0.98	0.01	1	0.6	1.01	0.002	0.97	0.27
None	1.01	0.10	0.35	0.0001	1	0.24	1.02	0.25
Roof Type								
Asphalt vs. others	1.05	0.0001	–	–	1.03	0.0001	1.02	0.4
Concrete vs. others	0.89	0.0007	–	–	0.94	0.05	0.82	0.04
Metal vs. others	0.97	0.0001	–	–	0.98	0.001	1.04	0.14
Tile vs. others	0.88	0.0001	–	–	0.89	0.0001	0.97	0.25
Wood vs. others	1	0.84			0.99	0.96	1.06	0.38
Combustible vs. resistant	–	–	1	0.75	–	–	–	–
Eaves								
Enclosed vs. others	0.79	0.0001	0.88	0.0001	0.95	0.0001	0.83	0.0001
None vs. others	1.06	0.0001	0.49	0.0001	1.02	0.004	1.35	0.0001
Unenclosed vs. others	1.04	0.0001	1.15	0.0001	1.5	0.0001	0.99	0.86
Vent Screen								
Screened vs. unscreened	0.94	0.0001	0.76	0.0001	0.97	0.0001	0.95	0.23
Exterior Siding								
Combustible vs. resistant	1.05	0.0001	1.03	0.0002	1.04	0.0001	1.07	0.0001
Window Panes								
Multi vs. others	0.94	0.0001	0.94	0.0001	0.97	0.0001	0.74	0.0001
None vs. others	1.01	0.12	0.25	0.0001	0.98	0.04	1.14	0.01
Unenclosed vs. others	1.06	0.0001	1.05	0.0001	1.02	0.0001	1.12	0.0001

3.2. *Building Inspection Characteristics*

Home construction materials explained a substantial amount of variation in housing losses statewide and across regions (Figure 1). Overall, eaves consistently explained more than any other structural parameters, and having enclosed eaves versus no eaves or unenclosed eaves had a highly significant protective effect as seen in the relative risk ratios (Table 2). The structural variable with the second highest deviance explained across all regions was windowpanes (Figure 1), although statewide this variable was ranked slightly lower than vent screens, and vent screens were also nearly as important as windowpanes in Southern California (Figure 1). The relative risk of having single pane windows was consistently and significantly higher than having multiple pane windows statewide and across all areas (Table 2). Structures that had no windows were not significantly different in relative risk compared to structures with windows statewide, but they had a lower relative risk than structures with windowpanes in the Bay Area and North-Interior, and this was reversed in Southern CA (Table 2). There was a consistent and significantly lower relative risk for structures with screened versus unscreened vents across the state and regions (Table 2).

Aside from eaves, windowpanes, and vent screens, the importance and relative risk of structural parameters associated with structure survival varied across the state and regions. Statewide and in the Bay Area, fire-resistant exterior siding material and deck or porch material were nearly as important as windowpanes (Figure 1), with consistently lower relative risk ratios for fire-resistant siding material (Table 2). In terms of deck or porch material, the most consistently significant effect was the significantly lower relative risk of having composite decking material versus other materials (Table 2). Although roofing material did not explain substantial variation in any of the regions (Figure 1), for the North-Interior and Southern CA regions, where the material types were broken out, concrete and tile both had lower relative risk ratios, although tile was not significant for Southern CA (Table 2). In the North-Interior, metal roofs also had slightly lower significant relative risk (Table 2).

Although structure age, a proxy for all building construction materials, was only recorded for the North-Interior and Southern CA regions, it did not explain substantial variation in structure survival relative to individual building characteristics (Figure 1). On average, however, older homes were consistently more likely to be destroyed than younger homes (Figure 3).

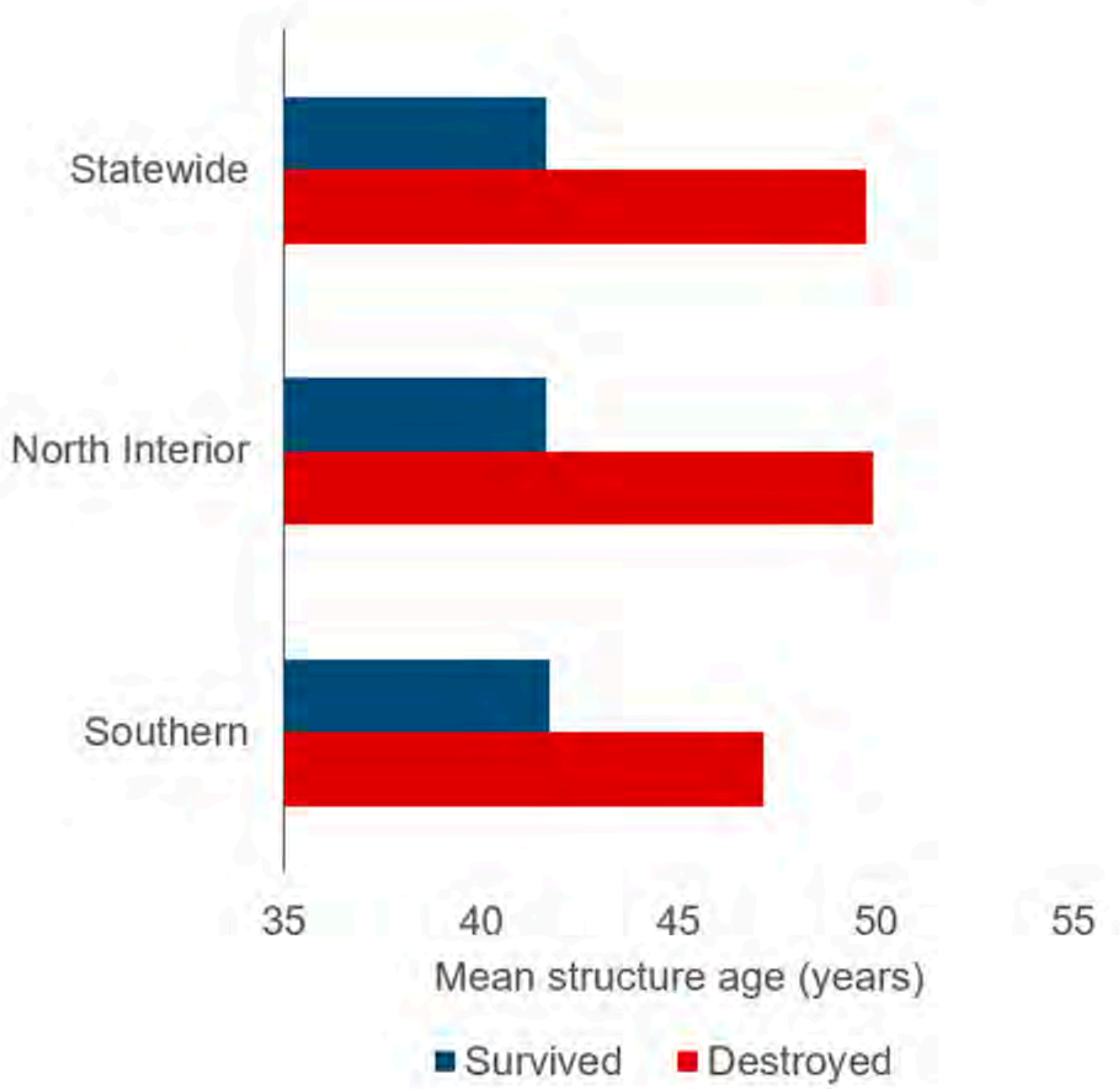

Figure 3. Mean age of structure for survived and destroyed homes in two California regions. The statewide calculations are based on combined totals of both regions (i.e., the Bay Area did not include this variable).

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4. Discussion

In terms of mitigation practices for protecting homes against wildfire, perhaps the most widely recognized and regarded action that homeowners can take is to create defensible space around structures [20,33]. In fact, defensible space and "hardening homes" via building construction

4. Discussion

In terms of mitigation practices for protecting homes against wildfire, perhaps the most widely recognized and regarded action that homeowners can take is to create defensible space around structures [20,33]. In fact, defensible space and "hardening homes" via building construction practices or structure retrofits, collectively referred to as the home ignition zone (HIZ), have often been considered the primary factors that matter in terms of structures surviving wildfire [34,35]. Despite the widespread advocacy of these practices, there has been little empirical study of their effectiveness under actual wildfires, and there is still debate on how much defensible space is critical to home survival despite the regulated distance of 30 m (100 ft).

In this study based on more than 40 k records of structures exposed to wildfires from 2013 to 2018, we found that, overall, defensible space distance explained very little variation in home survival and that structural characteristics were generally more important. Although the relative importance and relative risk ratios of different factors recorded by building inspectors varied slightly from region to region, there were also general similarities, particularly in that structure survival was highest when homes had enclosed or no eaves; multiple-pane windows, and screened vents.

The only region in which defensible space distance explained at least 1% variation in structure survival was the Bay Area, where survived structures had an average of 9.7 m (~32 ft) of defensible space versus 7.4 m (~24 ft) for destroyed structures. Although there were significant differences in relative risk between most pairs of distance classes of defensible space statewide and for the North-Interior, there were some conflicting patterns in the Bay Area and North-Interior, and there was no significant effect of defensible space distance for any comparison in Southern California. The other surprising finding was that, of the structures that did have more than 30 m of defensible space, the vast majority were destroyed in these fires (Figures S1–S8). This of course reflects the large proportion of destroyed structures in the dataset, but it also suggests that structures with greater amounts of defensible space are often still vulnerable.

One potential explanation for the limited importance of defensible space in these data may be that the defensible space distance classes were defined rather broadly, too broad to discern critical details that may have a much bigger impact. Of the few studies quantifying the most effective distance of defensible space for making a significant difference in structure survival probability, Syphard et al. and Miner [19,21] both found the optimum distance to be much shorter than the required 30 m, with the ideal range between 5–22 m. Distances longer than that provided no additional significant protection. Furthermore, these and other studies have shown that more nuanced characteristics of landscaping are most critical for structure protection, including vegetation touching the structure or trees overhanging the roof [36]. The arrangement of vegetation and irrigation are also important factors not accounted for [20]. In fact, despite defensible space traditionally being divided into zones, with the first being from 0–9 m (30 ft) from the structure, newer recommendations are beginning to isolate and focus heavily on the first zone being from 0–1.5 m (5 ft) [37], which may be the most critical zone to account for.

Most structures are lost in wildfires that are burning under severe weather and wind conditions [2], such that burning embers are capable of crossing large, multi-lane freeways and have been reported to blow as far as 1–2 km ahead of a fire front [2,25]. Therefore, one of the primary reasons for the importance of vegetation modification directly adjacent to homes as opposed to longer distances, is that homes are generally not ignited by the fire front but more often by wind-driven embers landing on combustible fuels in or on the house [17,29,38]. Material closest to the house is thus the most likely to cause a proximate spark that can penetrate the structure. To this point, irrigating vegetation and removing dead plant material to reduce ignitability may be as or more important than fuel volume, which is a finding borne out by recent research [24]. While defensible space distances <30 m may be sufficient for increasing structure survival probability, another important reason for requiring 30 m (100 ft) is firefighter safety and providing a zone of protection [39]. Finally, while the inspectors recorded defensible space distances, part of the definition of defensible space in California revolves around the horizontal and vertical spacing of fuels; thus, if these factors matter as much or more than distance, they could not be accounted for here.

The nature of building loss via ember flow factors such as exterior siding or roof material were much less important than exposed eaves, vents, or windows. This again is likely due to the extreme weather condition characteristics of destructive wildfires. That is, the fire-resistance of materials such as roofs or siding, i.e., preventing them from catching fire, was less important than building characteristics that provided gaps in the structure that could allow penetration of wind-borne burning debris. These results suggest that one of the potentially most effective methods of protecting homes from wildfire destruction would be to perform simple building retrofits, such as placing fine mesh screens over vents and coverings other openings in the structures, such as gaps in roofs, and enclosing structure eaves. Specific recommendations for these types of retrofits are easily found online, e.g., [40], and suggest that improving the fire safety of structures does not necessarily require expensive replacement of construction materials but rather careful attention to structure details.

The previous post-fire study of the role of construction materials in structure survival also found that windows, particularly framing material and panes, were more important than roof or siding material, although the methods and overall suite of variables differed in that study [23]. In the case of windows, they can, like other parts of the structure, provide an easy entry point for firebrands [26]. Additionally, however, they are also vulnerable to radiant heat, and multi-pane windows can withstand much higher levels of thermal exposure than single-pane windows [41]. Although not recorded here, the type of glass used in the window is also important for resistance to cracking [26].

Although individual structural characteristics were highly influential in this study, structure age did not explain a lot by itself, which may mean that, at a broad scale, it does not necessarily serve well as a proxy for the building characteristics most likely to protect homes. On the other hand, Syphard et al. [23] found that structure age did correlate with both building characteristics and structure survival, but that study was only conducted in San Diego County, where building codes had already been updated several times in response to wildfires in the regions. Although the state of California has also recently adopted strict building codes for wildfires [42], those codes only apply to new housing, so the effects may not have been seen yet. Further analysis might be warranted to compare structural characteristics and outcomes as a function of date of code enforcement.

Another consideration is that, despite the importance of structure age in the San Diego study, that study also determined that building location and arrangement were more important in predicting structure loss than structure age, building materials, or defensible space. The effect of structure age was primarily important in higher-density neighborhoods where structure loss was overall less likely. Thus, the role of housing arrangement and location, found to be the most important predictors of structure loss in several California studies [13–15] and nationwide [43] should ultimately be factored into discussions of reducing future fire risk; and this looks to be a challenge given trends of rapid ongoing development in the wildland–urban interface [44].

One of the reasons that housing arrangement and location are such strong predictors of structure loss may be structure accessibility by firefighters, who must divide manpower and resources to reach communities located in dispersed or remote locations [45,46]. The role of defensive actions in determining the extent and location of structure survival has been historically difficult to quantify, mostly because data are sparse, but also because defining suppression effectiveness is an inherently difficult task [47]. In the North-Interior region, defensive action explained more than any other factor in structure survival, although it was less important than building characteristics in Southern California. Even given the high importance of defensive action in the North-Interior, the total number of structures with unknown defensive action was substantial, and the proportion of unknown actions was even larger in Southern California. Thus, while these results suggest that defensive actions may be one of the most important and overlooked factors in structure survival, it remains difficult to make definitive conclusions. Given that building inspectors have just started collecting this information, it is important to recognize this is an on-going process of increasing our knowledge base as more data are collected.

5. Dataset and Limitations

Given the enormous number of structures lost in California in recent years, the dataset compiled for this study may represent the largest existing source of information on homeowner mitigation practices associated with structure loss. Other large databases and studies of house loss have been developed in other countries, however, where wildfires result in substantial losses in structures and human life; much of this work has been conducted in Australia, a country with a long history of destructive wildfires with substantial structure losses [48], and human fatalities [49]. This ongoing data collection process, especially if more exposed but unburned homes are included, will be important for continued understanding of structure loss and identifying the most effective strategies for prevention.

Despite the unprecedented opportunity the DINS data have provided for this broad-scale analysis of structure loss, there are nevertheless uncertainties and limitations within the data, and Cal Fire is working to improve the collection process on an ongoing basis [30].

The primary limitation is, as we discussed previously, that defensible space was presented uni-dimensionally as a function of distance categories and thus excluded other relevant factors such as vegetation spacing, height, type, age, moisture content, or composition. Nevertheless, given the broad scale of the data and similar conclusions for all study areas, these additional vegetation characteristics do not appear to be biased in one direction or the other; thus, our conclusions about distance classes are likely robust.

Another limitation of the dataset is the potential uncertainty inherent in recording building characteristics after a wildfire for homes that have been badly burned with materials largely consumed in the fire. This likely explains the missing data seen throughout the records. Cal Fire is aware of this and is beginning to combine their reports with pre-fire information from county assessors' offices [30]; however, the extent to which pre-fire data may have been incorporated in the reports used for this study is unclear.

Finally, as mentioned previously, this study only focused on the relative importance of the local-scale factors reported by the building inspectors, and full understanding of structure loss will need to include additional factors. Ongoing research will account for a fuller range of landscape-scale factors as well as information on fire behavior and spatial patterns.

6. Conclusions

We have explored the factors correlated with structure loss and survival during a recent five-year period in California. In most regions home structural characteristics are far more important in determining home survival than defensible space. Statewide, the most critical factor was eave construction. Windowpanes were also widely important in the state. Exterior siding was an important structural characteristic in the Bay Area, but vent screens were much more important in southern California. The likely explanation for why structure characteristics play a greater role than defensible space is that most homes burn by embers, which often come from long distances; and the impact of the ember cast is not likely affected by distance of defensible space. Whether or not the embers ignite is largely a function of structure.

Given that the primary role of building inspectors is to assess building damage, most structures in the data were destroyed. As such, one of the striking outcomes of this study is the finding that many of these destroyed structures could be characterized as "fire-safe," such as having >30 m defensible space or fire-resistant building materials. While the number of structures lost in these fire events was unprecedented in California history, structure loss during severe fire-weather and wind conditions similar to some of the fires represented here has occurred for decades in the state [2]. Therefore, it may be safe to assume that these data are broadly representative.

Supplementary Materials: The following are available online at http://www.mdpi.com/2571-6255/2/3/49/s1, Figure S1: Proportion of defensible space distance classes for survived and destroyed structures (a) and proportion of survived and destroyed structures within defensible space distance classes (b) for three California regions, Figure S2: Figure S2: Proportion of defensible action type for survived and destroyed structures (a) and proportion of survived and destroyed structures within defensive action types (b) for two California regions, Figure S3: Proportion of deck material type for survived and destroyed structures (a) and proportion of survived and destroyed structures within deck material type classes (b) for three California regions, Figure S4: Proportion of roof material type for survived and destroyed structures (a) and proportion of survived and destroyed structures within roof material type classes (b) for two California regions, Figure S5: Proportion of eave type for survived and destroyed structures (a) and proportion of survived and destroyed structures within eave type classes (b) for three California regions, Figure S6: Proportion of Exterior siding classes for survived and destroyed structures (a) and proportion of survived and destroyed structures within exterior siding classes (b) for three California regions, Figure S7: Proportion of vent screen classes for survived and destroyed structures (a) and proportion of survived and destroyed structures within vent screen classes (b) for three California regions, Figure S8: Proportion of windowpane type for survived and destroyed structures (a) and proportion of survived and destroyed structures within windowpane type (b) for three California regions. Table S1: Number or average value of destroyed and survived structures within building inspection classes for three California regions.

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Land Use Planning and Wildfire: Development Policies Influence Future Probability of Housing Loss

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Abstract

Increasing numbers of homes are being destroyed by wildfire in the wildland-urban interface. With projections of climate change and housing growth potentially exacerbating the threat of wildfire to homes and property, effective fire-risk reduction alternatives are needed as part of a comprehensive fire management plan. Land use planning represents a shift in traditional thinking from trying to eliminate wildfires, or even increasing resilience to them, toward avoiding exposure to them through the informed placement of new residential structures. For land use planning to be effective, it needs to be based on solid understanding of where and how to locate and arrange new homes. We simulated three scenarios of future residential development and projected landscape-level wildfire risk to residential structures in a rapidly urbanizing, fire-prone region in southern California. We based all future development on an econometric subdivision model, but we varied the emphasis of subdivision decision-making based on three broad and common growth types: infill, expansion, and leapfrog. Simulation results showed that decision-making based on these growth types, when applied locally for subdivision of individual parcels, produced substantial landscape-level differences in pattern, location, and extent of development. These differences in development, in turn, affected the area and proportion of structures at risk from burning in wildfires. Scenarios with lower housing density and larger numbers of small, isolated clusters of development, i.e., resulting from leapfrog development, were generally predicted to have the highest predicted fire risk to the largest proportion of structures in the study area, and infill development was predicted to have the lowest risk. These results suggest that land use planning should be considered an important component to fire risk management and that consistently applied policies based on residential pattern may provide substantial benefits for future risk reduction.

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Introduction

The recognition that homes are vulnerable to wildfire in the wildland-urban interface (WUI) has been established for decades [e.g., 1,2]; but with a recent surge in structures burning, this issue is now receiving widespread attention in policy, the media, and the scientific literature. Single fire events, like those in Greece, Australia, southern California, and Colorado have resulted in scores of lost lives, thousands of structures burned, and billions of dollars in expenditures [3–6]. With the potential for increasingly severe fire conditions under climate change [7] and projections of continued housing development [8], it is becoming clear that more effective fire-risk reduction solutions are needed. "Fire risk" here refers to the probability of a structure burning in a wildfire within a given time period.

Traditional fire-risk reduction focuses heavily on fire suppression and manipulation of wildland vegetation to reduce hazardous fuels [9]. Enormous resources are invested in vegetation management [10], but as increasing numbers of homes burn down despite this massive investment, the "business-as-usual" approach to fire management is undergoing reevaluation. One issue is that fuel treatments may not be located in the most strategic positions, i.e., in the wildland-urban interface [11]. Yet, even if treatments surrounded all communities, scattered development patterns are difficult for firefighters to reach [12–14], and fuel treatments do little to protect homes without firefighter access [15–16]. Fuel treatments may also be ineffective against embers or flaming materials that blow ahead of the fire front [17].

One alternative to traditional fire management that is receiving widespread attention is to prepare communities through the use of fire-safe building materials or creating defensible space around structures [17–18]. These actions represent an important shift in emphasis from trying to prevent wildfires in fire-prone areas to better anticipating fires that are ultimately inevitable. Nevertheless, the cost of building and retrofitting homes to be fire-safe can be prohibitive, and these actions do not guarantee immunity from fire [19].

Land use planning is an alternative that represents a further shift in thinking, beyond the preparation of communities to withstand an inevitable fire, to preventing new residential structures from being exposed to fire in the first place. The reason homes are vulnerable to fires at the wildland-urban interface is a function of its very definition: "where homes meet or intermingle with wildland vegetation" [20]. In other words, the location and pattern of homes influence their fire risk, and past land-use decision-making has allowed homes to be constructed in highly flammable areas [21]. Land use planning for fire safety is beginning to receive some attention in the literature [22–23], and there is growing recognition of the potential benefits of directing development outside of the most hazardous locations [8,19,24].

Despite recent attention in the literature, land use planning for wildfire has yet to gain traction in practice, particularly in the United States. However, fire history has been used to help define land zoning for fire planning in Italy [22], and bushfire hazard maps are integrated into planning policy in Victoria, Australia [25]. Although some inertia inevitably arises from complications with existing policy and plans, a primary impediment to the design and implementation of fire-smart land use planning is lack of guidance about specific locations, patterns of development, or appropriate methodology to direct the placement of new development. Without a solid knowledge base to draw from, planners will be misinformed about which planning decisions may result in the greatest overall reduction of residential landscape risk. Even worse, poor science could result in placement of homes in areas that actually have high fire hazard.

Research on how planning decisions contributed to structures burning in the past provides some guidance about what actions may work in the future. Analysis of hundreds of homes that burned in southern California the last decade showed that housing arrangement and location strongly influence fire risk, particularly through housing density and spacing, location along the perimeter of development, slope, and fire history [26]. Although high-density structure-to-structure loss can occur [27–28], structures in areas with low- to intermediate- housing density were most likely to burn, potentially due to intermingling with wildland vegetation or difficulty of firefighter access. Fire frequency also tends to be highest at low to intermediate housing density, at least in regions where humans are the primary cause of ignitions [29–30].

These results suggest, for example, that placing new residential development within the boundaries of existing high-density developments or in areas of low relief may reduce fire risk. However, it is difficult to know whether broad-scale planning policies would actually result in the intended housing arrangement and pattern at the landscape scale, and whether those patterns would result in lower fire risk. Our objective here was to simulate three scenarios of future residential development, and to project wildfire risk, in a rapidly urbanizing and fire-prone region where we have studied past structure loss [25]. We based all future development on an econometric subdivision model, but we varied the emphasis of subdivision decision-making based on three broad and common growth types.

Although cities vary in extent, fragmentation, and residential density [31–32], urban form typically adheres to a set of common patterns [33–34], and we based our development scenarios on the three primary means by which residential development typically occurs: infill, expansion, or leapfrog [34]. Infill is characterized by development of vacant land surrounded by existing development, typically in built-up areas where public facilities already exist. [35–36], and should result in higher structure density rather than increased urban extent. Expansion growth occurs along the edge of existing development, extends the size of the urban patch to which it is adjacent, and may have variable influence on structure density. Leapfrog growth occurs when development occurs beyond existing urban areas such that the new structure is surrounded by undeveloped land. This type of growth would expand the urban extent and initially result in lower structure density; but these areas may eventually become centers of growth from which infill or expansion can occur. We asked:

1) Do residential development policies reflecting broad growth types affect the resulting pattern and footprint of development across the landscape?
2) Do differences in extent, location, and pattern of residential development translate into differences in wildfire risk, based on the current configuration of structures?
3) Which development process, infill, expansion, or leapfrog, results in the lowest projected fire risk across the landscape?

Methods

Study Area

The study area included all land within the South Coast Ecoregion of San Diego County, California, US, encompassing an area of 8312 km^2. The region is topographically diverse with high levels of biodiversity, and urban development has been the primary cause of natural habitat loss and species extinction [37]. Owing to the Mediterranean climate, with mild, wet winters and long summer droughts, the native shrublands dominating the landscape are extremely fire-prone. San Diego County was the site of major wildfire losses in 2003 and 2007 [38], although large wildfire events have occurred in the county since record-keeping began, and are expected to continue, as fire frequency has steadily increased in recent decades [29,39]. The county is home to more than three million residents, and approximately one million more people are expected by 2030 [40]. Although most residential development has been concentrated along the coast, expansion of housing is expected in the eastern, unincorporated part of the county.

Econometric Subdivision Model

A host of alternative modeling approaches exist to simulate future land use scenarios [41], including a cellular automaton model that we previously applied to the study area [42]. We chose to use an econometric modelling approach for this study because we wanted to capture fine-scale, structure-level patterns and processes that are correlated with housing loss to wildfire [26]; and econometric models may perform better at the scale of individual parcels [43].

Although we based the three development scenarios on generalized planning policies, we also wanted to ensure that the residential projections were realistic and adhered to current planning regulations. The objective of the econometric modeling was to estimate the likelihood that residential parcels will subdivide in the future. Therefore, we used a probit model to estimate the transition probability of each parcel based on a range of potential explanatory variables typically associated with parcel subdivision and housing development [44–45].

To develop the model of subdivision probability, we acquired GIS data of the county's parcel boundaries in years 2005 and 2009 from the San Diego Association of Governments (SANDAG). The dependent variable was equal to 1 if a parcel subdivided between 2005 and 2009, and zero otherwise. Using these data layers we first determined which parcels were legally able to subdivide given current land use regulations. Minimum lot size restrictions are typically considered the most import restriction for determining future land use. We deemed a parcel eligible for subdivision if the current lot size was greater than twice the minimum legal size given the land class. To determine which parcels subdivided between 2005 and 2009, we queried parcel IDs where the total area was reduced by at least the minimum lot size between the two time periods. Finally, we were able to generate a suite of variables that determine the likelihood of a parcel developing in the future (Table S1).

We overlaid the parcel boundaries over a range of GIS layers representing our explanatory variables. These data are available to download at (http://www.sandag.org/index.asp?subclassid = 100&fuseaction = home.subclasshome). Our explanatory variables included: parcel size, parcel size squared, six dummy variables which capture non-linear effects of parcel size, distance to the coast, distance to the coast squared; distance to city center and its square, current zoning, slope, land use, roads, if the parcel is in a protected area, if the parcel is in a development area, if the parcel is in the redevelopment area (Table 1).

Spatial Model of Future Development under Planning Alternatives

The outcome of the land use change econometric model is the subdivision probability for each parcel for a five-year time step. Based on these probabilities, we developed a GIS spatial simulation model of future land use under three distinct planning scenarios: infill (development in open or low density parcels within already developed areas), expansion (development on the fringe of developed areas), and leapfrog (development in open areas). The model runs in four 5-year time steps from 2010 to 2030, and generates the spatial locations of new housing units in the county.

Although development decisions could feasibly depend on fire risk, we did not model that here. There is no evidence that fire has influenced past regional planning decisions, so it was not used as an explanatory variable in the econometric model. Although we could have evaluated the potential for future development decisions to be based in part on fire risk, this would have required simulation of feedbacks between fires and probability of development. Because our objective in this study was to isolate the effects of the three distinct growth types, we modeled fire risk only as a function of development pattern and not vice versa.

We constructed a complete spatial database of existing residential structures in the study area [26]. These structures and their corresponding parcel boundaries served as the initial conditions for all three scenarios of the spatial simulation model. The current and projected future GIS layers of structures were also subsequently used in the fire risk model (see below). The

Table 1. Variables and results from the probit regression model of parcel subdivision in San Diego County.

Subdivided (1 = yes,0 = no)	Coefficient	Std. Err.	z	P>|z|	[95% Conf. Interval]	
Acres of lot	0.0026342	0.00075	3.51	0	0.001164	0.004105
Acres of lot ^{2}	−3.02E-06	1.29E-06	−2.34	0.019	−5.55E-06	−4.93E-07
Distance to ocean	−7.42E-06	1.33E-06	−5.59	0	−0.00001	−4.82E-06
Distance to ocean ^{2}	2.33E-11	8.28E-12	2.82	0.005	7.11E-12	3.96E-11
Distance to major road	2.17E-07	2.74E-06	0.08	0.937	−5.16E-06	5.59E-06
Distance to major road ^{2}	−1.94E-11	1.70E-11	−1.14	0.252	−5.27E-11	1.38E-11
Distance to nearest city center	−0.0000115	1.70E-06	−6.76	0	−1.5E-05	−8.16E-06
Distance to nearest city center ^{2}	2.89E-11	9.70E-12	2.98	0.003	9.91E-12	4.79E-11
Slope between 0–5%	0.6211289	0.211761	2.93	0.003	0.206085	1.036173
Slope between 5–10%	0.3911427	0.210684	1.86	0.063	−0.02179	0.804076
Slope between 10–25%	0.0716669	0.212725	0.34	0.736	−0.34527	0.4886
Rural Residential	−0.3563149	0.071512	−4.98	0	−0.49648	−0.21615
Single Family	0.1361149	0.068678	1.98	0.047	0.001509	0.270721
Multi-Family	−0.2505093	0.151486	−1.65	0.098	−0.54742	0.046397
Road	0.015329	0.086094	0.18	0.859	−0.15341	0.184069
Open Space	−0.7440933	0.099145	−7.51	0	−0.93841	−0.54977
Orchard/Vineyard	−0.5813305	0.097867	−5.94	0	−0.77315	−0.38951
Agriculture	−0.9785208	0.132734	−7.37	0	−1.23867	−0.71837
Vacant Land	−0.5222501	0.074586	−7	0	−0.66844	−0.37606
Zoned protected	0.253769	0.076881	3.3	0.001	0.103086	0.404452
Area marked for redevelopment	−0.2680261	0.14069	−1.91	0.057	−0.54377	0.007722
Area marked for development	0.5780101	0.064103	9.02	0	0.452371	0.703649
Parcel between 10–20 acres	−0.3379532	0.065899	−5.13	0	−0.46711	−0.20879
Parcel between 5–10 acres	−0.6119036	0.067012	−9.13	0	−0.74325	−0.48056
Parcel between 2–5 acres	−1.16297	0.07062	−16.47	0	−1.30138	−1.02456
Parcel between 1–2 acres	−1.563956	0.090286	−17.32	0	−1.74091	−1.387
Parcel between.5–1 acres	−1.999939	0.099893	−20.02	0	−2.19573	−1.80415
Parcel between.25–.5 acres	−2.178273	0.117101	−18.6	0	−2.40779	−1.94876
Constant	−1.397931	0.227467	−6.15	0	−1.84376	−0.9521

Sample size 113 001, LR Chi^2 1535.23, pro>chi 0, pseudo R^2 0.22. Further description of the variables is provided in Table S1.
doi:10.1371/journal.pone.0071708.t001

dataset of existing housing includes locations of 687,869 structures, of which 4% were located within the perimeter of one of 40 fires that burned since 2001. During these fires, 4315 structures were completely destroyed, and another 935 were damaged.

For future development scenarios, we wanted to allocate an equal number of new structures to the landscape. This was to ensure that any predicted difference in fire risk was a function of the arrangement and location of structures, not the total number of structures. Nevertheless, differences in the total number of structures were simulated with each of the 5-year time steps. We determined the number of housing units to add during the simulations based on projections made by San Diego County [46]. Using factors such as development proposals, general plan densities, and information from jurisdictions, the county estimated that between 331,378 units and 486,336 units could be supported within the developable residential land by 2030. Because the eastern, desert portion of the county was not included in our study area, we used a conservative approach and simulated the addition of 331,378 new dwelling units. We divided this number by four to define the number of new dwelling units to add at each time step, assuming a linear growth rate.

One output of the econometric model was the prediction of the maximum number of new dwelling units that could be added to each parcel. However, dwelling units may consist of apartments as well as single family homes. The mix of single and multifamily units in the region has remained relatively constant over time, and the overall trend has been a mix of roughly 1/3 multifamily and 2/3 single family units. Because the fire risk model is based on points representing structure locations across the landscape, regardless of the number of dwelling units per structure, we needed to generate a conversion factor from dwelling units to structures. We therefore defined a minimum lot size of 0.25 acre on which no more than a single structure could be built, regardless of the number of dwelling units in it (i.e., a single family home or apartment complex). Then, once a parcel was selected for development by the model (see details below), we divided its total area by the maximum number of dwelling units to be added, according to the econometric model. If the result was larger than 0.25, we subdivided parcels according to the result. If not, we quantified how many 0.25 acre parcels fit into the original parcel, and generated the new parcel boundaries accordingly.

Using the initial map of parcels (year 2010), we classified each parcel that was defined as eligible for development (in the previous stage) as suitable for one of the three planning scenarios described above, according to the number of developed parcels in its immediate neighborhood (i.e., those parcels that share a boundary with the focal parcel). We defined 'developed parcels' as ones that had more than one house per 20 acres (8.09 ha). Therefore, according to these density thresholds, we allowed some parcels with nonzero housing density to be considered as 'undeveloped' because these large, rural parcels might contain a single or a handful of houses but they exist within a large open area. In other words, the overall land cover of these parcels was effectively undeveloped, and we therefore assumed that development in adjacent parcels would be akin to development in open areas.

We defined infill parcels as those that were completely surrounded by developed parcels. Expansion parcels had at least one neighboring parcel that was undeveloped; and leapfrog parcels were those with no developed parcels in their immediate surroundings. We reclassified the type of each available parcel in the same manner after each time step, to account for changing dynamics in the development map of the county.

We conducted three simulations, one for each development scenario (infill, expansion, and leapfrog). In each simulation, all parcels were eligible to subdivide, regardless of their class. Therefore, to build a simulation for a specific scenario, we increased the development probability of parcels of the selected scenario by 20%, to favor their development compared to the other types of parcels, without prohibiting development in the other parcel types. This approach was necessary because the projected number of dwelling units was much larger than it would be possible to fit in infill and leapfrog class parcels solely. For example, as the spatial coverage of developed parcel expands, there is less contiguous area that is undevelopable and suitable for leapfrog development. Therefore, the scenarios are not exclusive, but rather a mixture of the three development types. Yet, in each scenario, there is one main type of development, and smaller amounts of development events of the other two types.

Due to the immense computational demand of the simulations, we adopted a deterministic, rather than a stochastic approach to decide on which parcels were subdivided. After enhancing the transition probability according to the corresponding scenario, we ranked and then sorted all parcels according to their probability of subdivision. We then sequentially selected parcels, while simultaneously tallying the number of dwelling units in them, until the development target in that time step (one fourth of the total number of dwelling units to be added: 82,795) was reached. Once the development target was reached, we moved to the next time step. After each time step, the remaining parcels that were still eligible for development were re-classified to development types according to the new spatial configuration of the landscape.

Once a parcel was selected for subdivision, and the number of new parcels to develop in it was calculated (as detailed above), an equal-area spatial splitting model was employed to split the parent parcel to the predefined number of equal-area child parcels. We developed a simple splitting model which is based on iterative splitting of larger parcels into two smaller parcels using a straight line splitting boundary. Once the parcel was fully split into the needed number of sub-parcels, we allocated a new structure inside each new parcel by generating a point at its centroid (center of gravity). The point datasets of all structure locations per time step per scenario were passed over to the fire risk model, which is described below.

Fire Risk Modeling and Analysis

To project the distribution of fire risk under alternative scenarios, we used MaxEnt [47–48], a map-based modeling software used primarily for species distribution modeling [48], but we have used it successfully for ignition modeling [50] and for projecting current fire risk in the study area [26]. For this study, we slightly modified the model from Syphard et al. [26]. The dependent variable was the location of structures destroyed by fire between 2001 and 2010. Although inclusion of damaged structures in the data set does not significantly affect results [26], we only included completely destroyed structures to avoid the introduction of any uncertainty.

The MaxEnt software uses a machine-learning algorithm that iteratively evaluates contrasts among values of predictor values at locations where structures burned versus values distributed across the entire study area. The model assumes that the best approximation of an unknown distribution (i.e., structure destruction) is the one with maximum entropy. The output is an exponential function that assigns a probability to every cell of a map. Thus, the resulting continuous maps of fire risk represented the probability of a structure being destroyed by fire. In these output maps, areas of predicted high fire risk that did not have structures on them represented environmental conditions similar to those in which structures have actually burned.

We based the explanatory variables on those that were significantly related to burned structures in Syphard et al. [26], including maps depicting housing arrangement and pattern, housing location, and biophysical factors. Housing pattern variables reflected individual structure locations as well as the arrangement of structures within housing clusters. We calculated housing clusters, defined as groups of structures located within a maximum of 100 m from each other, by creating 100 m buffers around all structures and dissolving the overlapping boundaries [51].

Because burned structures were significantly related to small housing clusters [26], we calculated the area of every cluster as an attribute, and then created raster grids based on that attribute. Low-to intermediate housing density and distance to the edge of the cluster were also significant explanatory variables relative to housing pattern and location [26], so we also created raster grids for those. GIS buffer measures at 1-km have been found to explain approximately 90% of the variation in rural residential density [52], so we developed density grids using simple density interpolation based on a 1-km search radius, with area determined through square map units. To create grids representing distance to the edge of clusters, we first collapsed the cluster polygons into vector polyline files, and then created grids of interpolated Euclidean Distance to the edge within each cluster.

Because the MaxEnt model randomly selects background samples in the map to compare with locations of destroyed structures, we used a mask to restrict sampling to the developed environment within cluster boundaries; the distance to the edge of the cluster would represent a different relationship inside a cluster boundary versus outside in the wildland. We also modified the grids to ensure that any random sample located within the 100m buffer zone would receive a value of 100m; thus, all points within the buffer were considered "the edge of the development".

After creating the grids representing housing pattern and arrangement of the current configuration of structures, we applied the same algorithms to the maps of simulated future structure locations. We thus generated grids representing future housing pattern and arrangement under alternative development scenarios. The other explanatory variables, including fire history, slope, fuel type, southwest aspect, and distance to coast [26] remained constant through time for current and future scenarios. Although historic fire frequency and fuel type typically change through time, we did not simulate their dynamics here because we wanted to isolate the effect of planning decisions on housing pattern and arrangement while holding everything else constant.

We conditioned the MaxEnt model on present distributions of housing using ten thousand random background points and destroyed structures located no closer than 500-m to minimize any effect of spatial autocorrelation. We used 80% (260 records) of these data for model training, and 20% [66 records) for testing. We repeated the process using cross-validation with five replicates and used the average of these five models for analyses. For smoother functions of the explanatory variables, we used hinge features, linear, and quadratic with an increase in regularization of beta set at 2.5, based on Elith et al. [48]. The smoother response curves minimize over fitting of the model. We conducted jackknife tests of explanatory variable importance.

We first developed the model using mapped explanatory variables derived from the current configuration of structures. To project fire risk under the different time steps of the alternative development scenarios, projected the model conditioned upon current conditions onto maps representing future conditions by substituting the grids representing future housing pattern and arrangement. This is similar to how potential future distributions of species are projected under climate change scenarios [49].

To quantify differences among current and future alternative scenarios, we calculated metrics representing housing density, pattern, and footprint to determine the extent to which the planning policies produced differences in housing pattern and location. We compared the modeled structure fire risk of the scenarios by overlaying all maps of structure locations with their respective mapped output grids from the MaxEnt models and calculating probability of burning for every structure point. We also calculated total area of risk by selecting three threshold criteria [53]. These criteria, at 0.05, 0.25, and 0.5 represented three different degrees of risk, and we calculated the proportion of structures that were located in risk areas for every time step in all scenarios.

Results

The probit econometric model, run on 113 001 observations, showed that larger parcels were most likely to subdivide, although the relationship between parcel size and subdivision probability was non-linear (Table 1). Parcels closer to existing roads, the ocean, those with lower slopes, and those designated as fit for development were all most likely to develop. Parcels designated in redevelopment areas were less likely to develop. Overall, the model had a pseudo r –squared of 0.22.

The land use simulation model, based on a combination of the econometric subdivision model and three different growth policies, resulted in substantial differences in the extent and pattern of housing of the three scenarios. The total area of housing development, or the housing footprint, was largest for simulations where leapfrog growth dominated, followed by expansion-type development, and then infill (Figure 1a). The differences in the housing footprint became larger among the scenarios over time, but the largest difference was between infill and the other two development types. As the housing footprint expanded in the three scenarios, the corresponding housing density declined, so that leapfrog growth resulted in the lowest housing density per 1-km, followed by expansion and then infill (Figure 2b). Despite the near inverse of this relationship, there was generally a larger separation among scenarios with regard to housing density. With larger housing footprints and lower housing density, the number of separate housing clusters increased while their size decreased (Figure 2c).

In the first two time steps of the model (2015 and 2020), the simulated development pattern closely followed the desired pattern in the scenario, although some of the growth in the infill scenario ended up becoming expansion or leapfrog (Table 2). In the last two time steps (2025 and 2030), there were not enough infill parcels left, and thus, the majority of growth in these simulations became expansion, followed by infill, and then leapfrog. In the last time step, there were not enough isolated parcels in the leapfrog scenario and thus, the majority of development became expansion. Thus in general, as more development occurred in the simulations by the year 2030, the majority took the form of expansion.

The area under the curve (AUC) of receiver operating characteristic (ROC) plots, indicating the ability of the MaxEnt model to discriminate between burned and unburned structures, averaged across five cross-validated replicate runs was 0.91. The AUC represents the probability that, for a randomly selected set of observations, the model prediction was higher for a burned structure than for an unburned structure [49].The two most important variables in the model according to the internal jackknife tests in MaxEnt [47] were related to housing pattern:

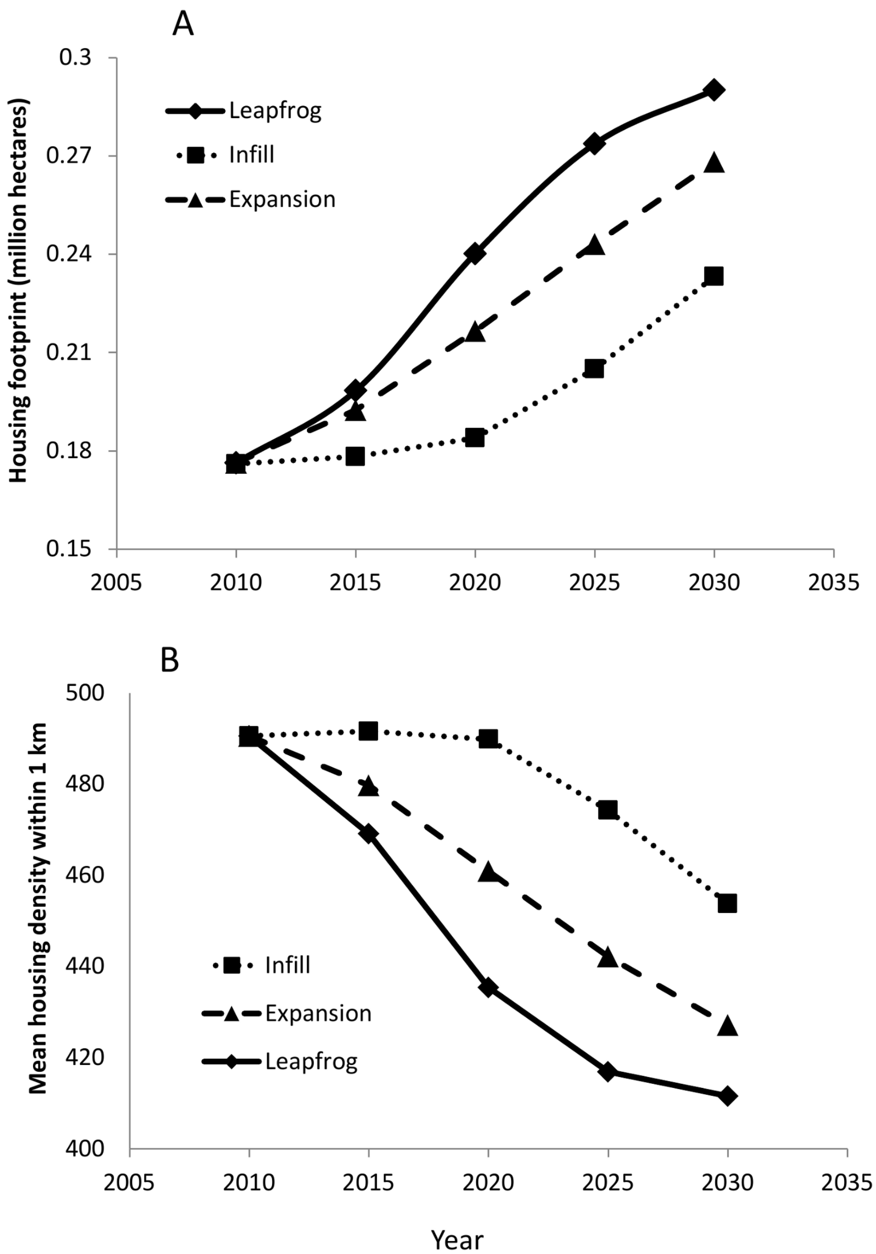

Figure 1. Trends of development extent and pattern for three planning policy simulations from 2010–2030, including A) total housing footprint representing the area of land within all housing clusters, and B) mean housing density averaged across all housing clusters.
doi:10.1371/journal.pone.0071708.g001

low to intermediate housing density and small cluster size and housing density (Figure 3). The distance to the edge of housing cluster was a less important contribution.

Maps showing the probability of a structure being destroyed in a wildfire, displayed as a gradient from low to high risk, show broad agreement relative to the general areas of the landscape that are riskiest, with correlation coefficients ranging from 0.85–0.91 (Figure 4). Nevertheless, subtle differences are apparent in the three development-scenario maps by year 2030, with the highest-risk areas in the expansion scenario located farther east than infill, and the highest-risk areas in leapfrog occupying a wider extent than either of the other two scenarios.

Differences among current housing and the three development scenarios are clearly illustrated through the mean landscape risk, or total probability of all structures burning (Figure 5). All three development scenarios were predicted to experience an increase in mean landscape risk over the duration of the simulations, except for infill at year 2015. The highest landscape risk to structures was predicted for the leapfrog scenario, followed by expansion, and then infill. The increase in risk over time is more gradual for the infill scenario than the other two scenarios.

The ranking of scenarios varied according to the proportion of structures located within different levels of risk defined through binary thresholding (Figure 6). When the continuous risk maps were thresholded at the lowest number of 0.05, a large proportion

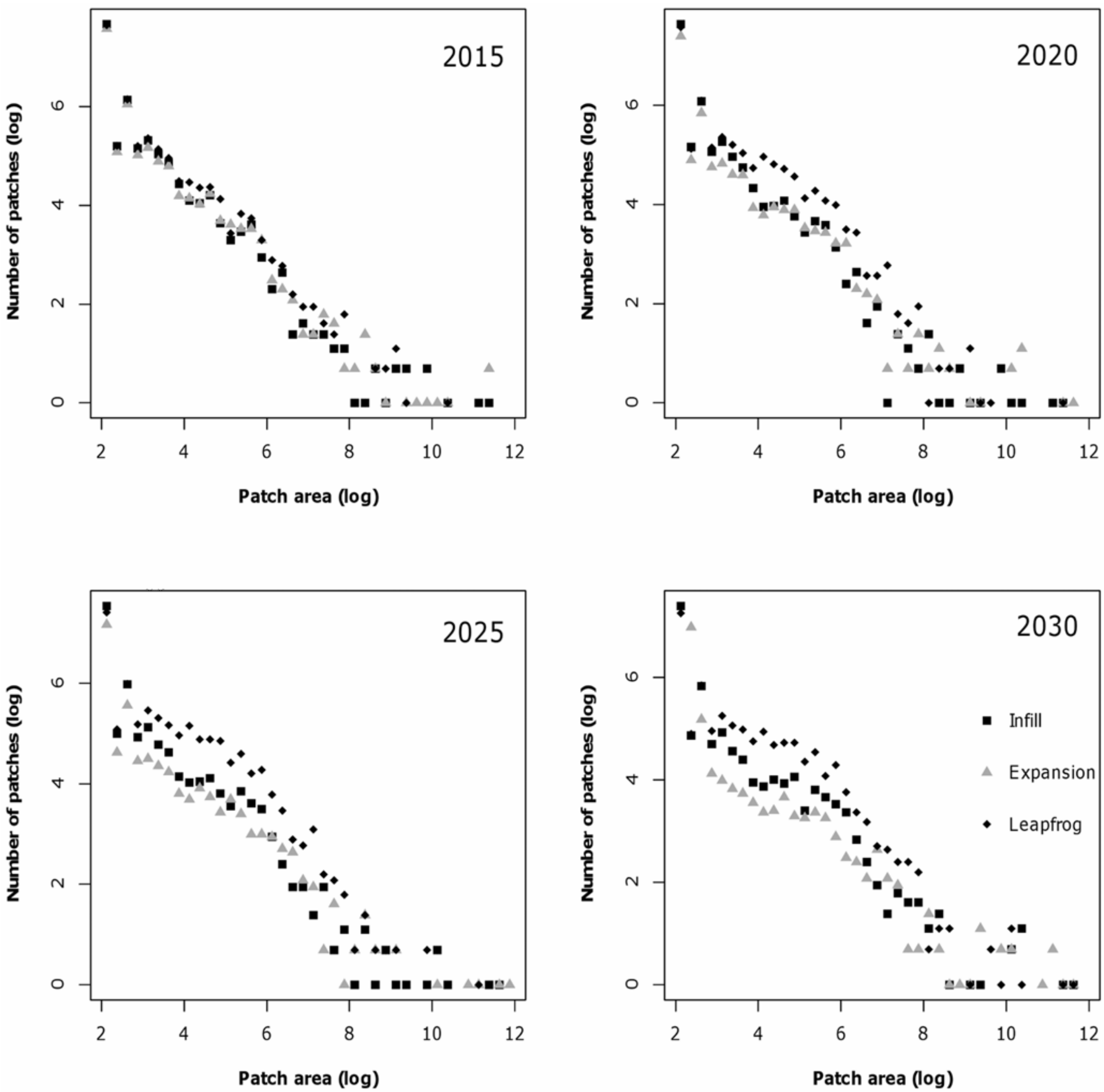

Figure 2. Trends in number of patches and patch area for three planning policy simulations from 2010–2030. Numbers were log-transformed for better visual representation of the scenarios.
doi:10.1371/journal.pone.0071708.g002

of structures in all scenarios fell within areas defined as risky according to this criterion. At this threshold, the proportion of structures in high-risk areas increased linearly for the expansion and leapfrog development scenarios while the proportion of infill homes increased more gradually. When risk was defined more conservatively at 0.25, temporal trends for the leapfrog and infill scenarios were similar to the 0.05 threshold. However, the proportion of structures at risk in the expansion scenario initially increased to 2020, but this proportion leveled off and declined by 2030. When the threshold was highest at 0.50, a very low proportion of structures in any scenario were located in areas at risk. But in these high-risk areas, the expansion scenario switched places with infill to have the lowest proportion of structures at risk in all time steps. Leapfrog had the largest proportion of homes at risk. This proportion of homes located in areas at risk with a threshold at 0.5 declined over time for all three scenarios.

Discussion

Our simulations of residential development showed that planning policies based on different growth types, applied locally for subdivision of individual parcels, will likely produce substantial and cumulative landscape-level differences in pattern, location, and extent of development. These differences in development pattern, in turn, will likely affect the area and proportion of

Table 2. Pattern of simulated development under infill, expansion, and leapfrog growth policies.

		Actual development		
Development scenario	**year**	***Infill***	***Expansion***	***Leapfrog***
Infill	2015	9450	18	6
	2020	11787	153	29
	2025	236	624	144
	2030	325	890	179
Expansion	2015	0	772	0
	2020	0	1243	2
	2025	0	1871	1
	2030	0	2662	0
Leapfrog	2015	0	10	408
	2020	0	5	1132
	2025	1	83	3563
	2030	34	917	0

The numbers in the table denote the numbers of patches of a given development type.
doi:10.1371/journal.pone.0071708.t002

structures at risk from burning in wildfires. In particular, the scenarios with lower housing density and larger numbers of small, isolated clusters of development, i.e., leapfrog followed by expansion and infill, were generally predicted to have the highest predicted fire risk to the largest proportion of structures in the study area. Nevertheless, rankings of scenarios were affected by the definition of risk.

Theoretically, it makes sense that leapfrog development produced fragmented development with larger numbers of small patches, lower housing density, and a larger housing footprint; and that infill resulted in the opposite, with expansion in the middle. By definition, leapfrog development requires open space around all sides of the newly developed parcel, whereas infill requires development on all sides, and expansion requires development on one side and open space on another. Implementing these planning policies on real landscapes, however, can be complex if there are more houses to build than there are parcels that meet the definitions of the three planning rules, and thus not all development conforms strictly to the policy [54]. In our simulations, parcels meeting the definition of each growth type had a higher probability of subdividing; yet, as we were simulating a real landscape, many newly developed parcels did not meet the scenario criteria. That the three scenarios nevertheless produced substantial differences in landscape-level development patterns shows that decision-making at the individual level can lead to meaningful broad-scale effects.

The objective of the econometric model was to provide a baseline probability to predict which parcels were most likely to subdivide; thus, the econometric model itself provides no explanation of how a given policy affects likelihood of subdivision, although it does indicate the correlation between the policy and the outcome. In our setting, which areas are protected, marked for redevelopment, or marked for development may be endogenous to the land owner decision to subdivide. In the case of these variables especially, our results should not be interpreted as causal predictors. Likewise, we use data only from 2005–2009 to predict changes to 2030. If major changes in the land market take place

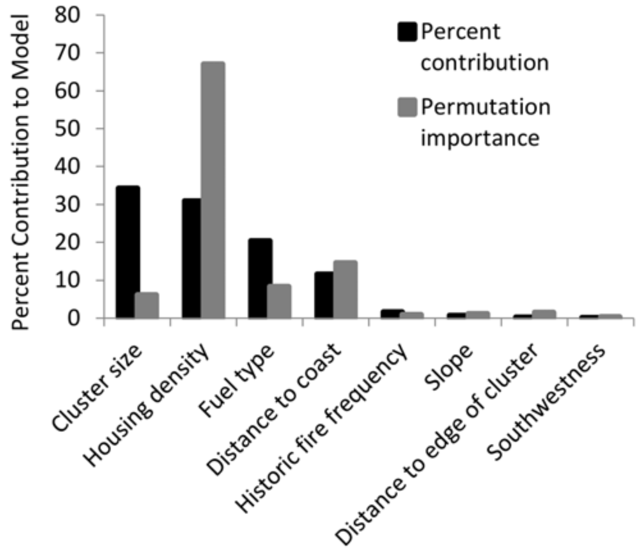

Figure 3. The importance of explanatory variables averaged across five cross-validated replications in the MaxEnt fire risk model. Percent contribution is determined as a function of the information gain from each environmental variable throughout the MaxEnt model iterations. Permutation importance reflects the drop in model accuracy that results from random permutations of each environmental variable, normalized to percentages.
doi:10.1371/journal.pone.0071708.g003

over this time horizon our model will not be able to take this into account.

Although some differences in predicted fire risk among the three scenarios likely stemmed from location of new structures relative to variables such as distance to coast, fuel type, or slope, the most important variables in the fire risk model were housing density and cluster size, with most structure loss historically occurring in areas with low housing density and in small, isolated housing clusters. Thus, leapfrog development was generally the riskiest scenario and infill the least risky. The most surprising result was the variation in predicted risk for the expansion scenario over time and at different thresholds. While leapfrog and infill showed similar trajectories across thresholds, expansion went from being the highest-risk scenario at the low threshold to being the lowest-risk scenario at the highest threshold. Because the threshold is merely a way to group structures into a binary classification, this means that, while the average risk calculated across all homes shows expansion to rank in the middle of infill and leapfrog throughout the simulation (Figure 5), the other two scenarios have a relatively larger proportion of homes that are modeled to be at a very high risk (i.e., 0.25 or 0.5), particularly by the end of the simulations. Because the total number of structures with a risk greater than 0.25 or 0.5 is relatively low in all scenarios, this difference in distribution of homes at the highest risk is not reflected in the mean. Another reason for the shift in rank of expansion over time is that, as more development occupied the landscape, there were fewer parcels remaining to accomplish infill or leapfrog type growth in the other scenarios. Thus, by the end of the simulations in year 2030, the majority of growth in all scenarios was expansion, and there was some convergence between scenarios. Finally, the change in risk of expansion growth over time may reflect that, despite the relatively low importance of distance to edge of cluster as an explanatory variable, expansion growth is characterized as having an initially fragmented landscape pattern that eventually merges into large patches with low edge.

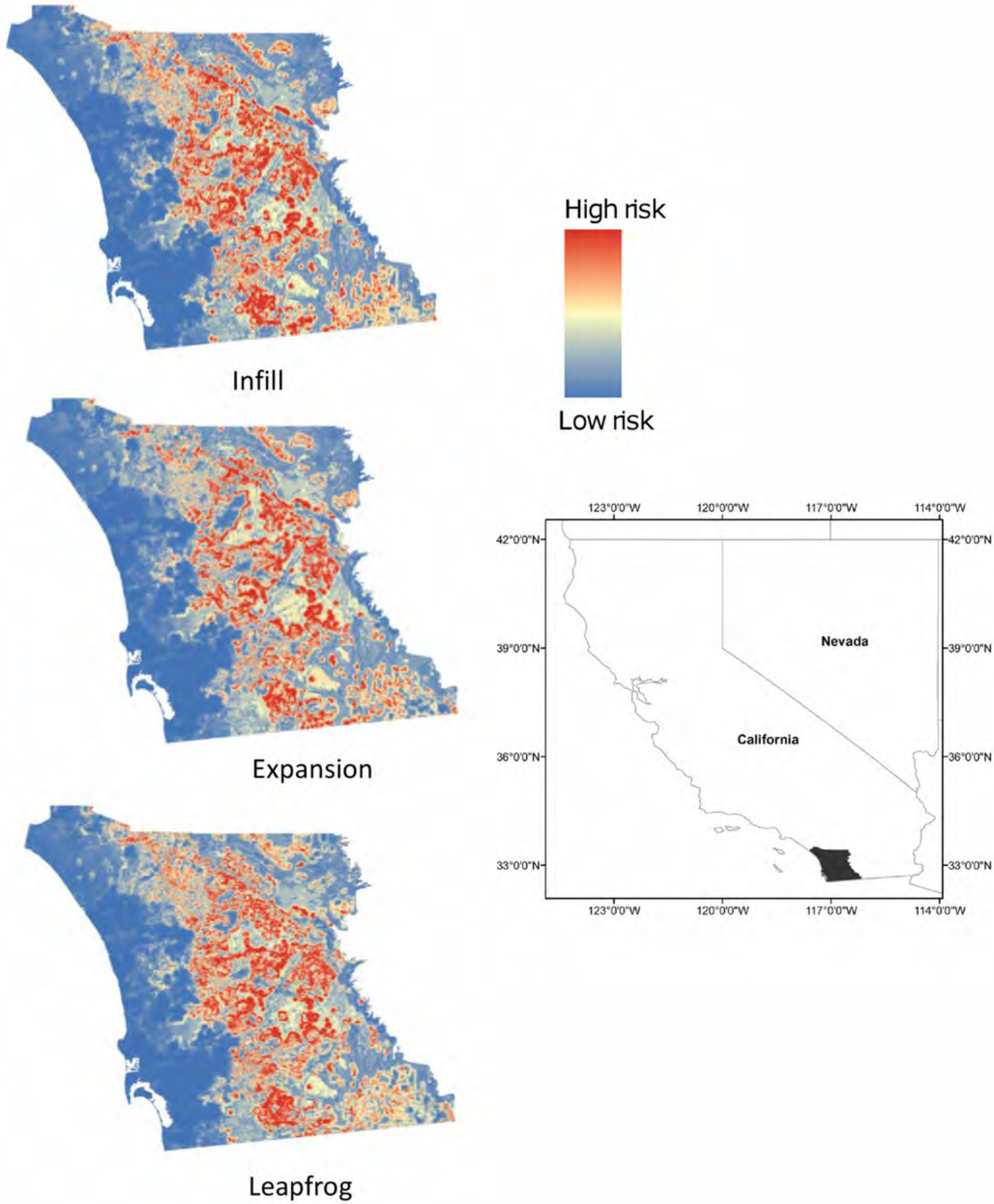

Figure 4. Maps of the study area showing projected wildfire risk at year 2030 for simulations of residential development under policies emphasizing infill, expansion, or leapfrog growth.
doi:10.1371/journal.pone.0071708.g004

Although leapfrog development clearly ranked highest in terms of fire risk, the interpretation of which planning policy is best may depend on fire management objectives and resources, as well as other considerations such as biodiversity or ecological impacts.

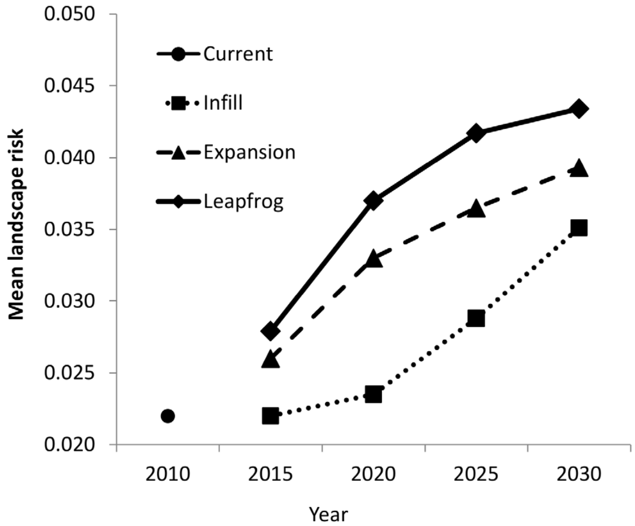

Figure 5. Projected landscape fire risk, reflecting the probability of burning in a wildfire averaged across all residential structures on the current landscape and in three development scenarios of infill, expansion, and leapfrog for year 2030.
doi:10.1371/journal.pone.0071708.g005

The spatial pattern of development affects multiple ecological functions and services [55], with potentially varying conservation implications; both leapfrog and expansion development consumed more land than infill, which would likely lead to more ecological degradation [56]; nevertheless, higher-density clustered development may be dominated by more invasive species [57]. Trade-offs between fire protection and conservation are common, but techniques are available for identifying mutually beneficial solutions [58].

Different perceptions of the fire risk results could also potentially translate into different planning priorities for management. For example, if the priority is to plan for the lowest overall risk to structures, then the mean landscape risk clearly delineates the rankings of options, with infill being the winner. However, if the objective is to reduce the number of structures at the highest risk threshold, i.e., $>= 0.5$, then expansion is the best option, at least by 2030. An important consideration for fire management is the total area that needs to be protected, as well as the length of wildland-urban interface [8,13]. Therefore, despite the lower number of structures at the highest risk thresholds, expansion creates more edge than infill and may translate into greater challenges for firefighter protection.

Although we did not create separate scenarios for high or low growth, the results at different time steps can be substituted to envision the potential outcome of developing more or fewer houses. In the short term, the total fire risk is projected to increase proportionately as more land is developed. However, given the inverse relationship between housing density and fire risk, it is possible that this trend could reverse if housing growth eventually resulted in expansive high-density development.

Land use planning is one of a range of options available for reducing fire risk, and the best outcome will likely be achieved through a combination of strategies that include homeowner actions, improvements in fire-safe building codes, and advanced fire suppression tactics. Although we isolated the effect of land use planning policy in the three development scenarios, the fire risk model nevertheless showed that the pattern and location of structures in this study area were the most important out of a suite of factors influencing structure loss. We used a correlative approach that did not incorporate mechanisms or feedbacks, but our models clearly illustrated differences in the cumulative effects of individual planning decisions. The relationship between spatial pattern of development and fire risk is likely related to the intermixing of development and wildland vegetation [29,59]; thus, these results likely apply to a wide range of fire-prone ecosystems with large proportions of human-caused ignitions. Nevertheless, because fire risk is highly variable over space and time, and due to a range of human and biophysical variables [60], we recommend planners develop their own models for the best understanding of where the most fire-prone areas are in their region [19].

With projections of substantial global change in climate and human development, we recommend that land use planning should be considered as an important component to fire risk management, potentially to become as successful as the prevention of building on flood plains [61]. History has shown us that preventing fires is impossible in areas where large wildfires are a natural ecological process [4,9]. As Roger Kennedy put it, "the

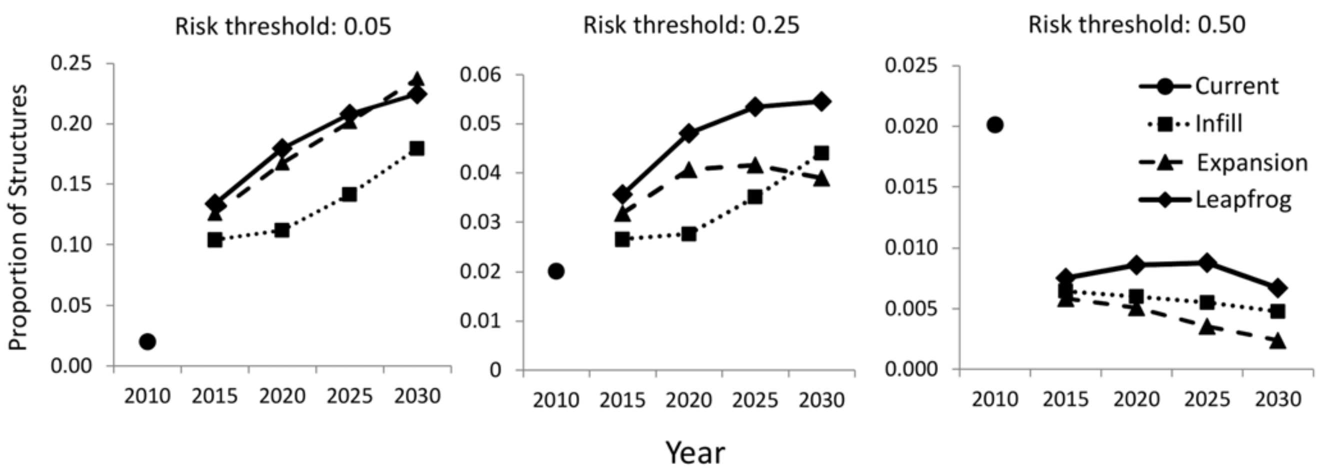

Figure 6. Proportion of residential structures that are located in areas of high fire risk defined using thresholds from the fire risk model of 0.05, 0.25, and 0.5 for current structures and for structures simulated under infill, expansion, and leapfrog growth policies.
doi:10.1371/journal.pone.0071708.g006

problem isn't fires; the problem is people in the wrong places [62]."

Supporting Information

Table S1 Definitions and summary statistics for variables used in the probit model.
(DOCX)

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Author Contributions

Conceived and designed the experiments: ADS JEK ABM VB. Performed the experiments: ADS ABM VB. Analyzed the data: ADS ABM VB. Wrote the paper: ADS JEK ABM VB.

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Predicting spatial patterns of fire on a southern California landscape

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Abstract. Humans influence the frequency and spatial pattern of fire and contribute to altered fire regimes, but fuel loading is often the only factor considered when planning management activities to reduce fire hazard. Understanding both the human and biophysical landscape characteristics that explain how fire patterns vary should help to identify where fire is most likely to threaten values at risk. We used human and biophysical explanatory variables to model and map the spatial patterns of both fire ignitions and fire frequency in the Santa Monica Mountains, a human-dominated southern California landscape. Most fires in the study area are caused by humans, and our results showed that fire ignition patterns were strongly influenced by human variables. In particular, ignitions were most likely to occur close to roads, trails, and housing development but were also related to vegetation type. In contrast, biophysical variables related to climate and terrain (January temperature, transformed aspect, elevation, and slope) explained most of the variation in fire frequency. Although most ignitions occur close to human infrastructure, fires were more likely to spread when located farther from urban development. How far fires spread was ultimately related to biophysical variables, and the largest fires in southern California occurred as a function of wind speed, topography, and vegetation type. Overlaying predictive maps of fire ignitions and fire frequency may be useful for identifying high-risk areas that can be targeted for fire management actions.

Additional keywords: fire frequency, fire ignitions, generalised linear model, predictive mapping, wildland–urban interface.

Introduction

Altered fire regimes threaten ecosystem structure and function, create hazards for people, and increase fire suppression costs (Calkin *et al*. 2005; Stephens 2005; Steele *et al*. 2006). In the United States, fire regimes have been altered both through fuel accumulation due to fire suppression and from the dramatic increase in the number of human-caused ignitions in fire-prone areas, particularly the wildland–urban interface (WUI) (Keeley and Fotheringham 2003), which is the contact zone where human development abuts and intermingles with undeveloped vegetation (Radeloff *et al*. 2005). The convergence of these trends has resulted in substantial federal funding, and social and political pressure, to decrease fire hazard by reducing fuel loads (USDA and USDI 2001; NPS 2005).

Although fuel buildup creates conditions favourable for intense, large-scale fires (Pyne *et al*. 1996; Allen *et al*. 2002), human population growth contributes to increased ignitions and fire frequency (Keeley *et al*. 1999; Rundel and King 2001; Radeloff *et al*. 2005; Syphard *et al*. 2007*a*). Information on fuel loading is often the only factor considered when planning management activities to reduce fire hazard (Dickson *et al*. 2006). In some forests, widespread fuel reduction methods, such as landscape-scale prescribed fire, can be beneficial for restoring natural disturbance regimes (Miller and Urban 2000; Scheller *et al*. 2005). However, in regions where human ignitions have increased fire frequency beyond its natural range of variability, widespread prescribed fire can be ecologically damaging to native plant communities (Keeley and Fotheringham 2003).

Also, management strategies based solely on fuel as a risk factor can become needlessly expensive if fuel treatments are placed in locations where fire hazard to humans is of little concern (G. Aplet and B. Wilmer, http://www.tws.org/OurIssues/Wildfire/CFPZ/index.cfm, accessed 11 August 2008). Considering that fire regimes vary among vegetation types and that humans impact fire regimes in different ways, there is growing awareness that fire management should be adapted to both the human and ecological landscape characteristics that vary from region to region (Odion *et al*. 2004; Halsey 2005; Badia-Perpinya and Pallares-Barbera 2006). With better understanding of regional context, fuels treatments can be prioritised and strategically placed in areas where fire is most likely to threaten values

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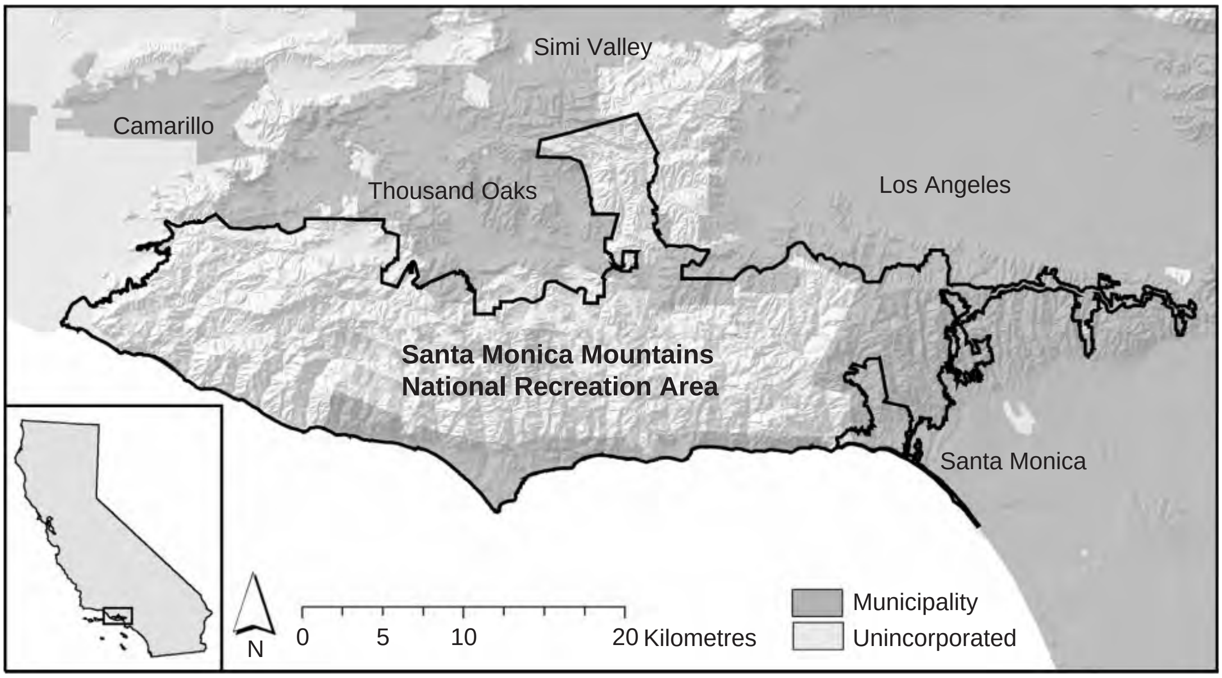

Fig. 1. The Santa Monica Mountains National Recreation Area, California, USA.

at risk or where placement will minimise ecological impacts (Halsey 2005; Dickson *et al*. 2006).

To identify the best locations for strategically placed fuels treatments, it is first necessary to understand how and why fire patterns vary across landscapes (DellaSala *et al*. 2004). Fire behaviour is largely a physical phenomenon, as illustrated by the fire environment triangle that places fire as a function of weather, fuels, and topography (Countryman 1972). Therefore, many fire risk and probability assessments have focussed on biophysical and climate variables (e.g. Bradstock *et al*. 1998; Fried *et al*. 1999; Diaz-Avalos *et al*. 2001; Rollins *et al*. 2002; Preisler *et al*. 2004), and several models and methods have been used to predict fire behaviour within different fuels types and from weather condition inputs (Burgan and Rothermel 1984; Forestry Canada Fire Danger Group 1992). Models that predict the probability of lightning ignitions have also been useful for identifying places where fires are likely to occur (Larjavaara *et al*. 2005; Wotton and Martell 2005). Although these biophysical approaches are critical for understanding fire patterns and behaviour, it is also important to understand the human influence on the frequency and spatial pattern of fire to help identify where fire risk is highest on a landscape, especially in places where fire regimes have been altered (Pyne 2001; DellaSala *et al*. 2004; Haight *et al*. 2004).

Human effects on the spatial distribution of fire have been accounted for in recent efforts to map or model fire risk. Most of these studies focussed on fire ignition points (i.e. the spatial location of fire's origin) (e.g. Pew and Larsen 2001; Badia-Perpinya and Pallares-Barbera 2006; Dickson *et al*. 2006; Yang *et al*. 2007), but fire risk probability has also been mapped using fire occurrence data (i.e. any location that burned regardless of point of origin) (e.g. Chou 1992; Chou *et al*. 1993). One problem is that fire patterns depend on both ignition locations and fire spread, but these are not necessarily determined by the same factors (Dickson *et al*. 2006; Syphard *et al*. 2007*a*, 2007*b*). For example, ignitions may or may not occur in fuel types that are highly flammable.

Our objective for the present research was to use a combination of biophysical and human explanatory variables to produce spatially explicit statistical models and maps predicting patterns of fire ignitions and fire frequency in a human-dominated southern California landscape. Most fires in the region result from human ignition sources (Keeley 1982; NPS 2005), so we expected proximity to human infrastructure to most strongly influence fire ignition patterns because the human activities that are likely to lead to ignitions are concentrated in or near these locations. The rate of spread for the largest fires in southern California is largely determined by wind speed, topography, and vegetation type (Keeley 2000). Therefore, we also expected the distribution of biophysical variables to be important predictors of fire frequency.

Methods

Study area

The Santa Monica Mountains National Recreation Area (hereafter referred to as the Santa Monica Mountains) encompasses ~60 000 ha of Mediterranean-type habitat, characterised by steep, coastal mountains that form the southernmost range in the Transverse Ranges of southern California (Fig. 1). Slightly more than half of the land in the mountains is in public ownership (including the National Park Service), and much of the privately owned land remains undeveloped. However, the Santa Monica Mountains include a substantial amount of WUI and have been experiencing increased development pressure due to their proximity to the Los Angeles metropolitan region, which is

Table 1. Variables analysed in the regression models explaining fire ignitions and fire frequency in the Santa Monica Mountains, CA
WUI, wildland–urban interface

Variable	Resolution	Source	Description or range
Dependent variables			
Ignition points	Point	National Park Service	$n = 126$, V = 67, from 1981 to 2003
Fire frequency	10 m	National Park Service fire perimeters	0 to 9, from 1925 to 2003
Explanatory variables			
Human			
Distance to development	10 m	Syphard *et al*. 2005	Mean Euclidean distance
Level of development	500-m buffer	Syphard *et al*. 2005	None (0); low (0.01–0.33); intermediate (0.34–0.66); high (0.67–1.0)
Distance to WUI	10 m	Radeloff *et al*. 2005	Mean Euclidean distance
Level of WUI	500-m buffer	Radeloff *et al*. 2005	None (0); low (0.01–0.33); intermediate (0.34–0.66); high (0.67–1.0)
Distance to roads	10 m	US Census Bureau TIGER/Line files	Mean Euclidean distance
Distance to trails	10 m	National Park Service	Mean Euclidean distance
Biophysical			
January temperature	1 km	J. Michaelson (Franklin 1998)	Interpolated by kriging
Elevation	30 m	USGS Digital Elevation Model (DEM)	
Slope gradient	30 m	Derived from DEM	
South-westness	30 m	Derived from DEM	SW = (con(aspect(<dem>) == −12, 201,(cos(((aspect(<dem>) − 255) div deg) + 1) * 100)))
Vegetation type	30 m	J. Franklin, J. J. Swenson and D. Shaari, pers. comm., 1997	Coastal sage scrub; northern mixed chaparral; chamise chaparral; non-native grass; oak woodland; riparian; other (less flammable vegetation such as salt marshes, agriculture, or urban)

home to more than 17 million people (Rundel and King 2001). The region that includes the study area is biologically rich, with ~1000 plant species, 50 mammal species, 400 bird species, and 35 species of reptiles and amphibians (NPS 2005). The region is also home to more than 20 federal or state-listed threatened or endangered animals and plants and another 46 animal and 11 plant species listed as species of concern (NPS 2002). The primary vegetation types are chaparral (e.g. *Ceanothus* spp. or *Adenostoma fasciculatum*, ~60%); coastal sage scrub vegetation (e.g. *Salvia* spp. or *Artemisia californica*, ~25%); exotic grass (~5%); oak woodland (~5%); and riparian vegetation (~5%).

Fire is a natural process in southern California Mediterranean-type ecosystems, and many of the region's native species are resilient to a range of fire frequencies (Zedler 1995). However, explosive population growth in the region has increased ignitions to the point that fire frequency exceeds its natural range of variability in many areas (Keeley *et al*. 1999). Repeated fires in short succession can also exceed the resilience of native species, and some shrublands have type-converted to exotic annual grasses under high fire frequencies (Zedler *et al*. 1983; Haidinger and Keeley 1993; Jacobsen *et al*. 2007). In the last 75 years, humans have been responsible for 98% of the fires in the Santa Monica Mountains, and some areas have burned up to 10 times (NPS 2005). Chaparral-dominated shrublands are typified by high-intensity, stand-replacing fires that are difficult or impossible to suppress under severe, high-wind weather conditions (Keeley 2000). Therefore, considering that fire frequency has increased despite aggressive fire suppression efforts, the most recent fire management plan in the Santa Monica Mountains recommends against using prescribed fire to reduce fuel across the entire landscape (NPS 2005). Instead, the National Park Service (NPS) recommends strategically positioned fuels treatment in areas with high fire hazard near the WUI.

Data description

Dependent variables – fire ignitions and frequency

The ignition data included 126 coordinate points acquired from the NPS fire records from 1981 to 2003 (Table 1, Fig. 2). Ignition locations were entered into the Shared Applications Computer System (SACS) at the National Interagency Fire Center (NIFC) in Boise, ID, and then converted into a Geographic Information System (GIS) database. The median accuracy of the ignition locations was 100 m.

Fire perimeter polygons originally reported by NPS and County Fire Departments were compiled by the California Department of Forestry–Fire and Resource Assessment Program (CDF-FRAP) into a GIS database (http://frap.cdf.ca.gov/data/frapgisdata/select.asp, accessed 8 August 2008). Although this database generally provides the most complete digital record of fire perimeters in California, the fire record was incomplete, with a minimum mapping unit of 4.04 ha (10 acres). Therefore, the NPS staff at the Santa Monica Mountains updated this database to include additional smaller fires (less than 1 ha), which resulted in a fire frequency map that delineated overlapping fire perimeter boundaries from 1925 to 2003. Within this database, more than 75% of the fires occurred within the last 20 years. Although the average area burned also increased over time, the fire size distribution has remained generally stable, with a slight decline (Table 1, Fig. 2).

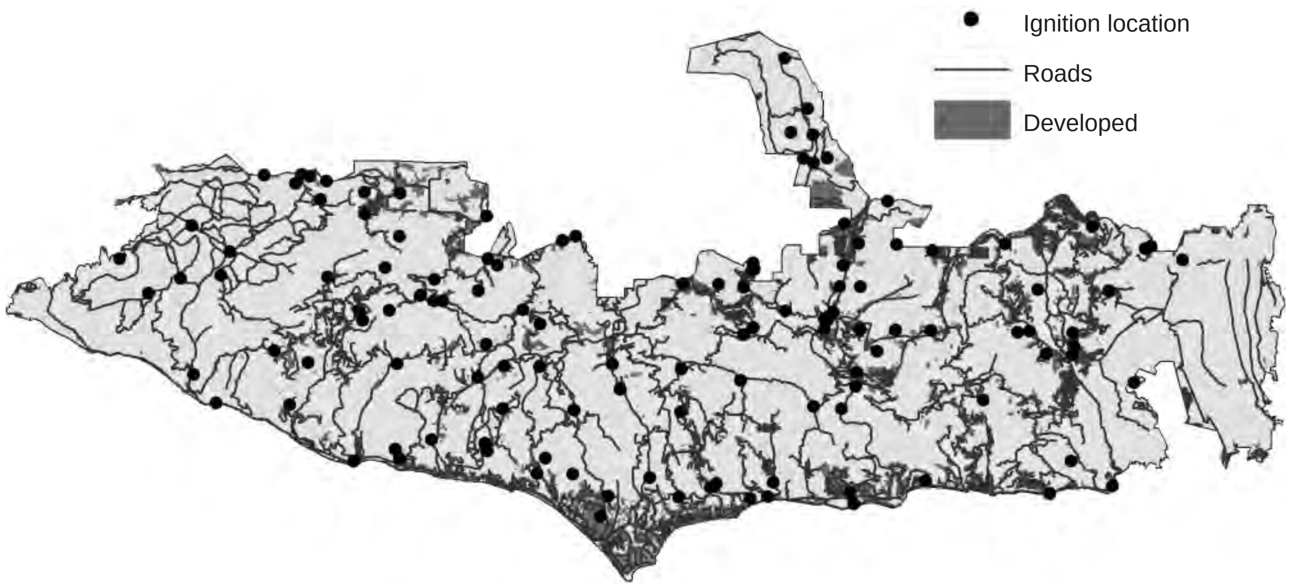

Fig. 2. Map showing proximity of ignition points (1981–2003) to roads and development in the Santa Monica Mountains, CA.

Using these boundaries, we created a continuous grid surface reflecting the number of fires that occurred during those 78 years for each cell. From this fire frequency grid, we randomly selected 1000 points to relate number of fires to the explanatory variables. We selected 1000 data points as our sample size because we wanted to use as many points as possible given the practical limitations of our statistical models. To ensure that the sample size was large enough to adequately represent the study area, we performed χ^2 goodness of fit tests to compare the true distribution of fire frequency (14 million points) with the distribution of fire frequency in our sample size of 1000, and we found no significant difference between them.

Explanatory variables – human

Human-caused ignitions frequently occur along transportation corridors and other areas where human activity is concentrated (Keeley and Fotheringham 2003; Stephens 2005). The ignition data points from the Santa Monica Mountains also appeared to be close to roads and development on a map (Fig. 2). Therefore, our explanatory human variables included distance to development, roads, trails, and WUI (Table 1, Fig. 2). We included trails because they provide a means of human access to otherwise undeveloped areas in the parks and protected areas. We created the map of development through airphoto interpretation and onscreen digitising of development evident on 1 : 12 000 at 1-m resolution digital orthorectified quarter quadrangles (DOQQs) from the US Geological Survey (USGS) for 2000. 'Development' included any part of the landscape with houses or other buildings, in addition to golf courses. We used 2000 US Topologically Integrated Geographic Encoding and Referencing system TIGER/Line files (US Census 2000) for our road data, and the NPS provided the GIS map of trails.

The interactions between human activities and natural dynamics tend to be spatially concentrated at the WUI, which has received national attention because housing developments and human lives are vulnerable to fire in these locations and because human ignitions are believed to be most common there (Rundel and King 2001; USDA and USDI 2001). Our WUI map was created as part of a nationwide mapping project that produced fine-scale maps of the conterminous United States (Radeloff *et al*. 2005; http://www.silvis.forest.wisc.edu/silvis.asp, accessed 8 August 2008). These data were created based on the definition of WUI published in the Federal Register (USDA and USDI 2001) using housing density data obtained from the US Census and land cover data obtained from the USGS National Land Cover Dataset (at 30-m resolution).

Explanatory variables – biophysical

From a biophysical perspective, the expression of fire on a landscape is a function of its fire environment, including the climate, terrain, and fuels in a region (Pyne *et al.* 1996). Therefore, spatially explicit models that simulate fire behaviour use input measurements of elevation, slope, aspect, weather, and vegetation (Anderson 1982; Andrews *et al*. 2005). Likewise, we selected climate and terrain-derived variables, as well as vegetation type, as potential biophysical explanatory variables (Table 1, Fig. 2). The biophysical factors that influence fire ignitions and fire spread may produce multiple direct and indirect effects on the fire regime (Whelan 1995). For example, slope angle affects soil moisture and development, which in turn affects vegetation distribution and composition, and thus fuel characteristics and flammability (Franklin 1995). At the same time, slope produces a direct physical effect on active fire fronts because the flames are closer to the ground, and fires typically burn faster in an upslope direction (Whelan 1995). We expected that the spatial variability and distribution of these influential biophysical variables across the landscape would provide substantial explanatory power to predict and map where fire ignitions and fire frequency were likely to occur.

Our terrain variables included elevation, percentage slope, and transformed slope aspect ('south-westness'). These topographic factors explain variation in local climate, provide natural firebreaks, and indirectly influence factors such as fuel moisture, vegetation distribution, and relative humidity (Whelan 1995). We scaled aspect to an index of 'south-westness' using a cosine transformation because the index better distinguished xeric exposures (high index values) from mesic exposures (low index values) (Franklin *et al*. 2000).

Because we were not simulating annual fire behaviour or weather, we used spatially interpolated climate variables (mean annual precipitation, average January minimum temperature and average July maximum temperature), which were more appropriate for the broad spatial and temporal scale of our study. Moisture and temperature affect vegetation productivity and rate of fuel accumulation as well as soil moisture, rate of combustion, and rate of spread (Whelan 1995). We evaluated both January minimum and July maximum temperatures because these represented upper and lower limits, both of which would therefore maximise the distribution of variability in temperature gradients and plant species distributions across the landscape (Franklin 1998). Annual precipitation had high correlation with other variables and was removed from the analysis. The temperature data layers were developed as a 1-km^2 gridded surface that was interpolated from climate station data, elevation, and a digital elevation model. The surfaces were interpolated using universal and ordinary kriging (Franklin 1998).

Several sophisticated systems have been developed to create fuels models to use in fire behaviour prediction (e.g. Forestry Canada Fire Danger Group 1992). However, only three of the thirteen standard fuel models used in the United States (by the National Forest Fire Laboratory) are considered applicable to chaparral shrublands (Anderson 1982). In southern California shrublands, the fire regime is strongly differentiated according to broadly defined, structurally similar vegetation types, and fire tends to behave uniformly within those types (Wells *et al*. 2004). Therefore, instead of using fuel types as predictor variables, we used a generalised map of vegetation types, created through a classification of 30-m Landsat Thematic Mapper (TM) data (J. Franklin *et al*., pers. comm., 1997).

The fact that post-fire age (and thus fuel buildup) is a less critical factor in California chaparral than in some other vegetation types is an important additional consideration. Fire spread in North American coniferous forest areas is strongly affected by post-fire age, with younger stands having lower fuel loads and lower rates of fire spread. In contrast, post-fire age has relatively little effect on the spread of fires in California chaparral, particularly during high wind conditions (Moritz 2003). Owing to rapid post-fire fuel accumulation, chaparral and coastal sage shrublands can burn at high intensities at young ages (Radtke *et al*. 1982). Therefore, we assumed that post-fire age would not strongly influence temporal patterns of fire frequency in the Santa Monica Mountains as strongly as it would in other regions, and therefore we did not include it as a variable in our analysis. Some studies in forested regions have considered post-fire age and temporal autocorrelation when explaining fire frequency (e.g. Reed *et al*. 1998; Preisler *et al*. 2004).

Data manipulation

Because we expected fire to occur close to human infrastructure, we created continuous surfaces reflecting mean Euclidean distances to all of the human explanatory variables, and we used these distances in our models. To obtain better precision in our Euclidean distance calculations, we resampled all of our grids to a 10-m resolution and used those for overlay and extraction of data to relate the explanatory variables to fire ignitions and frequency. Because fire frequency and area burned also tend to be highest at intermediate levels of human activity and are a function of the spatial pattern of development and fuels (Keeley 2005; Syphard *et al*. 2007*a*), we created 500-m buffers around all point locations and calculated the proportion of development and WUI within those areas (total extent = 78 ha). We chose this buffer size because the dense nature of chaparral makes it difficult for humans to traverse far into the vegetation (Halsey 2005); therefore, we assumed that human influence would not exceed 500 m. The proportions were then classified into four arbitrary categories: none (0), low (0.01–0.33), intermediate (0.34–0.66), and high (0.67–1.0) (Table 1). We used the Spatial Analyst Extension of *ArcGIS*, in addition to *ArcInfo Workstation*, for our GIS analysis and data processing.

Modelling approaches

Fire ignitions

To predict the estimated probability, *P*, of a cell, i, in the study area experiencing an ignition, we developed a multiple logistic regression model. For logistic regression, if we let P_i be the probability of an ignition in cell i, and x_{ji} be the value of the jth covariate in cell i, the logistic regression model is:

$$P_i = \exp(\beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \ldots + \beta_n x_{ni}) / (1 + \exp(\beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \ldots + \beta_n x_{ni}))$$

where β_0 is a constant and β_n are regression coefficients for the human and biophysical explanatory variables, x_{ni}. To determine whether the explanatory variables affected the ignition locations differently than what would be expected by chance, we also generated a random sample of 700 control points in the study area. Therefore, our model predicted the probability that ignitions would occur disproportionately as a function of multiple landscape characteristics compared with 700 randomly selected available locations within the study area. We chose 700 control points because we wanted to sample enough points to adequately capture the variability in the predictors across the entire landscape without substantially decreasing the ratio of ones to zeros. Our ratio (1 : 5.5) was similar to that of Brillinger *et al*. (2003) (1 : 4).

We first developed univariate logistic regression models for all of the explanatory variables because we wanted to evaluate their independent influence on the response variables and to determine the values and direction (i.e. positive or negative) of the coefficients independently of their interactions with other variables. The *P* values for these models were Bonferroni-corrected to account for the large number of tests performed. Next, we developed a multiple logistic regression model using the R statistical package (R Development Core Team 2005). We selected the final model through a backwards elimination process using the Akaike Information Criterion (AIC)

(Venables and Ripley 1999). Significance of effects was determined using the likelihood ratio test.

To ensure that there were no collinearity problems, we implemented a collinearity diagnostic procedure, the variance inflation factor (VIF), to ensure low correlation (VIF lower than 10) between the variables in the multiple regression model (Belsey *et al*. 1980). Because July maximum temperature was correlated with other variables, we removed this variable and refitted the multiple regression models. We also plotted semi-variograms of the models' deviance residuals to ensure there was no evidence of spatial autocorrelation. For all of our models, we evaluated the variables for non-linear relationships with the response through graphical checks and by fitting the models with quadratic terms included and determining whether those terms were significant.

To evaluate the performance of the multiple logistic regression model, we used a leave-one-out cross-validation approach (Lachenbruch 1967; Bautista *et al*. 1999). The procedure was to drop a single data point (i.e. an ignition), fit the model without it, and then calculate the predicted probability of an ignition at that point. This was repeated for every point. We then performed a receiver operating characteristic (ROC) analysis to determine the optimal probability cutoff for predicting that an ignition would occur. Based on this prediction rule, we were able to compare the yes–no ignition prediction with whether an ignition actually occurred, and estimate the sensitivity (fraction of true positive), specificity (fraction of false positive), and overall predictive ability of the fitted model (Fielding and Bell 1997).

The overall area under the curve (AUC) reflected the overall probability that, when we drew one ignition and one non-ignition point at random, our prediction rule correctly identified them. AUC values vary from 0.5 (no apparent accuracy) to 1.0 (perfect accuracy), but the interpretation of what is considered high or low predictive ability is subjective and can vary according to sample size, with lower sample sizes resulting in lower evaluations of model accuracy (Hernandez *et al*. 2006).

Fire frequency

Instead of using logistic regression, we used Poisson univariate and multiple regressions to develop the fire frequency models because they were appropriate for count data (Agresti 1996). For Poisson regression, if N_i is the number of fires observed in cell i, and x_{ji}, β_0 and β_n are as above, the model is:

$$N_i = \exp(\beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \ldots + \beta_n x_{ni})$$

As with the ignition multiple regression models, we developed univariate regression models for all of the explanatory variables because we wanted to evaluate their independent influence on the response variable, and adjusted the P values using the Bonferroni correction. For our multiple Poisson regression analysis, we again used a backwards stepwise elimination procedure based on the AIC to select the final model.

Although no spatial autocorrelation was present in the ignition data, we refitted the Poisson multiple regression model with allowance for a spatial exponential correlation between the deviance residuals owing to significant spatial autocorrelation in the fire frequency data (Littell *et al*. 1996). We fitted this model using the *GLIMMIX* macro of *SAS* Software (PROC GLIMMIX 2005).

To evaluate the performance of our multiple Poisson regression model, we randomly selected 300 independent observations in the study area. To determine how closely the observed and predicted values agreed in relative terms, we calculated Pearson's correlation coefficient. We also calculated the root mean square error (RMSE) and average error, which illustrate the discrepancy between the observed and predicted values (Potts and Elith 2006).

Predictive mapping

To convert our models into predictive map surfaces, we applied the formulae from the multiple Poisson and multiple logistic regression models to the entire study area using the predicted coefficients and the GIS map layers of the significant explanatory variables. Because logistic regression uses a prespecified number of control points, the intercept for the logistic regression is meaningless. However, we were able to adjust the intercept, and thereby map meaningful predicted probabilities, by using the ratio of control to experimental points (Preisler *et al*. 2004). We used the formulae from the Poisson model to predict and map fire frequency.

Owing to the difference in scales of fire ignition and fire frequency maps (probability of ignition *v.* predicted number of fires), we reclassified both maps into five equal-interval categories using the GIS and then summed these derived maps to generate a new map. This combined map was beneficial for identifying areas where ignitions and fire frequency were either both high or both low; however, intermediate values on the combined map did not differentiate between areas of high ignitions and low fire frequency and areas of high fire frequency and low ignitions. Therefore, we created a second map that reflected the differences in the predicted map surfaces.

Results

Fire ignitions

All of the human variables were significant ($P \leq 0.05$) in explaining fire ignitions in the univariate models except for distance to WUI after the Bonferroni adjustment (Table 2, Fig. 3). Ignitions were negatively related to all the distance variables and occurred closer to human infrastructure than the randomly selected points (Table 2). Although logistic regression coefficients can only be interpreted with respect to the intercept for categorical variables, the univariate models did indicate that fewer ignitions occurred when there was no development within a surrounding 500-m buffer, and more ignitions occurred with low or high proportions of nearby development. Similarly, fewer ignitions occurred when there was no WUI in the buffer, and more occurred with higher proportions of WUI. In addition to the human variables, the pattern of ignitions was also significantly related to slope and vegetation type, with ignitions being negatively related to slope.

When all of the variables were evaluated in the multiple logistic regression analysis, the final model for fire ignitions retained most of the human variables (distance to development, distance to roads, distance to trails, and level of WUI) as well as January minimum temperature and vegetation type (Table 3). The final model was highly significant at $P < 0.0001$.

Table 2. Univariate regression results for all variables explaining fire ignitions and fire frequency in the Santa Monica Mountains, CA
WUI, wildland–urban interface

Explanatory variable	Fire ignitions			Fire frequency		
	Coefficient	s.e.	*P* value	Coefficient	s.e.	*P* value
Distance development	−0.001201	0.000258	<0.0001	0.000131	0.000043	0.0026
Distance WUI	−0.000298	0.000137	0.0183	0.000065	0.000045	0.1513
Distance roads	−0.002635	0.000637	<0.0001	0.000097	0.000059	0.1028
Distance trail	−0.001785	0.0007	0.0045	−0.00002	0.000073	0.7837
January	−0.00012	0.000115	0.2964	0.000194	0.000057	0.0007
South-westness	0.002373	0.001392	0.0869	0.000334	0.00012	0.0055
Slope	−0.039957	0.009359	<0.0001	0.001927	0.00092	0.0364
Elevation	−0.000414	0.000169	0.0132	0.000079	0.000044	0.0726
Level of development						
None (0)	−2.3706[A]	0.2012	0.0002	1.2394	0.3444	<0.0001
Low (0–0.33)	0.9784	0.2349		1.1649	0.3426	
Intermediate (0.34–0.66)	0.6127	0.3972		0.9595	0.3338	
High (0.67–0.1)	0.9843	0.8158		−0.2587[A]	0.3604	
Level of WUI						
None (0)	−2.3302[A]	0.2095	<0.0001	0.07604	0.05809	0.5728
Low (0–0.33)	1.174	0.2704		0.03285	0.04838	
Intermediate (0.34–0.66)	0.8506	0.3119		0.01377	0.04237	
High (0.67–0.1)	0.4861	0.285		0.8651[A]	0.08816	
Vegetation type						
Coastal sage scrub	−1.39872[A]	0.17656	<0.0001	−0.02177	0.6849	0.3812
Northern mixed chaparral	−0.99918	0.24968		−0.00314	0.06824	
Chamise chaparral	0.01242	0.58624		−0.09035	0.1025	
Non-native grass	0.3001	0.3657		−0.05593	0.0823	
Other	0.19474	0.30509		−0.099	0.08529	
Oak woodland	0.64495	0.46368		−0.1134	0.09551	
Riparian	0.41789	0.69965		0.9235[A]	0.1039	

[A]Intercept of the model; the coefficients of the categorical variables (level of development and WUI, and vegetation type) are relative to the value of the intercept.

The map surface generated by applying the formula and coefficients of the final model to the original GIS maps showed the distribution of predicted ignition probabilities across the study area (Fig. 4). The spatial pattern of those areas predicted as having the highest likelihood of ignition reflected the influence of development, WUI, and roads, as seen through their similar distributions (Fig. 2).

The leave-one-out cross-validation of the final multiple logistic model resulted in an AUC of 0.71. An AUC of 0.71 indicates that, although our ability to predict is not perfect, our model performs considerably better than chance, and thus provides useful and novel information about the properties of the locations where ignitions are likely to occur. Our maximum sensitivity (true positive fraction) and specificity (false positive) occurred at a cutoff of 0.16, which yielded sensitivity $= 0.685$, and specificity $= 0.667$ (Fig. 4). In other words, if the model predicts a probability of ignition of 0.16 or more, we predict an ignition, otherwise we predict no ignition.

Fire frequency

Unlike the univariate models for fire ignitions, there were more biophysical variables than human variables that were significant ($P \leq 0.05$) in explaining fire frequency (Table 2, Fig. 3). Specifically, January minimum temperature, south-westness, slope, and elevation all had a positive influence on fire frequency. However, elevation, slope, and south-westness were not considered significant with the Bonferroni adjustment. Whereas distance to development negatively influenced the likelihood of ignition, it had a significant positive influence on fire frequency, so that fires were more likely to burn farther away from development. Fire frequency was also significantly related to level of development, but the influence was opposite that for fire ignitions in that fires were more likely to occur in none, low, and intermediate levels than in high levels of development.

Except for distance to development, all of the variables that were significant in the non-adjusted univariate models were also retained in the final model for fire frequency (Table 3). This model was also highly significant at $P < 0.0001$. The spatial pattern of predicted fire frequency on the map generated from the final regression model showed a strong influence of level of development and reflected the influence of the 500-m buffers (Fig. 4). The influence of January temperature was also visually apparent in the predictions, with more fires occurring along the coast where the temperature is generally warmer. The areas predicted to experience the most fires roughly corresponded to the fire history map (Fig. 2).

The evaluation of our multiple Poisson regression fire frequency model with the independent dataset showed that we predicted the number of fires correctly 40% of the time,

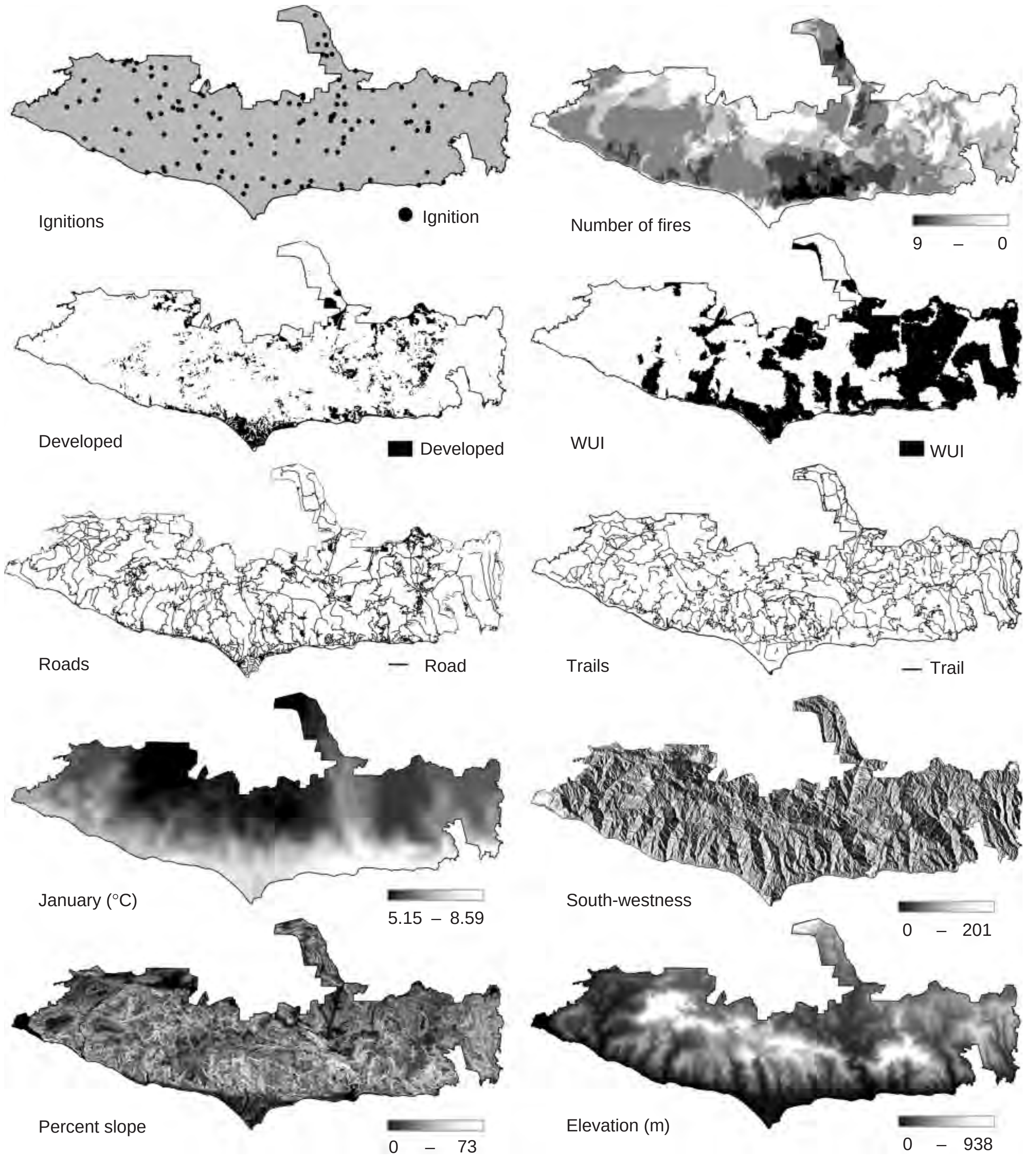

Fig. 3. Maps of variables used for regression models and predictive mapping of the Santa Monica Mountains, CA. Dependent variables included ignitions and number of fires; independent variables included developed, wildland–urban interface (WUI), roads, trails, mean January minimum temperature, south-westness, percentage slope, and elevation. Vegetation map not shown. The WUI is the area where houses meet or intermingle with undeveloped wildland vegetation, based on the definition in the Federal Register.

80% were within one fire of being correct, and 95% were within two. The Pearson's correlation coefficient was 0.490, the RMSE was 1.219. These statistics indicate that the model's performance was fair, but the positive error shows that we tended to underestimate fire frequency.

The combined map showed that, although some areas had a high potential for both fire ignition and frequency, not all areas with high potential for ignition were likely to experience many fires. In some of the most remote portions in the interior of the landscape, both fire ignition probability and fire frequency were predicted to be low. Along the coast and through some of the more developed canyons in the interior, however, both ignitions and frequency were predicted to be higher (Fig. 4).

Discussion

As we expected, humans significantly influenced the spatial pattern of ignitions, which were located in close proximity to all measures of human infrastructure included in our univariate models and were most strongly related to distance to development and roads in the multivariate models. Previous research showed that fire frequency and area burned were highest at intermediate levels of human activity; however, at lower and higher levels of human activity, fire activity was lower (Keeley 2005; Syphard *et al*. 2007*a*, 2007*b*). In the present study, ignitions were more likely to occur with consistently larger proportions of both development and WUI within 500-m buffers. However, the spatial extent of these buffers may not have captured the intermediate effects that were apparent through the landscape and county scales used in the other studies. Slope, vegetation type, and January temperature were also significantly related to ignitions, which may in part reflect the fact that fire ignition success is conditional on factors such as fuel moisture content and stand structure (Tanskanen *et al*. 2005).

Considering that humans start most fires in the Santa Monica Mountains and that human activities are concentrated around roads and developed areas, these results are not surprising. Yet, statistically modelling these human relationships and their interactions with biophysical variables is necessary for more precisely explaining and mapping the parts of the landscape that are most likely to ignite. Although other regions may not experience the same proportion of human ignitions as southern California, human-caused ignitions along transportation corridors have been documented broadly (Stephens 2005), and the significance of our results underscores the importance of considering more than just fuel loads in fire risk assessments. The WUI is not just the area with the highest concentration of human

Table 3. Variables retained in the multiple regression models explaining fire ignitions and fire frequency in the Santa Monica Mountains, CA
WUI, wildland–urban interface

Model	Explanatory variable	*P* value
Ignitions	Distance development	<0.0001
	Distance roads	0.002
	Vegetation type	0.002
	Level of WUI	0.011
	January	0.016
	Distance trails	0.08
	Full model	<0.0001
Fire frequency	Level of development	<0.0001
	January	<0.0001
	South-westness	0.005
	Elevation	0.036
	Slope	0.045
	Full model	<0.0001

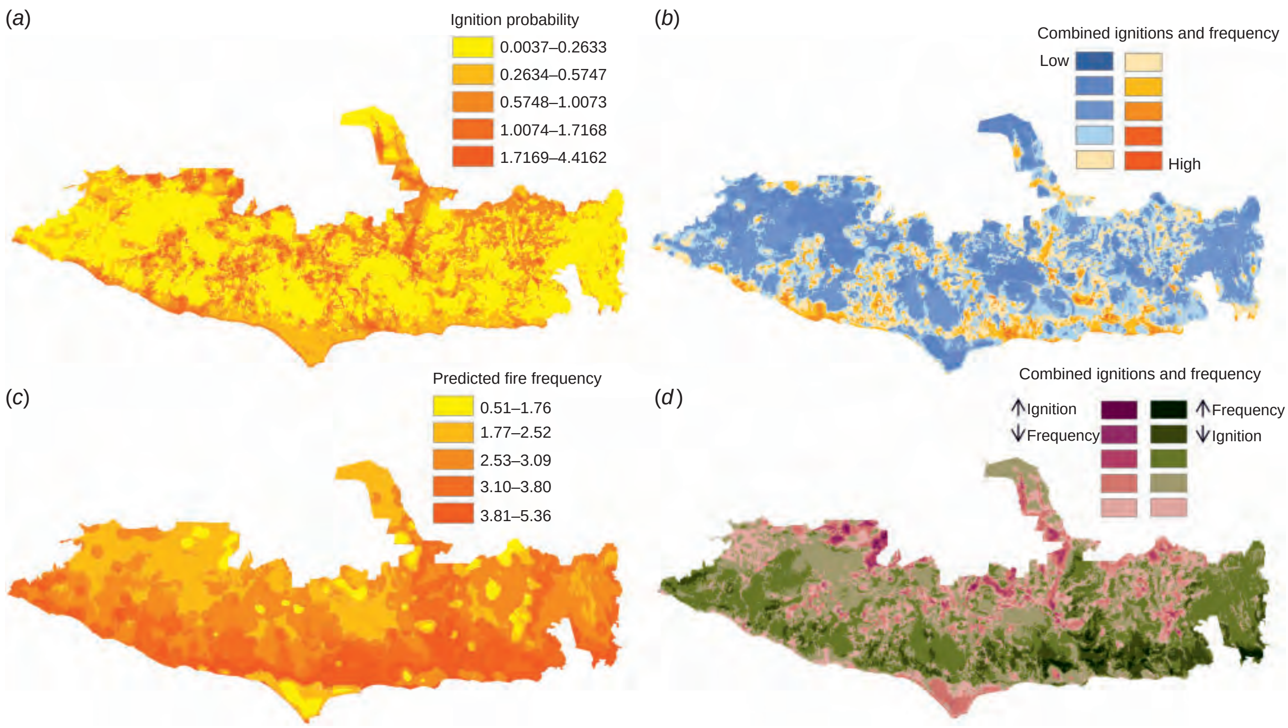

Fig. 4. Maps showing predicted probability of ignition (*a*), predicted fire frequency (*b*), overlay and sum of the classified ignition and fire frequency maps (*c*), and the distribution of differences between predicted ignition probabilities and predicted fire frequency (*d*) developed from multiple regression models in the Santa Monica Mountains, CA.

values at risk; it is also the area where humans are most likely to put these valuable assets at risk by starting fires, intentionally or not.

Although ignition locations were primarily related to the distribution of human activities, fire frequency was mainly determined by biophysical variables, which was expected because fire spread is ultimately a function of vegetation characteristics, climate, and terrain (Pyne *et al*. 1996). Fire frequency was significantly related to two human variables, but more fires occurred with longer distances to development and with lower proportions of development within buffers. Although this result seems surprising given the location of ignitions, one likely reason that fires burned more frequently when they were farther from human infrastructure is that there is typically more continuous vegetation in remote areas. Therefore, fires would not be interrupted by fragmented fuels that characterise urban areas. Also, there are lower concentrations of fire suppression resources outside urban areas (Calkin *et al*. 2005), so fires will be able to consistently burn longer and grow larger when they spread beyond their ignition source into more remote regions. This means that, although fires start closer to roads or development, the areas that actually burn most frequently are the non-urban regions where fire spreads after ignition.

A possible shortcoming in our fire frequency models was that the human explanatory variables only represented the contemporary time period, but the fire frequency data spanned a period of 78 years (although more than 75% of the fires in the record occurred within the last 20 years). Despite this temporal mismatch, our results were consistent with previous research in California that showed that, whereas human variables are the best predictors for the number of fires that start, biophysical variables are better at explaining the variation in area burned (Syphard *et al*. 2007*a*). Therefore, the most important predictors for the fire frequency models were the biophysical variables that remained constant over the temporal extent of the fire frequency data.

Although it would have been ideal to incorporate temporally extensive human variables in our multiple regression analysis, adding these data would have likely only improved the fit of our models, particularly because human development patterns have high spatial autocorrelation, particularly in the Santa Monica Mountains (Syphard *et al*. 2007*b*). Historic housing data were most likely distributed in the exact same locations as the contemporary housing data that we used in our analysis because houses persist over time. Nevertheless, the fair performance of our fire frequency models may have been improved if we had had access to temporally extensive data for the human variables.

The fact that the variables that best predicted fire ignitions differed from those that best predicted fire frequency explains why the spatial patterns in the predictive maps of ignitions and frequency were somewhat different from one another. Nevertheless, there were regions in the interior of the landscape where fire ignitions and fire frequency were predicted to be very low. Therefore, although fires spread away from ignition sources and burn more frequently outside urban areas, there are also even more remote areas that burn with much less frequency. However, some of the coastal areas and interior canyons are more likely to experience greater numbers of ignitions and more frequent fire. The coastal areas tend to be warmer and dryer than the more remote interior regions of the landscape, which makes them more conducive to fire. These regions also have gentler slopes and are more favourable for housing development and human activity.

From a management perspective, overlaying the two predictive maps is useful because the resulting combined map can identify areas that are not only at a high risk for experiencing an ignition, but also where those ignitions are likely to initiate into a full, spreading fire. Areas where high predicted ignition probability coincides with high predicted fire frequency can then be targeted for fire management actions, such as fuel reduction. The Santa Monica Mountains fire management plan has outlined additional criteria, including socioeconomic variables and other resources at risk, to further the decision-making process for identifying potential strategic fuel modification locations (NPS 2005). These additional criteria are important for ensuring that treatments are not placed in low-hazard areas where protection is not needed.

The present and other studies have determined that fire ignition locations, as well as areas where frequent fires occur, can be statistically modelled using readily measurable sets of social, biological, and physical features (e.g. Keeley *et al*. 1999; Cardille *et al*. 2001; Pew and Larsen 2001; Prestemon *et al*. 2002; Mercer and Prestemon 2005). Therefore, the approach used here can be used in other landscapes to refine the strategic placement of fuels treatments and to better anticipate where fires are most likely to occur. To adapt these methods to other regions, scientists and managers should be aware that the relative influence of human or biophysical variables is likely to vary according to region, temporal or spatial scale of analysis, and type of human activity. Therefore, the choice of predictor variables should be relevant to the primary characteristics driving each region's fire regime.

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Comparing the role of fuel breaks across southern California national forests

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ABSTRACT

Fuel treatment of wildland vegetation is the primary approach advocated for mitigating fire risk at the wildland–urban interface (WUI), but little systematic research has been conducted to understand what role fuel treatments play in controlling large fires, which factors influence this role, or how the role of fuel treatments may vary over space and time. We assembled a spatial database of fuel breaks and fires from the last 30 years in four southern California national forests to better understand which factors are consistently important for fuel breaks in the control of large fires. We also explored which landscape features influence where fires and fuel breaks are most likely to intersect. The relative importance of significant factors explaining fuel break outcome and number of fire and fuel break intersections varied among the forests, which reflects high levels of regional landscape diversity. Nevertheless, several factors were consistently important across all the forests. In general, fuel breaks played an important role in controlling large fires only when they facilitated fire management, primarily by providing access for firefighting activities. Fire weather and fuel break maintenance were also consistently important. Models and maps predicting where fuel breaks and fires are most likely to intersect performed well in the regions where the models were developed, but these models did not extend well to other regions, reflecting how the environmental controls of fire regimes vary even within a single ecoregion. Nevertheless, similar mapping methods could be adopted in different landscapes to help with strategic location of fuel breaks. Strategic location of fuel breaks should also account for access points near communities, where fire protection is most important.

1. Introduction

Wildfire is a key natural process in many ecosystems, but fire frequency, extent, and/or severity have surged across the globe in recent decades (Bowman et al., 2009; Flannigan et al., 2009; Westerling et al., 2006). The social and economic consequences of these fires are immense, with dramatic increases in property destruction and firefighting expenditures (Butry et al., 2001; NIFC, 2009). Altered fire regimes also threaten ecosystem integrity and biodiversity (Pausas and Keeley, 2009; Pyne, 2004). In many parts of the world the fire problem has been exacerbated by the continued expansion of the wildland–urban interface, where homes and lives are most vulnerable to wildfires, and where human ignitions increase the likelihood of fire occurring (Radeloff et al., 2005; Syphard et al., 2007). Mitigating the risk of wildfire at the wildland–urban interface, therefore, is now described as a major objective in the National Fire Plan (2001), the Healthy Forests Restoration Act (2003), and other federal fire management documents. The primary approach advocated for mitigating fire risk is to reduce hazardous fuel loads through fuel treatments of vegetation in wildland areas. In the last decade, expenditures on fuel treatments and area treated has increased markedly (Mell et al., 2010), with U.S. federal land management agencies receiving billions of dollars and treating millions of hectares of land (Schoennagel et al., 2009).

Despite this recent surge in treatment area and expenditure, fuel treatments have been a cornerstone of fire management in the U.S.A. for the better part of the 20th century. Yet, little systematic research has been conducted to understand what role fuel treatments have played in controlling fire, which factors influence this role, or how the role of fuel treatments may vary over space and time. A number of simulation studies have improved our understanding of potential fuel treatment effectiveness in modifying forest fire behavior (e.g., Finney et al., 2007; Miller and Urban, 2000; Schmidt et al., 2008). However, most empirical studies have focused on relatively localized effects when fires have intersected fuel treatments on forests (e.g., Finney et al., 2005; Martinson and Omi, 2003; Raymond and Peterson, 2005; Schoennagel et al., 2004). Due to this relatively small temporal and spatial scale (but see

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Syphard et al., in press-b), these studies have not contributed to an understanding of factors that influence sustainable fuel treatment performance over broad landscapes. This is important because many parts of the western U.S. that intersect with urban environments comprise heterogeneous landscapes that include forest and non-forested ecosystems and because strategic planning requires an understanding of how repeated fire events over time are affected by fuel treatments.

Due in part to the paucity of appropriate research, there is no comprehensive fire policy in the United States that provides forest mangers with science-based guidance on where, how, and when fuel treatments should be conducted (Agee et al., 2000; Franklin and Agee, 2003). Instead, within-agency policies are established and implemented according to the agencies' missions and objectives, and many policies are not publicly reviewed or debated (Franklin and Agee, 2003). Developing scientifically based general principles and guidelines for using fuel treatments to control fires could benefit managers if these guidelines were to facilitate decision-making with regards to strategic placement and tactical response. Given limits in time and money, managers need to prioritize where to place new fuel treatments and to determine the level of maintenance needed for current fuel treatments (Dellasala et al., 2004). Thus, a scientifically based methodology and set of principles could make the decision-making process not only easier but more defensible as well. Furthermore, a better understanding of the factors that influence the role of fuel treatments could lead to the identification of additional management considerations and the development of improved management practices.

The primary problem with development of general guidelines for fuel treatments is that fire-prone regions are highly variable with regards to their natural fire regimes and the factors that control them. Fire regimes vary as a function of forest type, fuels, terrain, climate, and ignition sources (Pyne et al., 1996; Keeley et al., 2009), and fuel treatment effectiveness may also vary according to these factors (Schoennagel et al., 2004). In addition, human development and other infrastructure strongly influence fire regimes and vulnerability to fire. Humans start and stop fires both directly (e.g., via suppression or accidental ignitions) and indirectly (e.g., via land use planning, land cover change, exotic species introduction, climate change), and their influence varies by scale and by locale (Cardille et al., 2001; Prestemon et al., 2002; Syphard et al., 2009). These variations in fire regime and human influence complicate the notion of general principles because management programs need to account for these differences (Noss et al., 2006).

Another reason that a "one size fits all" approach to fire management is problematic is that fuel treatment objectives are likely to vary from region to region, particularly for wildland areas versus the wildland–urban interface (Keeley et al., 2009). In wildland areas, particularly in western U.S. forests, fuel treatments are intended to change fire behavior and to reduce the severity of fire effects, whereas fuel treatments in the wildland–urban interface are intended to prevent fire from spreading into communities (Radeloff et al., 2005; Reinhardt et al., 2008). Therefore, the effectiveness of fuel treatments, and the factors that contribute to their effectiveness, may change as a function of fuel treatment objectives.

One way to determine how well certain guidelines may transfer from region to region is to identify which factors affecting fuel treatment outcome are most likely to vary. Identifying these could help to determine what aspects of plans need to be developed separately for each management area. Common decision-making tools could be developed that account for regional differences in those variables. If there are factors that are universally influential across different regions or landscapes, these could help in the development of general management considerations.

In California, where a substantial portion of the landscape comprises non-forested ecosystems such as chaparral and sage scrub, fuel breaks have been a major part of fire management activities since the 1930s (Davis, 1965). Unlike forests where mechanical fuel treatments remove only surface fuels (preserving larger, older trees), fuel break construction in chaparral typically involves complete removal of vegetation, chemical herbicides, and permanent conversion of native shrublands to weedy herbaceous associations (Wakimoto, 1977).

In southern California, differences in natural fire regimes and the way fire regimes have been altered by past land use complicate fire management in the region. In the shrubland-dominated foothills and coastal valleys, fire frequency has substantially increased along with population growth and urban expansion (Keeley et al., 1999; Syphard et al., 2007). This increased fire frequency not only threatens homes and lives, but many shrublands cannot tolerate repeated fires and under such conditions are often replaced with non-native grasslands (Keeley and Fotheringham, 2003; Syphard et al., 2006). In shrubland-dominated regions, fuel manipulation projects involve a trade-off. On one hand, fuel breaks are needed to protect homes and lives, which are at an elevated risk in these crown fire shrublands; on the other hand, construction of fuel breaks typically involves complete removal of vegetation and may result in a range of ecological impacts. Thus, fire management in the region is greatly complicated by the need to balance both fire and resource management.

In the less extensive montane coniferous forests in the region, fire frequency has been unnaturally low during the last century, and fire hazard has consequently increased due to accumulated fuels associated with fire suppression and logging (Keeley, 2006), problems similar to other forests in the western U.S. (Miller et al., 2009). Because thinning and fuel manipulation is intended to improve forest vigor and reduce risk of catastrophic loss to wildfire (often by restoring forests to more historic conditions), fuel treatments and resource benefits are likely to be compatible in these forested regions (Schwilk et al., 2009). However, this model of fuel accumulation and ecological compatibility with fuel treatments has often been inappropriately applied to chaparral (Keeley and Fotheringham, 2004, 2006).

To better understand the factors that influence the role of fuel treatments in controlling large fires in southern California, and how the role of fuel treatments varies across different landscapes, we assembled a spatial database of fuel breaks and fires from the last 30 years in four national forests. For this analysis, we only considered fuel manipulation projects that were clearly intended to serve as fuel breaks, which are defined as wide blocks, or strips, on which vegetation was manipulated to create lower fuel volume and reduced flammability (Green, 1977). Thus, prescribed fires and burn piles were excluded, as were any dozer lines created to aid suppression activities during the time that a fire was burning. We analyzed relationships among fires and fuel breaks to answer:

(1) What are the most important environmental and management variables affecting the role of fuel breaks in controlling large fires, and do these factors vary among national forests?
(2) What are the primary factors affecting the spatial pattern of fires and fuel break intersections, and do they vary among national forests?

Because we restricted our analysis to U.S. Forest Service national forests, we assumed these landscapes would be broadly similar in the tactical approaches used in the construction and maintenance of fuel breaks. Thus, this study could help determine how well management approaches for one national forest may transfer to other national forests. Also, on these largely non-forested landscapes we assumed that the primary management objective for fuel breaks in the region is to control the spread of fire and protect communities.

Table 1
Characteristics of fires and fuel breaks in the four southern California national forests. Fire rotation was calculated from 1980 to 2007.

	Angeles	Cleveland	Los Padres	San Bernardino
Area (ha)	26,375	21,117	61,464	30,408
Number of fires since 1980	175	118	96	253
Fire rotation period (years)	32	14	35	30
Fuel break length (km)	1834	482	550	1199

2. Methods

2.1. The national forests of southern California

The area of study included the Los Padres, Angeles, San Bernardino, and Cleveland National Forests (Table 1), an area spanning the extent of the state's South Coast Ecoregion (Keeley, 2006), which encompasses approximately 3.4 million ha (8% of the state) and is home to more than 19 million people (US Census 2000) (Fig. 1). Although the region is the most threatened hotspot of biodiversity in the continental US (Hunter, 1999), the national forest lands together occupy more than 1.5 million ha and offer some measure of protection for the region's biodiversity.

The South Coast Ecoregion is characterized by a Mediterranean-type climate, with cool, wet winters and warm, dry summers. Chaparral shrublands are the most extensive vegetation type, but there is extraordinary ecosystem diversity in the region, owing largely to a relatively sharp elevational gradient from sea level to more than 3500 m. Therefore, chaparral forms a mosaic with other vegetation types, including coastal sage scrub shrublands, grasslands, oak woodlands, and montane coniferous forests, and natural fire regimes are correspondingly variable (Keeley, 2006; Wells et al., 2004).

Fire management on the national forests is the responsibility of the U.S. Forest Service. The two primary strategies for management are to (1) suppress all actively burning fires, and (2) reduce the extent of future fires through mechanical construction of fuel breaks and limited use of prescription burning. We focus exclusively on fuel breaks in this study.

2.2. Data for dependent variables: fuel break outcome and fire/fuel break intersections

We acquired information on historic fuel breaks and their location from U.S. forest service staff on each of the four forests. We developed a digital spatial database of fuel breaks for the four forests by combining existing GIS layers with files that we created ourselves by digitizing fuel breaks that had been drawn on paper maps. Due to the substantial number of fuel breaks that were hand drawn, we conducted follow-up interviews to validate the newly digitized data.

On all the forests, we overlaid the fuel break GIS layer with fire perimeter polygons compiled by the California Department of Forestry-Fire and Resource Assessment Program (CALFIRE). The fire perimeter data represent the largest fires, with a minimum mapping unit of 4.04 ha (10 acres).

To evaluate factors affecting fuel break outcome, we first used a GIS overlay to identify all events in which a fire intersected a fuel break (within a 100 m buffer distance to account for potential data uncertainty). These events were considered potential case studies to retain for subsequent analysis. To be included for consideration, the date of the fire had to be later than the date of fuel break construction. For the case studies, we conducted a preliminary assessment as to whether fires stopped or crossed over fuel breaks, and then confirmed the outcome during personal interviews with firefighters who had first-hand knowledge of the event.

Table 2
Variables considered and retained in the multiple regression models explaining number of fire and fuel break intersections in three national forests. All variables retained in the models are designated through a significance symbol.

	Angeles	Los Padres	San Bernardino
Elevation	*		*
Slope			
Solar radiation		*	
USFS fuel model	*		*
Distance road		**	
Distance development			
Distance trails		**	
Historic fire frequency	***	**	***
Ignition density	*	*	
Deviance explained	37.27	27.55	54.7

* $p = 0.05$.
** $p = 0.01$.
*** $p = 0.001$.

Although data for some of the explanatory variables were acquired during personal interviews, we also used a GIS to extract information for other explanatory variables to relate to the fuel break outcome. See below for description of explanatory variables. For this analysis, we extracted data only from the portion of the fuel break that intersected the fire and averaged values across that area. In some cases, fires stopped at a portion of the fuel break, but ultimately crossed over the fuel break. For those cases, we classified the fuel break as not having stopped fire (for statistical analysis purposes only), and we only extracted explanatory variables for the section of the fuel break where the fire crossed over.

To analyze factors influencing the number of times fires intersected fuel breaks, we spatially stratified and classified all fuel breaks according to the number times they intersected fires during the study period. We only considered fires that had occurred since 1980, and to ensure that all fuel breaks had an equal chance of experiencing a fire, we only looked at fuel breaks that had been constructed before 1980. From this spatially stratified layer, we randomly selected point samples (greater than 1 km apart, to avoid spatial autocorrelation) to extract environmental data used as explanatory variables. The dependent variable was number of intersections at each sample location.

2.3. Explanatory variables for role of fuel breaks

The factors we considered as potentially influencing the role of fuel breaks on the forests included human and biophysical variables that have previously explained landscape-scale fire patterns in the region (Syphard et al., 2008), and that we used in a previous study of fuel breaks on a single national forest (Table 2, Syphard et al., in press-a). In addition to static landscape features, we also considered variables related to the actual event when a fire intersected a fuel break, including characteristics of fires, fuel breaks, vegetation age, and firefighting activities.

For the human variables, we considered distance to roads, trails, and development (Table 2) because fire ignitions in the region tend to occur near human activities (Syphard et al., 2008). We also hypothesized that these human variables may influence firefighting access and resources. For these three variables, we developed continuous grid surfaces reflecting the Euclidean distance to the nearest feature (road, trail, or development) and extrapolated values from those grids for the areas where fuel breaks intersected fires.

Biophysical variables (including climate, terrain, and fuels) influence fire spread rate, fuel moisture, flammability, and fire intensity (Pyne et al., 1996; Whelan, 1995). Therefore, we evaluated the potential influence of elevation, slope, solar radiation, vegetation age, and fuel model on fuel break outcome (Table 2). After

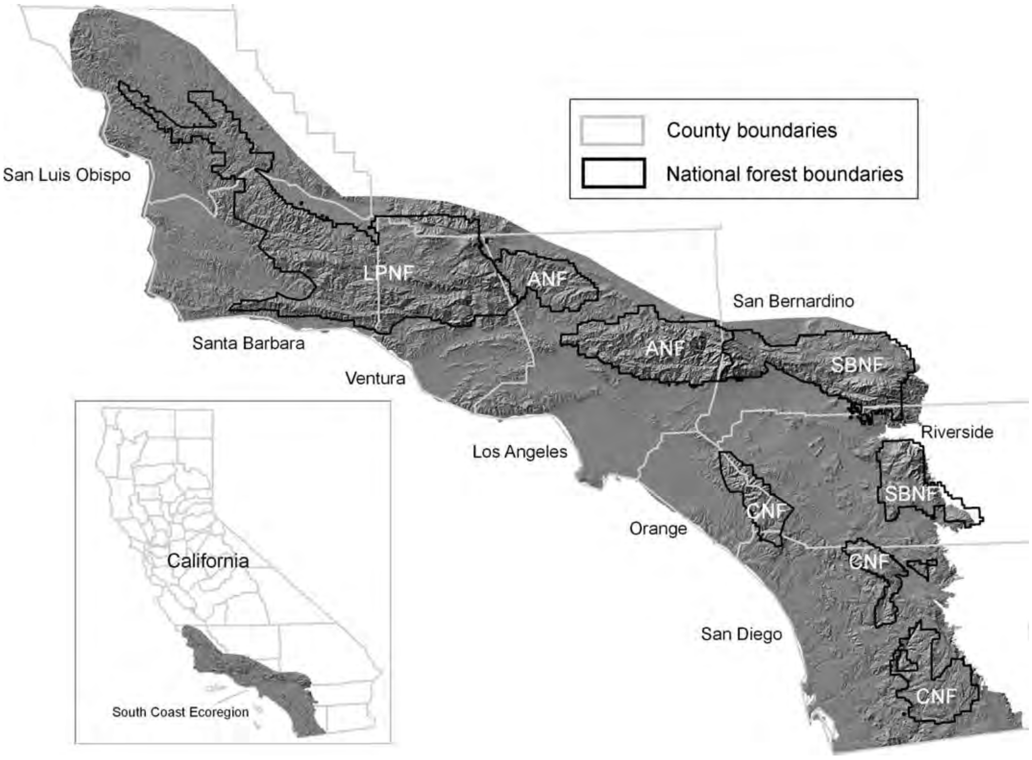

Fig. 1. Study area showing the four national forests of southern California. ANF is Angeles National Forest, CNF is Cleveland National Forest, LPNF is Los Padres National Forest, and SBNF is San Bernardino National Forest.

preliminary regression analysis, we found that climate variables were significantly correlated with terrain variables, so we did not include them. Because most fires are stand-replacing in southern California shrublands, we determined vegetation age by calculating the time since last fire in the area immediately adjacent to the fuel break before the fire intersected it.

Severe weather conditions are likely to strongly influence fire spread rates and intensity (Moritz et al., 2004; Keeley and Zedler, 2009), and lead to conditions that are dangerous for firefighters (Halsey, 2005). However, previous analysis indicated that, because weather is highly variable over space and time, it is difficult to attribute exact weather conditions to the moment of intersection (Syphard et al., in press-a). Instead, we considered fire size and season as potential explanatory variables because they indirectly reflect the severity of weather conditions (Finney, 2003; Westerling et al., 2004), particularly because of the importance of autumn Santa Ana winds in this region (Moritz et al., 2010). We calculated fire size from the fire perimeter data through GIS calculations, and we derived fire season from the attributes of the fire perimeter data. We reclassified the months of the fires into winter and spring (January through May), summer (June through August), and autumn (September through November) to reduce the degrees of freedom in the data.

We obtained information on fuel break condition and firefighting activities through personal interviews with firefighters and managers who were most familiar with the fire events. Fuel break length was calculated from the GIS files, but data on fuel break width were largely unavailable for all four forests. Because written fuel break maintenance records were often unavailable, we determined how well the fuel break had been maintained by asking fire personnel to indicate the condition of the fuel break at the time the fire intersected it on a scale from one to three. The ranking reflected poor to excellent conditions, with poor reflecting fuel breaks where the vegetation had almost entirely regrown, and excellent reflecting fuel breaks that were either entirely grass, or no vegetation had regrown. To evaluate the importance of management activities, we also asked personnel to indicate whether they were able to gain access to the fuel break for firefighting (yes or no) and whether they had sufficient resources available (including manpower and equipment) to fight the fire, again on a scale of one to three, from poor (no resources) to excellent (full resources).

2.4. Explanatory variables for mapping number of intersections

To explain and map areas where fires and fuel breaks are most likely to intersect, we evaluated the same human and biophysical variables as for the fuel break outcome (Table 2). However, we did not consider fire and management variables related to single events because we were interested in trends across the entire study period (1980–2007). In addition, we hypothesized that significantly more fire and fuel break intersections would occur in areas that were historically fire-prone. Therefore, we additionally explored historic fire frequency (derived through overlay of fire perimeters from 1878 to 2007) as well as spatially interpolated ignition density as explanatory variables.

2.5. Fuel treatment outcome: structural equation modeling

Structural equation modeling provides advantages over traditional multiple regression analysis because it uses existing information to examine potential causal pathways among intercorrelated variables and identify indirect relationships (Bollen, 1989; Grace and Pugesek, 1998). The model is statistically evaluated to determine the degree of consistency with empirical data and compare the outcomes of alternative models. Although structural equation modeling is a confirmatory approach that tests a priori hypotheses of about interrelationships among variables, it is often essential to use exploratory regression and correlation analysis to suggest which pathways to explore (Grace, 2006).

For the different national forests, we initially conducted correlation analyses and built simple and multiple logistic regression models to explore the relationships among the explanatory variables and fuel break outcome. We used logistic regression because the response variable for fuel treatment outcome was binary, indicating whether the fuel treatment stopped the fire or not. Based on the hypothesized interrelationships developed through correlation and regression analysis, we developed and tested structural equation models using Mplus version 5.1 software. Because we modeled categorical outcomes, we used the weighted least-squares with mean and variance adjustment (WLSMV) estimator. To ensure that we retained only the important pathways in the final models, we sequentially removed one path at a time to ensure that, if a path were removed, the chi-square did not increase more than 3.84 points (the single degree-of-freedom test) (James B. Grace, personal communication). We also examined the fit of alternative models through *p*-values, root mean square error of approximation, and weighted root mean square residual (Hooper et al., 2008).

2.6. Number of intersections: multiple regression and predictive mapping

To evaluate the relative influence of the explanatory variables on the number of times fires intersected fuel breaks on the forests, we developed simple and multiple Poisson regression models that were appropriate for count response variables (Agresti, 1996). Because the objective of this part of our study was to create predictive maps (rather than explore causal pathways), we only used multiple regression analysis, as opposed to structural equation modeling. We first conducted simple regression models with each variable (and quadratic terms for continuous variables) to establish rankings for entering the variables into a multiple regression.

For the multiple regression models, we entered variables according to the amount of deviance they explained [D^2, equivalent to the R^2 in ordinary least square models (Guisan and Zimmermann, 2000)] and only considered those variables that were significant at $p \leq 0.15$. We evaluated correlation coefficients in the models for all of the forests and avoided including two variables with a bivariate correlation ≥ 0.3. For each forest, we evaluated alternative plausible multiple regression models with different combinations of predictor variables and selected the best model as the one that explained the highest percentage deviance with the lowest Akaike information criterion (AIC) (Quinn and Keough, 2002). We also checked to ensure that overdispersion was not present in the models.

After selecting the best multiple regression models, we converted them into continuous map surfaces that reflected the predicted number of fires that would intersect fuel breaks across the entire forest. We created these maps by applying the Poisson regression formula and predicted coefficients onto the GIS layers of the significant explanatory variables (as in Syphard et al., 2008). We evaluated the correspondence of the predicted number of intersections to the actual intersections that occurred through Pearson correlation coefficients. We also quantified the magnitude of discrepancy among predicted and observed values by calculating the root mean square error (RMSE).

To test how well the models that explained the number of intersections on one national forest matched the models in the other forests, we applied the models developed on each forest to the entire South Coast Ecoregion and compared the maps. To quantify the spatial correspondence among the maps, we used a Pearson's correlation coefficient to calculate pairwise correlations (Termansen et al., 2006; Syphard and Franklin, 2009). High correlations among maps would indicate that the factors controlling the spatial pattern of fire and fuel break intersections were similar among the forests, and low correlations would suggest that those factors vary.

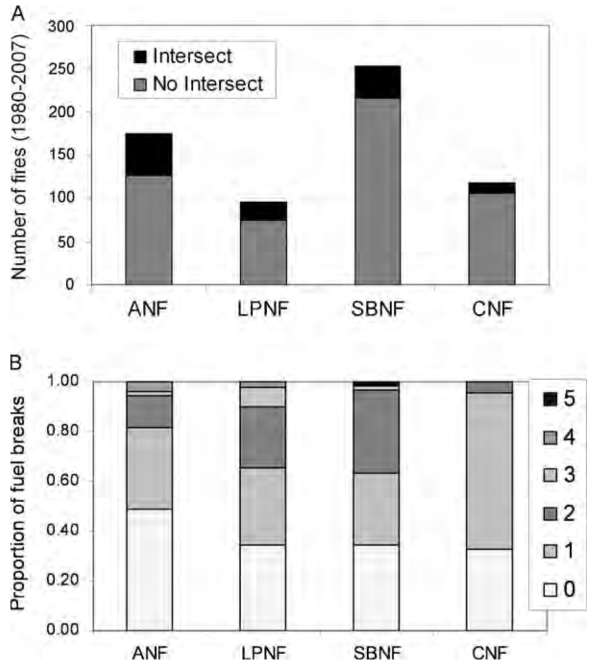

Fig. 2. Number of fires that occurred in four national forests divided into those that intersected a fuel break and those that did not intersect a fuel break (A); and proportion of fuel break area intersected by 0–5 fires from 1980 to 2007 (B). ANF is Angeles National Forest, CNF is Cleveland National Forest, LPNF is Los Padres National Forest, and SBNF is San Bernardino National Forest.

3. Results

3.1. Summary of fuel break and fire intersections and outcomes

During the 28 years of the analysis, 641 fires occurred within the boundaries of the four national forests. On average, 23% of those fires intersected a fuels treatment, but the proportion of intersections varied among the forests (Fig. 2A). In fact, the number of intersections among fires and fuel breaks on the Cleveland National Forest was only 13 (11% of the intersections), and this small number precluded us from including that forest in our statistical analyses.

For the fuel breaks that we considered in our spatial analysis of intersections (i.e., those constructed on or before 1980), approximately 25–50% of the fuel break area never intersected a fire. On the other hand, approximately 10–45% of the fuel break area intersected multiple (two or more) fires. The proportion of fuel break area that intersected fires varied among the four forests (Fig. 2B).

When fires intersected fuel breaks, the percentage that stopped at the fuel breaks ranged from 22 to 47%, and the percentage that crossed over the fuel breaks ranged from 29 to 65%, depending on the forest (Fig. 3). We distinguished another group of fuel break intersections where fires crossed over fuel breaks, but the fuel breaks did change fire behavior enough to facilitate firefighter access and eventually help with the suppression of the fire. When this group is considered along with the other cases in which the fuel break held a portion of the fire, the percentage ranged from 10 to 23% (Fig. 3).

3.2. Fuel treatment outcome: structural equation modeling

Among the three national forests that we analyzed, there were seven variables that significantly affected fuel break/fire outcomes. However, the structural equation models revealed differences in the number and combination of important variables as well as

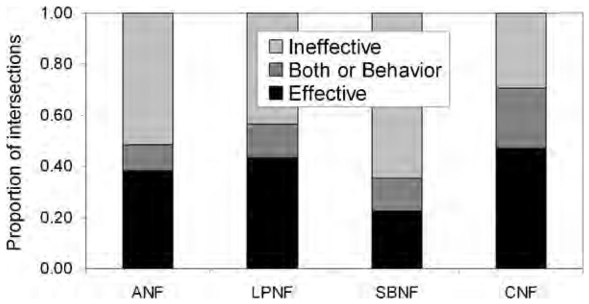

Fig. 3. Proportion of fire and fuel break intersections in four forests divided into those that effectively stopped a fire (Effective); those in which only a portion stopped a fire or that changed fire behavior (Both or Behavior); and those in which the fires crossed over the fuel break (Ineffective). ANF is Angeles National Forest, CNF is Cleveland National Forest, LPNF is Los Padres National Forest, and SBNF is San Bernardino National Forest.

differences in the interrelationships among them. We tested alternative models with different explanatory variables and different direct and indirect effects. The final model varied among the forests (Fig. 4). Despite these differences, most of the variables were common to at least two of the three forests; and three variables were common to all forests: firefighter access, fire size, and fuel break condition.

Firefighter access was the only variable to directly improve the outcome in all three forests, and it was the most influential variable for the Los Padres and Angeles National Forests. The proportion of events in which firefighters had access to fuel breaks was slightly lower in the Angeles than in the other two forests (Fig. 5C). On the Los Padres and San Bernardino forests, fire size was directly and negatively related to fuel break outcome; in the Angeles, fire size negatively affected firefighter access and thus indirectly influenced fuel break outcome. On average, the fires were smaller in the Angeles, but fire sizes were highly variable on all of the forests (Fig. 6). On the Los Padres and Angeles forests, fuel break condition facilitated firefighter access to fuel break and thus indirectly improved fuel break outcome; the relationship was direct in the San Bernardino, which reported the largest proportion of fuel breaks with low scores for fuel break condition (Fig. 5B).

The Los Padres was the only forest for which season was not important in explaining fuel break outcome, as later-season fires (i.e., September through November) had a direct negative influence on outcome for the Angeles; and for the San Bernardino, later-season fires contributed to increased fire size, so the effect was indirectly negative. Most of the fires on the Los Padres occurred in the summer months, whereas fires in the autumn were most common for the other two forests (Fig. 5E). The Los Padres was the only forest in which firefighting resources were not influential in explaining outcome. On both the Angeles and San Bernardino, resources indirectly improved fuel treatment outcome; but on the Angeles, the primary relationship was by improving access and on the San Bernardino, the primary relationship was through reduction in fire size. The overall distribution of firefighting resources, according to the interviews, was variable among the forests (Fig. 5A). Finally, the Los Padres was the only forest in which fuel break length had a significant direct and positive impact on fuel treatment outcome, and this forest had longer fuel breaks, on average, than the other two forests (Fig. 6).

The Angeles was the only forest in which vegetation age was not important. On the Los Padres, younger vegetation surrounding the fuel breaks improved firefighter access to the treatment, so the relationship was indirectly negative. On the San Bernardino, the relationship was direct and positive. Although the average vegetation age was lowest on the San Bernardino, there was a lot of variability in age for all the forests (Fig. 6).

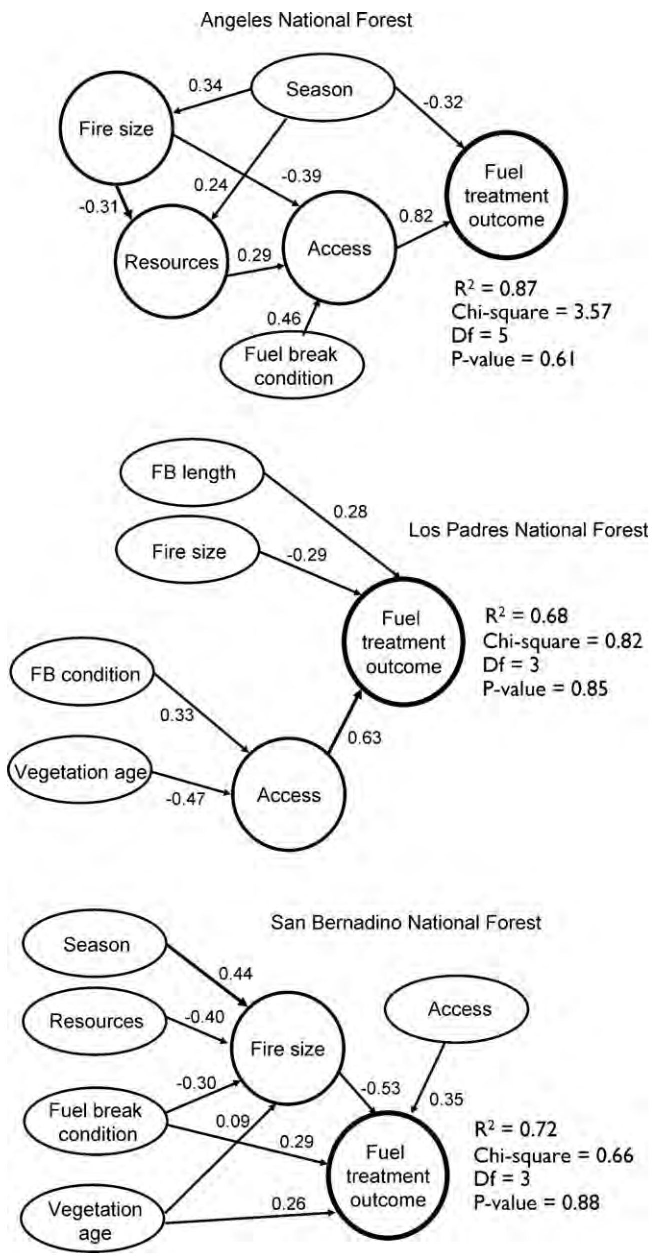

Fig. 4. Structural equation model of factors that directly and indirectly explain why fires stopped at fuel breaks in the Angeles, Los Padres, and San Bernardino National Forests. Solid arrows represent direction of effect, and coefficients shown along arrows are standardized values. Circles represent endogenous (or dependent) variables in the models. Due to insufficient number of fuel break/fire intersections the Cleveland National Forest was not included.

3.3. Number of intersections: multiple regression and predictive mapping

Of the variables we considered for explaining the number of fire and fuel break intersections in the forests, historic fire frequency was the only one that was retained in all three of the multiple regression models (Table 2). For all three forests, the number of intersections was strongly and positively related to the number of fires that had occurred since 1878 (date of the earliest fire in the database). Ignition density was also positively related to the number of intersections on the Angeles and Los Padres National

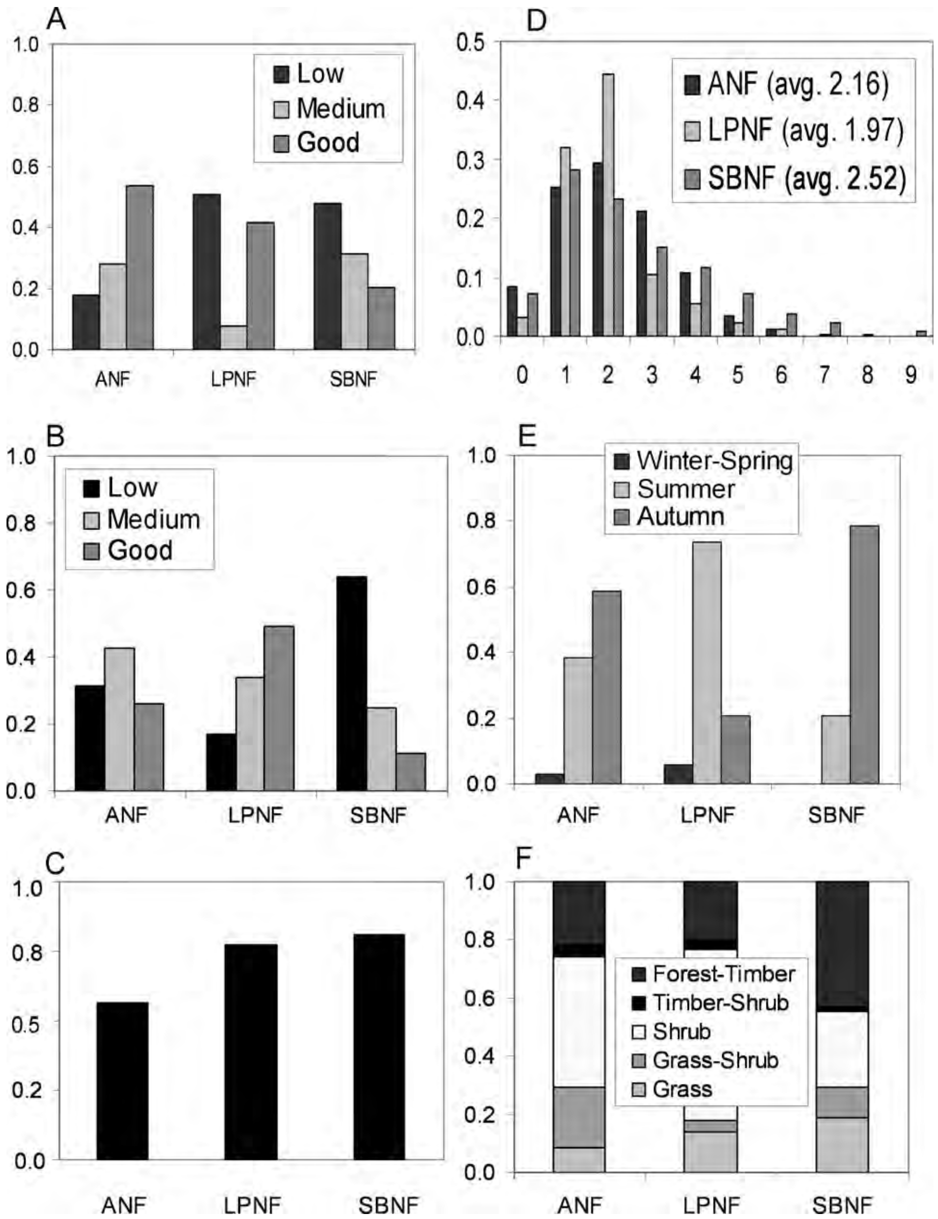

Fig. 5. Distribution of categorical variables for three national forests that were significant in any of the statistical models. The *y*-axis for all charts represents the proportion of observations within each forest. The charts represent (A) firefighting resources; (B) fuel break condition; C) Access to fuel break; (D) historic fire frequency (with the average for each forest indicated in the legend); (E) season when intersection occurred; (F) fuel type. ANF is Angeles National Forest, LPNF is Los Padres National Forest, and SBNF is San Bernardino National Forest.

Forests, but was not retained in the model for the San Bernardino National Forest. The Los Padres had the lowest average number of fires and lowest ignition density, whereas the San Bernardino had the highest fire frequency and ignition density (Figs. 5D and 6).

For both the Angeles and San Bernardino National Forests, the number of intersections was negatively related to elevation, which was slightly higher on average on the San Bernardino than the other forests (Fig. 6). The fuel model parameter was also significant in explaining model variation for only the Angeles and San Bernardino. A larger number of intersections occurred in forest and timber fuel models on the San Bernardino National Forest ("TU" or "TL", Scott and Burgan (2005)), whereas the shrub models ("SH", Scott and Burgan (2005)) were more influential in the Angeles (Fig. 5F). Three variables were retained in the multiple-regression model for the Los Padres that were not important in the other forests. On the Los Padres, fires were more likely to intersect fuel breaks when fuel breaks were in close proximity to trails, distance to roads was intermediate, and winter solar radiation was low. Both the average distance to trails and solar radiation were lower on the Los Padres than in the other two forests, but the average distance to roads was similar, with high variation in the three forests (Fig. 6).

The three map surfaces developed by applying the multiple-regression model formulas and coefficients to the GIS maps of the significant variables reflect a continuous probability distribution of where fires and fuel breaks are most likely to intersect (Fig. 6). The Pearson's correlation coefficients between the observed number of intersections and the number of intersections predicted by the model ranged between 0.59 and 0.74 (Table 3), and the root mean squared error ranged from 0.28 to 1.31 intersections. The correlations among the three maps generated by the differ-

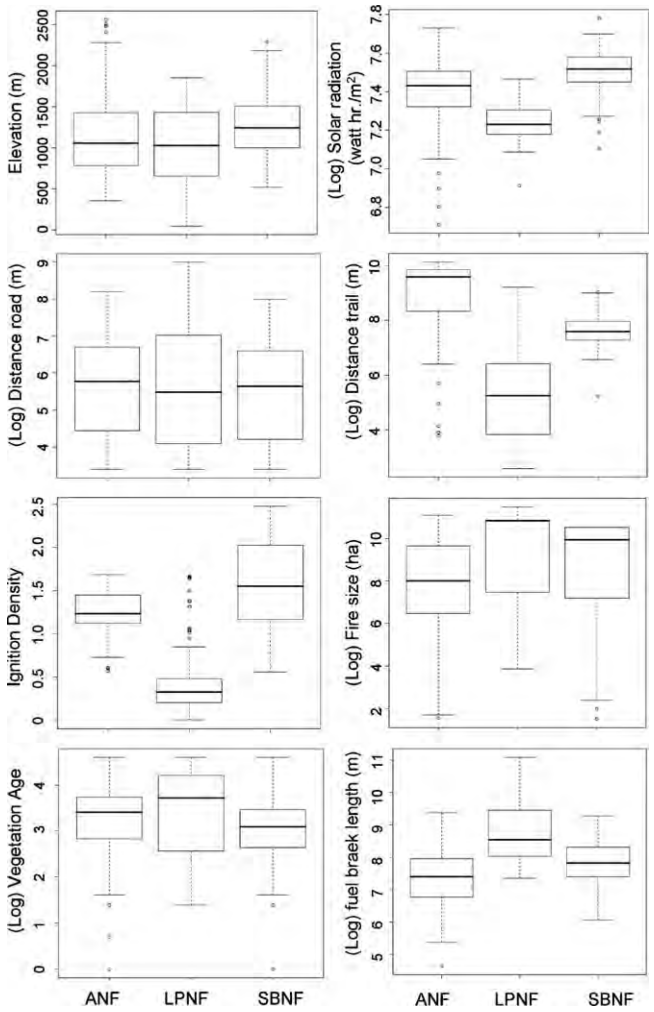

Fig. 6. Distribution of continuous variables for three national forests that were significant in any of the statistical models.

ent multiple-regression models were lower, particularly for the Los Padres model (correlation of 0.21 with the Angeles and 0.16 with the San Bernardino). The Angeles and San Bernardino maps, however, had a much stronger correlation (0.54) (Fig. 7).

4. Discussion

The four southern California national forests studied here all share several features in common; they are in rugged terrain, are dominated by non-forested ecosystems, and contain a substantial amount of wildland–urban interface. These national forests, however, differ in the proportions of vegetation types, biophysical characteristics, and the relative proportions of wildland–urban interface and intermix landscapes. These differences are part of the reason the significant factors explaining fuel break/fire outcomes and number of intersections were different among forests. Nevertheless, several factors were consistently important across all forests in explaining the number of intersections between fuel breaks and big fires and the role of fuel breaks in altering fire spread. These similarities support several general conclusions about the role of fuel breaks in controlling large fires in southern California.

One conclusion is that the primary role of fuel breaks in the region is to facilitate fire management activities. Two of the three fire management variables we considered (access and fuel break condition) were important in all three structural equation models (Fig. 4), and firefighter resources was important for two of the forests (Angeles and San Bernardino). Furthermore, while other important variables in the models (related to vegetation structure, fire size, and season) were not directly related to management, these variables often indirectly influence management, for example, by affecting access to treatment areas. Demonstrating the strength of these indirect effects is one of the benefits to structural equation modeling (Grace, 2006).

Firefighter access to fuel breaks was the most influential factor in fuel treatment outcome for the Los Padres and Angeles, and was also highly significant for the San Bernardino. The high level of significance for this variable supports the notion that, without firefighters present to control fires, fires will generally not stop at fuel breaks. Although three fires stopped on their own at the top of ridges on the San Bernardino, these fires constituted less than 1% of the cases. Only one fire stopped passively on the Los Padres, and none of the fires in our analysis stopped without firefighters on the Angeles. Despite this conclusion, it is important to point out that the fire perimeter database only includes fires greater than 10 ha; therefore, it is possible that some smaller fires do stop passively (i.e., without fire fighting actions) at fuel breaks. Many fire management personnel understand that fuel breaks are unlikely to passively stop most fires, particularly during extreme weather conditions, but the public, news media, and policy-makers may unrealistically expect otherwise. Our results show that such beliefs could lead to a false sense of security about the protective value of fuel breaks.

Most of the largest fire events in southern California occur during severe weather conditions in autumn, prior to winter rains, when dry, offshore Santa Ana winds can exceed 30 ms^{-1} (Miller and Shlegel, 2006; Moritz et al., 2010). Fighting fires during these weather conditions can be extremely dangerous, and during these wind events, multiple fires often break out simultaneously. These severe weather conditions likely explain why fire size was another variable that was highly significant in explaining fuel treatment outcome in all three forests. Discussions during the interviews confirmed that fires were more difficult to control, and likely to become large, under severe weather conditions. There are a number of reasons for this: the speed of such fires, which can cover 10,000 ha within a day or two, and thus the lack of time for accessing fuel breaks, the danger of aggressively attacking fires under such conditions, and firefighting resources spread too thin because of multiple fire fronts. Consistent with the effect of fire size, fire season was significant on the Angeles and San Bernardino because Santa Ana winds typically occur during the fall (and this was the season when fuel treatment/fire outcomes were poorest). The reason that season was not important for the Los Padres, but fire size was, is that Santa Ana winds are much less predictable there (Moritz et al., 2004, 2010). The Los Padres regularly experiences strong, hot wind downcanyon wind events known as “sundowners,” typically in summer (Ryan, 1996), but these are not annual events as are Santa Ana winds. It is possible for severe-weather fire events to occur in any season, not just the fall, across the entire southern California region. This explains why fire size was important on all three forests.

In addition to fire management and fire weather (i.e., size and season), there was evidence that vegetation structure played an

Table 3
Pearson correlation coefficients among prediction maps for three national forests and among predicted and observed number of intersections within each forest. Root mean squared error (RMSE) is calculated between the observed and predicted number of intersections within each forest.

	Angeles	Los Padres	San Bernardino
Angeles map	1.00	0.21	0.54
Los Padres map	0.21	1.00	0.16
San Bernardino map	0.54	0.16	1.00
Observed *N* intersections	0.61	0.59	0.74
RMSE	1.31	0.76	0.28

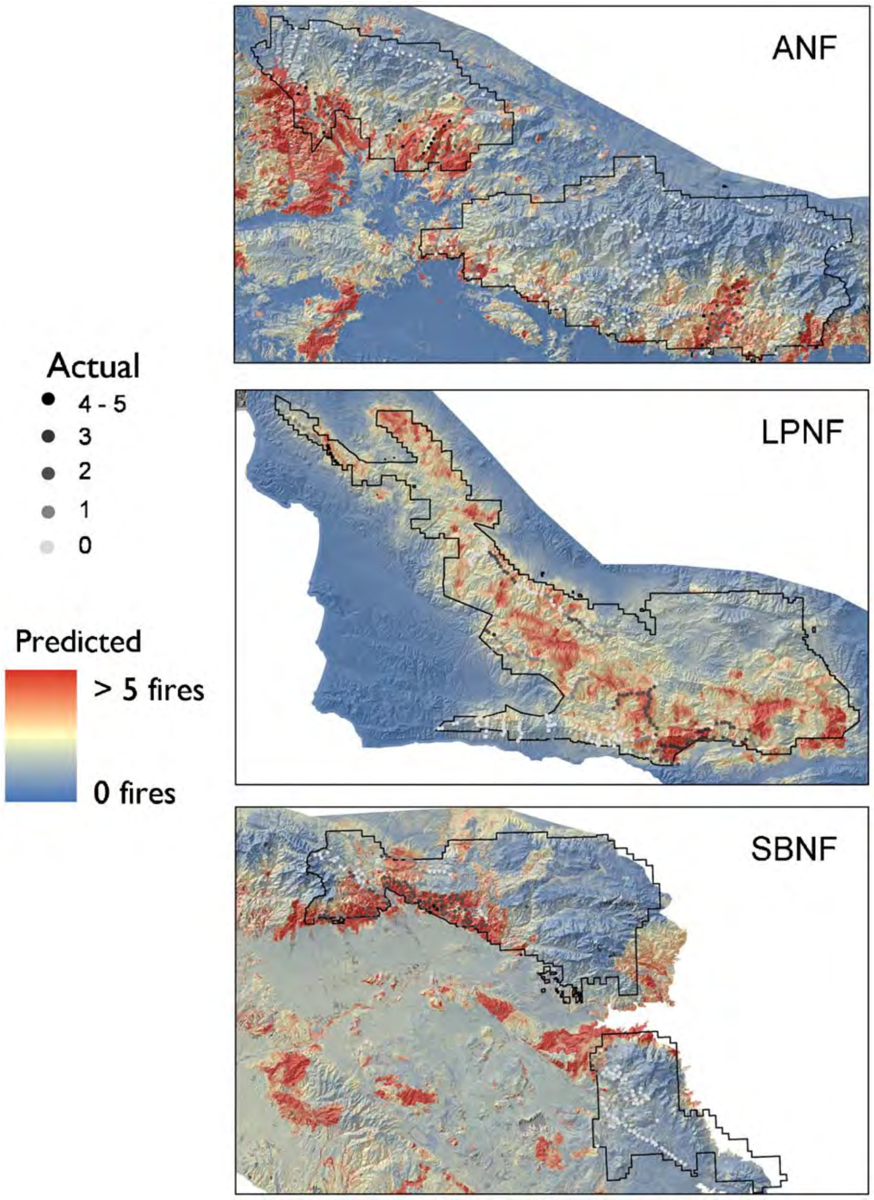

Fig. 7. Maps showing predicted distribution of areas most likely to intersect fuel breaks in the Angeles, Los Padres, and San Bernardino National Forests. The sample points along the fuel breaks also show the actual number of times fires intersected fuel breaks at those locations from 1980 to 2007.

important role in improving fuel break outcome in all three forests, and this was generally because well-maintained fuel breaks were much easier for firefighters to access in time to prepare the fuel break for suppression activities. Because young vegetation typically has a lower fuel load than old vegetation, one of the premises of conducting fuel manipulation is that young vegetation can directly slow or stop the spread of fire. However, in southern California shrublands, stand age and fuel loads play a limited role in stopping the spread of fire, particularly during extreme weather conditions, when fires often spread through or over very young age classes (Keeley and Zedler, 2009; Moritz, 1997; Moritz et al., 2004). Accordingly, while vegetation age was significant in the Los Padres, younger vegetation did not directly prevent fires from spreading, but helped facilitate firefighter access to fuel breaks. There are some parts of the Los Padres where, because of the lack of consistent Santa Ana influence, fuel age may play a role in controlling fire spread (Moritz, 1997). This particularly applies to the coastal area near the city of Santa Barbara. Regardless, the most significant relationship was between vegetation age and firefighter access.

Fuel break condition (i.e., how well it was maintained) played a similar role as vegetation age, and it was influential in all three forests. While the relationship was direct on the San Bernardino, better-maintained fuel breaks improved access to fuel breaks in the Los Padres and the Angeles, and thus, the relationship was indirect. Southern California chaparral forms a dense, continuous cover that is extremely difficult to maneuver in (Halsey, 2005), which likely explains why well-maintained fuel breaks improved the outcome.

As in the models for fuel break outcome, the models explaining the number of fire and fuel break intersections reflected regional landscape diversity and differences among the forests, while nevertheless suggesting several general conclusions. By far the most significant variable, and the only variable consistently significant for all forests, was historic fire frequency. This result is not surprising because areas that have burned most frequently in the past are likely to be most fire-prone in general. Ignition density patterns were also significant for two of the forests. Nevertheless, fire history was not the only factor explaining why fuel breaks intersect fires more in some places than in others. Fire and fuel break intersections were a function of a combination of biophysical and human variables for all the forests, but the biophysical variables were generally more important than the human ones. This is consistent with other regional studies that have shown biophysical factors to be strongly related to patterns of fire occurrence and area burned, whereas human variables are most significant for explaining ignition patterns and fire frequency (Parisien and Moritz, 2009; Syphard et al., 2007, 2008).

The maps of predicted distribution of areas where fuel breaks are most likely to intersect with large fires did not correlate well among the forests, yet there was good correlation among observed and predicted number of intersections within the forests. In other words, the combination of factors that best predicted the number of intersections in one forest did not match well with the combination of factors that best predicted the intersections in the other forests. These differences reflect how the environmental controls of fire regimes vary from region to region, even within a single ecoregion. Therefore, a "one size fits all" management approach would be inappropriate if the objective were to map likely areas for fires and fuel treatments to intersect. While developing a model for one region and applying it to a different region may be inappropriate, the modeling methodology adopted here could easily be applied anywhere. These types of maps could be part of a manager's toolset in helping to identify areas where new fuel breaks could be constructed or where current fuel breaks should be maintained.

We cannot directly attribute differences in the influential variables of our models to differences among the forests because we only statistically analyzed three national forests. Nevertheless, the differences among the national forests do provide a perspective on the variability of the region, despite the fact that it all falls within the same ecoregion. This is striking considering that southern California has a distinctive fire regime, owing to the defining characteristics of the region's Mediterranean-type climate. Because of the cool, wet winters and hot, dry summers, and the specific properties of chaparral, this vegetation is particularly flammable for a substantial portion of the year and burns in large, stand-replacing, high-intensity fires (Pyne et al., 1996). The region's fire regime and fire management issues are typically most starkly contrasted against those in forested regions (Keeley et al., 2009). While it has been recognized that many fire management practices in forested regions are inappropriate for southern California shrublands (Halsey, 2005; Keeley and Fotheringham, 2006), this study shows how certain aspects of fire management may need to be individually tailored at even finer scales, dependent on terrain, proximity to urban environments, regional weather patterns, and fuel type composition.

In southern California, fuel treatments can lead to ecological degradation because they often involve complete removal of vegetation, facilitate the spread of exotic species, and may thus indirectly contribute to increased fire frequency in a region where recurrent fire already threatens the native shrublands (Merriam et al., 2006, 2007). These resource costs should be considered relative to the benefits of protecting communities, and these trade-offs should be considered when constructing new fuel breaks in the region. This is in contrast to forested regions, where the objective of protecting communities is often coupled with the objective of reshaping the age structure and composition of forests to resemble historic conditions (Reinhardt et al., 2008). In these forests, fuel breaks and resource benefits generally are mutually beneficial. Regardless of the region, mitigating fire risk to communities is a priority for federal land managers, yet most fuel treatments are not placed within the wildland–urban interface where they may have the greatest potential for protecting homes. Across the western United States, only 3% of the area treated from 2004 to 2008 was located in this interface (Schoennagel et al., 2009).

Many new fuel breaks are currently being constructed in southern California. In fact, the most likely reason there were not enough fire and fuel break intersections to complete a statistical analysis in the Cleveland National Forest is because a large proportion of the fuel treatments have been recently constructed. Despite the large amount of new fuel break construction, the results of this study show that many fires never actually intersect fuel breaks, and large areas of fuel breaks never intersect fire. Also, the forests that had the highest density and area of fuel breaks did not have the highest overall effectiveness of fuel breaks, suggesting that treating more area alone does not necessarily increase the safety of a region. It may be more effective to have fewer fuel breaks in strategically placed locations than to have greater area of fuel breaks overall, at least in terms of protecting communities. The results from all three forests show that fuel breaks played an important role in controlling large fires primarily where they provided access for firefighting activities. Strategically locating fewer fuel breaks could also reduce the potential for resource costs.

Discussion in the interviews revealed that many strategic decisions do go into placing fuel breaks. While these decisions are often based on years of fire management experience, quantitative and spatially explicit analyses could potentially be helpful in refining these strategic decisions. For example, maps like the ones generated here, showing where fuel treatments are mostly likely to intersect fires, could be combined with further spatial analyses of where access is best and where communities need the most protection. In particular, this study strongly supports the notion of constructing fuel breaks along the wildland–urban interface where firefighters will have better access to the fuel breaks, and where the fuel breaks will provide an immediate line of defense adjacent to homes that are at risk. The case studies from all four national forests demonstrate that fuel breaks will not stop fires without firefighter presence. Therefore, constructing fuel breaks in remote, backcountry locations will do little to save homes during a wildfire because most firefighters will be needed to protect the wildland–urban interface, and fires will not be stopped by those fuel breaks that are located farther away. Finally, because access to fuel breaks was consistently improved when vegetation structure was favorable, this study suggests that maintaining fuel breaks in strategic locations may be just as important as constructing new fuel breaks.

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Factors affecting fuel break effectiveness in the control of large fires on the Los Padres National Forest, California

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Abstract. As wildfires have increased in frequency and extent, so have the number of homes developed in the wildland–urban interface. In California, the predominant approach to mitigating fire risk is construction of fuel breaks, but there has been little empirical study of their role in controlling large fires. We constructed a spatial database of fuel breaks on the Los Padres National Forest in southern California to better understand characteristics of fuel breaks that affect the behaviour of large fires and to map where fires and fuel breaks most commonly intersect. We evaluated whether fires stopped or crossed over fuel breaks over a 28-year period and compared the outcomes with physical characteristics of the sites, weather and firefighting activities during the fire event. Many fuel breaks never intersected fires, but others intersected several, primarily in historically fire-prone areas. Fires stopped at fuel breaks 46% of the time, almost invariably owing to fire suppression activities. Firefighter access to treatments, smaller fires and longer fuel breaks were significant direct influences, and younger vegetation and fuel break maintenance indirectly improved the outcome by facilitating firefighter access. This study illustrates the importance of strategic location of fuel breaks because they have been most effective where they provided access for firefighting activities.

Additional keywords: chaparral, firefighter, mapping, pre-fire fuel treatment, southern California, strategic location, structural equation model, suppression, wildland–urban interface.

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Introduction

In recent decades, wildfire frequency, extent or severity have increased across much of the western United States (Stephens 2005; Westerling *et al.* 2006; Miller *et al.* 2009), as well as other regions around the world (e.g. Pausas and Vallejo 1999; Montenegro *et al.* 2004). Concurrently, the number of homes built in the wildland–urban interface (WUI, where development meets or intermixes with wildland vegetation), and the areal extent of the WUI have grown dramatically – and are expected to continue growing for decades to come (Radeloff *et al.* 2005; Theobald and Romme 2007). The social and financial cost of so many homes located in fire-prone areas has been high. From 2002 to 2006 in the western US, US$6.3 billion was spent fighting fires, 92 lives were lost and more than 10 000 homes were destroyed (Gude *et al.* 2008). Considering the enormity of these effects, there is tremendous pressure to develop wildland fire-management practices to reduce urban losses.

Although reducing wildfire losses ultimately will require a combination of urban and wildland changes, historically the main focus has largely centred on wildland fuel reduction, often in the form of mechanical fuel treatments (Dellasala *et al.* 2004). Between 2001 and 2006, federal land management agencies in the western United States spent US$2.7 billion for fuel treatments (Schoennagel *et al.* 2009). Although the objective for constructing fuel treatments is generally to reduce the severity and spread of wildfires, specific expectations regarding how fuel treatments are supposed to function tend to vary among different stakeholders (e.g. public, special-interest groups, policy-makers or management agencies (Reinhardt *et al.* 2008). The typical objective of fuel treatments in many western US forests is to change fire behaviour, reduce the severity of fire effects and restore forest structure to conditions that would safely support a natural fire regime of frequent, low-intensity fires (Reinhardt *et al.* 2008). In urbanised areas, treatments are instead intended to prevent fire from spreading into development (Raab and Martin 2001; Radeloff *et al.* 2005), but there may be unrealistic expectations that these treatments can 'fire-proof' those areas (Reinhardt *et al.* 2008; Keeley *et al.* 2009*a*).

Along with differing expectations, the effectiveness or appropriateness of treatments are also likely to vary according to regional differences in vegetation type and structure, natural fire regime, weather conditions and local topography

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(Stratton 2004). The ecological implications of fuel treatments, and ecological effects of altered fire regimes, are also likely to vary from region to region, but ecological considerations are rarely incorporated into current forest laws and policies (Noss *et al*. 2006). Although fuel treatments and resource benefits are likely to be compatible in many forest types (Schwilk *et al*. 2009), treatments potentially create negative ecological effects in non-forested communities such as chaparral shrublands in southern California (Keeley *et al*. 2009*b*). Unlike forests, in which mechanical fuel treatments typically remove only surface fuel (preserving larger, older trees), fuel break construction in chaparral typically involves complete removal of vegetation, chemical herbicides and permanent conversion of native shrublands to weedy herbaceous associations (Wakimoto 1977). The range of ecological effects includes exotic species expansion, erosion and watershed issues, and fragmentation of important habitat for threatened and endangered species.

Despite the potential ecological effects of fuel treatments in southern California shrublands, the pressure to mitigate fire risk is enormous. In this region, almost 1 million ha of land has burned since 2000, much of which was consumed in fires larger than 50 000 ha. In the fires of 2003 and 2007, ~5000 homes were destroyed. The population of the region is growing rapidly, and much of the housing development is distributed in scattered patterns that create thousands of miles of edge between houses and fire-prone vegetation (Pincetl *et al*. 2008). There are consequently complex trade-offs among the costs and benefits related to fuel management in southern California, as well as other fire-prone regions dominated by extensive development: creating fuel breaks is costly financially and may result in substantial ecological effects, but fuel breaks may play an important role in protecting communities from catastrophic losses.

Adding to the dilemma over costs and benefits in implementing fuel treatments is the uncertainty over the conditions under which fuel treatments are effective at mitigating fire risks. For example, the behaviour of chaparral fires under moderate weather conditions is very different than the behaviour during Santa Ana conditions, and the role of fuel breaks may vary accordingly (Keeley 2005; Keeley *et al*. 2009*a*). Although many managers recognise that the primary role of fuel breaks in developed areas and the WUI is to provide an anchor point and a safe place for firefighters to control and extinguish fires (Conard and Weise 1998; Witter and Taylor 2005), sometimes too much faith is placed in the ability of treatments to passively stop the spread of fire, which may be unlikely under severe weather conditions. A quantitative analysis of the role of fuel breaks may therefore provide critical insights that can inform peoples' expectations and can help to construct fuel breaks more efficiently.

Most research on fuel-treatment effectiveness has been conducted with simulation models at relatively small scales (e.g. Miller and Urban 2000; Finney *et al*. 2007; Schmidt *et al*. 2008), and there is some empirical research documenting how fires have responded to individual fuel treatments (e.g. Schoennagel *et al*. 2004; Raymond and Peterson 2005; Safford *et al*. 2009). However, there are insufficient examples to form general conclusions, particularly at a landscape scale.

Another consideration is that, if fuel breaks are constructed in locations where fires rarely or never encounter them, then those treatments will have no opportunity to play any role. In other words, two conditions need to be satisfied before a fuel treatment can function effectively: (1) the fire needs to actually intercept the treatment, and (2) the treatment must perform according to its expected role.

Considering these two conditions, and to better understand what role fuel treatments have played in reducing the effects of large fires, we analysed the relationships among fires and fuel breaks in the Los Padres National Forest in southern California over a period of 28 years to answer these research questions:

1. What proportion of treatments intersected fires, and can we explain and predict why some treatments encounter more fires than others?
2. What is the role of fuel breaks in controlling large fires, and what factors influence this role?

We expected this study to provide deeper understanding of the relative importance of factors influencing fuel-treatment success in southern California and to provide guidance on how to develop more efficient treatment strategies.

Methods

Study area

Our study area included all lands (~590 000 ha) within the Main Division (central ranger districts) of the Los Padres National Forest in southern California. The climate is Mediterranean, with cool wet winters and hot dry summers. The landscape is dominated by chaparral shrublands, which are highly flammable owing to dense community structure and the annual 6 months of drought every summer and autumn (Radtke *et al*. 1982; Conard and Regelbrugge 1994). Broad swaths of chaparral are often broken up by patches of coastal sage scrub, riparian woodlands, oak woodlands, grassland and coniferous forest. The region is topographically complex and rugged, with slopes often exceeding 35°, and much of the interior of the Los Padres National Forest study area is relatively inaccessible.

Adjacent to this rugged terrain are several urban areas, such as Santa Barbara and Ojai, and housing developments border much of the forest boundary, increasing the potential for wildfire to threaten lives and property. Slightly more than 10% of the land inside the forest boundary is occupied by privately owned inholdings (V. Radeloff, unpubl. data), and low-density housing exists within much of the forest, particularly near the boundary. Thus, the primary objective of firefighting and constructing fuel breaks is to stop fires and to prevent them from threatening structures. Humans also cause the majority of fire ignitions in the region (Moritz 1997).

Fuel treatment and fire data

The Los Padres National Forest provided written, pictorial and oral data on historic fuel treatments. Many recent fuel-treatment locations were provided digitally, but we also digitised older fuel breaks from hard-copy maps. To identify case studies for follow-up interviews and subsequent analysis, and to analyse the intersections among fuel treatments and fires, we used a Geographic Information System (GIS) to overlay the fuel treatment data with fire perimeter polygons, compiled by the California Department of Forestry-Fire and Resource Assessment Program (CALFIRE). The fire perimeter data only represent the largest fires (with a minimum mapping unit of 4.04 ha (10 acres)), but they serve as the most comprehensive source of fire data in the state. The largest fires also account for the majority of area burned.

Quantifying number of intersections

Through GIS overlay analysis, we counted the number of times fires crossed fuel breaks from 1980 to 2007. We restricted our analysis to fires that occurred after 1980 owing to greater uncertainty in accuracy of GIS data before 1980 and because of the limited availability of firefighters and managers familiar with fires before 1980, which was critical for personal interviews. Some sections of fuel breaks intersected fires more frequently than other sections, so we stratified each fuel break spatially and classified it according to the number of intersections (ranging from 0 to 4). From this spatially stratified data layer, we randomly selected point samples (244 points; see below) to extract environmental data to relate to the number of intersections that occurred at those points. To ensure that all fuel breaks had an equal chance of intersecting fire, for this part of the analysis, we only evaluated those fuel breaks that had been constructed before 1980 and were intersected by fire that occurred in the period 1980–2007.

Based on a previous analysis of fire frequency (Syphard *et al*. 2008), we suspected that fire intersections and our predictor variables were likely to be spatially autocorrelated, which would violate the assumption of independence in regression models and potentially inflate model significance (Fortin *et al*. 1989; Haining 1990). The influence of spatial autocorrelation can be avoided by using a minimum distance to separate observations that is larger than the range of spatial autocorrelation (Miller *et al*. 2007). Therefore, after we estimated initial regressions models (see below), we plotted semivariograms of the models' deviance residuals. We determined that spatial autocorrelation was present when samples were within 1 km of each other, so we subsampled our data to avoid observations within that lag distance, which resulted in a sample size of 244 observations.

Selecting fuel break case studies

Through GIS overlay analysis, we identified all events in which a fire occurred within 100 m of a fuel break, to account for any spatial uncertainty in the boundaries of either the fires or the fuel breaks. For this analysis, we considered fuel breaks constructed at any date, but only fires later than the date of fuel break construction were included. After identifying all potential intersections between fires and fuel breaks, we conducted preliminary analyses to identify whether the fire appeared to have stopped at the fuel break or whether it spread across it. We then arranged personal interviews with fire personnel having first-hand knowledge of the incident.

Explanatory variables

To understand and to predict why fires intersect some sections of fuel breaks more than others, we explored the potential influence of several human and biophysical variables known to be associated with the spatial distribution of fire at a landscape scale (Syphard *et al*. 2008). We also considered the potential for historic fire regime (fire frequency and ignition density) to explain the number of intersections because we expected the fire history to reflect how some areas in a landscape are more fire-prone than others. Because the data for the number of fuel break intersections were collected from across the entire time period in the study (1980–2007), we did not consider variables related to specific points in time for that analysis. However, to identify the primary factors that affect the role of fuel breaks, we additionally considered variables related to fire events, including characteristics of the fires, fuel breaks, suppression activities and vegetation age, although we did not consider historic fire regime.

For the environmental and fire regime variables, we used a GIS to extract data values to relate to the dependent variables. For the analysis of number of intersections, we extracted data from the locations of the random sample points. For the case studies where fires intersected fuel breaks, we extracted data from the portion of the fuel break where the fire intersected and averaged the values for that area. By constraining the area of analysis, we ensured that we were only considering the potential local influence of those variables because some fuel breaks are quite long and may span large areas.

Human and biophysical environmental variables

Because the majority of fires in California are started by humans, the spatial distribution of fire tends to be strongly related to the distribution of human infrastructure (Syphard *et al*. 2007, 2008). Therefore, our explanatory human variables included distance to development, roads and trails (as in Syphard *et al*. 2008). We expected a larger number of intersections to occur in close proximity to human infrastructure, and we expected fires to stop more frequently near human infrastructure because firefighters would be able to access those areas more quickly. We used the Development Footprint data layer from CALFIRE (http://frap.cdf.ca.gov/data/frapgisdata/select.asp, accessed 13 July 2011) that delineates developed lands from 2000 Census block data, 2000 land ownership data, 1990s US Geological Survey National Land Cover Data (NLCD), and 2000 Census Urbanised Area data at 30-m resolution. The road data came from the 2000 US Topologically Integrated Geographic Encoding and Referencing system TIGER/Line files. The trail data came from the US Forest Service online GIS clearinghouse (http://www.fs.fed.us/r5/rsl/clearinghouse/gis-download.shtml, accessed 13 July 2011).

Independently of human influence, a region's fire regime and the distribution of fire patterns are influenced by biophysical factors, or the fire environment (Pyne *et al*. 1996). Based on the biophysical variables that significantly influenced fire patterns in another southern California landscape (Syphard *et al*. 2008), we explored the potential influence of elevation, slope gradient, solar radiation, fuel model and vegetation age. We also considered several climate variables, but they were strongly correlated with elevation, so we removed them from the analysis. Because these biophysical variables may affect fire spread rate, fuel moisture, flammability of fuels and fire intensity both directly and indirectly (Whelan 1995), we expected that their distribution and spatial variability would influence where fires would most frequently intersect fuel breaks. We expected them to also potentially influence the role of fuel breaks in constraining fire because of their influence on fire spread rates, which could inhibit firefighting efforts.

We acquired elevation data from the 30-m US Geological Survey Digital Elevation Model, and used it to derive slope gradients and to develop grids of terrain-distributed solar radiation, which mediates temperature and available fuel moisture (Dubayah and Rich 1995). Solar radiation tools in the Spatial Analyst extension of *ArcGIS 9.x* were used to calculate daily insolation for winter solstice with site latitude of 33°N, sky size of 200 cells per side and 0.2 clear sky irradiance, the fraction of global normal radiation flux that is diffuse. This has been shown to be a significant predictor of regional plant species distributions (Syphard and Franklin 2009).

Vegetation and fuel characteristics are often classified into fuel models that exemplify relatively uniform fire behaviour and rates of spread. We obtained spatial fuel model data from statewide maps developed by the US Forest Service (N. Amboy, pers. comm. January 2010) at 30-m resolution to evaluate whether number of intersections would vary according to fuel models. We were unable to evaluate fuel model in the statistical analysis of fuel break outcome because there were several fuel model types with only one observation in the data.

We also evaluated whether or not fuel break outcome would vary based on the age of surrounding vegetation at the time of fire. Because the majority of fires are stand-replacing in California shrublands, we used fire-history maps to determine the age of the vegetation by subtracting the time of last fire from the year of every fire event.

Fire history

Because some parts of a landscape are more fire-prone than others, we expected the number of intersections among fires and fuel breaks to be positively associated with those areas that have historically burned most frequently. To associate number of intersections with historic fire regime, we converted the fire perimeter polygon data layer into a continuous grid surface that reflected the number of fires that occurred in each cell throughout the fire history (1878–2007). We included the full history of fires for this variable because it provided a larger sample of fires to quantify which parts of the landscape tend to burn more frequently than others.

In addition to the fire perimeter database, we also used a database of ignitions (that occurred from 1970 to 2007) to evaluate whether number of intersections was positively related to areas of high ignition density. The ignition data were compiled from original fire reports on file at the Los Padres National Forest and included 1380 ignitions (71% caused by humans). To create the ignition-density grid, we used a point density function in a GIS that calculated, across the entire landscape, the relative magnitude of ignition occurrences per unit area based on the number ignition points that fell within a specified neighbourhood (3 km) around each cell.

Fire events

We calculated the size of every fire that intersected a fuel break using a GIS, and the month of the fire was listed in the fire perimeter database. To reduce the degrees of freedom in the analysis, we reclassified the fire months into spring–summer (April through July) *v.* fall (autumn)–winter (September–December). No fires occurred in the month of August in our dataset.

We explored two sets of weather data in relation to the fires that intersected fuel breaks. One was from the global surface summary of day product from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) (ftp://ftp.ncdc.noaa.gov/pub/data/gsod). There were seven NOAA weather stations within the proximity of the study area, and the available data included the mean, maximum and minimum daily temperature, mean and maximum wind speed, and daily precipitation. For some historic fires that burned over the course of many days, we had no way of knowing the date when the fire intersected the fuel break. Therefore, we downloaded and explored data for all dates in which the case-study fires occurred. We calculated the mean, maximum and minimum values, as well as the range and standard deviation, of weather data during the duration of the fire to relate them to fuel break outcome.

In addition to the NOAA data, we explored a data product developed by John Abatzoglou and colleagues at the Desert Research Institute Western Regional Climate Center in Reno, NV. The development of this product involved a hierarchical process in which 32-km North American Regional Reanalysis data, including relative humidity, temperature and wind speed parameters (http://www.emc.ncep.noaa.gov/mmb/rreanl/) were bias-corrected to fine-scale 4-km PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate data, monthly temperature and precipitation (http://www.prism.oregonstate.edu/) and further corrected using Remote Automated Weather (RAWS) stations. From the 4-km continuous grids of weather data, we extracted minimum and maximum daily relative humidity, temperature, wind speed and direction from within the perimeters of case-study fires during the range of dates that they occurred. As with the NOAA data, we explored the potential influence of mean, maximum and minimum values, as well as the range and standard deviation, of weather data during the duration of the fire to relate them to fuel break outcome.

Characteristics of fuel breaks

We used GIS to calculate the length of the fuel breaks, and we included the entire fuel break length as our explanatory variable. The fuel break width was included in the attributes of the files that the forest service crews provided and ranged from 6 to 183 m (20–600 feet). A few of the fuel break widths were presented as ranges (e.g. 6–12 m or 91–180 m), so we used the mean of the range for the width value of those fuel breaks.

Because it was difficult to determine the condition of the fuel break (i.e. the amount of vegetation regrowth) at the moment of intersection through maintenance records or through GIS mapping, we asked fire personnel to indicate the condition of the fuel break on a scale from one to three (poor to excellent). All personnel based their ranking on the same criteria. A ranking of one meant that the fuel break was barely discernable from the surrounding vegetation; a ranking of two meant that the fuel break was apparent, but that vegetation was starting to regrow; and a ranking of three meant that the fuel break was in excellent condition with no vegetation regrowth or was primarily grass.

Suppression activities and other fire event information

Data on suppression activities were obtained during personal interviews based on a questionnaire to determine whether there was access to the fuel break (yes or no) and the availability of firefighting resources (manpower and equipment) on a scale from one to three. For firefighting resources, a ranking of one meant that the firefighters did not have the equipment or manpower available to fight the fire; a ranking of two meant that equipment and manpower were available but not completely sufficient for properly fighting the fire; a ranking of three meant that the firefighters had all the equipment and manpower they needed to fight the fire. We also asked the firefighters to specify the vegetation type at the time of fire, but this variable was highly correlated with condition of fuel break, so we did not include that variable in the statistical analysis. In addition to asking specific interview questions, we documented any additional notes or insights about the fire events.

Statistical analysis

Number of intersections

To evaluate the influence of the explanatory variables on number of fuel break–fire intersections, we developed Poisson regression models because they are appropriate for count data (Agresti 1996). To explore the effects of the explanatory variables independently of their interactions with other variables, we first developed simple regression models. We evaluated linear and quadratic relationships for all the continuous variables, and then ranked variable importance based on the deviance explained in the simple models. In generalised linear models (which include Poisson and logistic regression), models are optimised through deviance reduction, and the deviance explained (D^2) is the equivalent to the R^2 in ordinary least-square models (Guisan and Zimmermann 2000). We used the rankings to establish the order to enter variables in a multiple regression, and we considered those variables that were significant at $P \leq 0.15$ and that were not correlated with other variables (bivariate correlation ≥ 0.3). Because distance to development was correlated with ignition density ($R = -0.4$) and distance to road ($R = 0.37$), we removed it from the multiple-regression analysis.

For the multiple-regression modelling, we were primarily interested in selecting the best model for predicting and mapping the number of intersections. Therefore, we identified several plausible multiple-regression models and selected the best-fit model as the one that explained the highest percentage deviance explained with the lowest Akaike information criterion (AIC) (Quinn and Keough 2002). We checked our Poisson model to ensure that overdispersion did not exist and that our residual deviance was equal to our residual degrees of freedom.

To evaluate the multiple-regression model, we predicted the number of intersections for the random sample points and calculated the Pearson's correlation coefficient between the actual number of intersections and the predicted number of intersections. We also calculated the root mean square error (RMSE) to quantify the discrepancy between observed and predicted values. All modelling was carried out in the R 2.7.0 statistical programming environment (R Development Core Team 2004).

We converted the multiple-regression model into a predictive map surface by applying the formula from model to the entire landscape using the regression coefficients and the GIS layers for the significant explanatory variables. For Poisson regression, the formula is:

$$n = \exp(B_0 + B_1 \times X_1 + B_2 \times X_2 + \ldots + B_k \times X_k)$$

where n is the number of fire–fuel break intersections, B_0 is a constant, and B_i are coefficients of the explanatory variables.

Fuel-treatment outcome

The response variable for fuel-treatment outcome was binary and indicated whether the fuel treatment constrained the fire or not. Therefore, instead of using Poisson regression, we estimated simple and multiple logistic regression models using the same approach as for number of intersections, although we did not create a predictive map. To evaluate the performance of the logistic multiple-regression model, we performed a leave-one-out cross-validation, which iteratively leaves one observation out of the model, fits the model and then calculates the predicted probability of the observation for every observation in the sample. Based on the cross-validated predictions, we calculated the area under the curve (AUC) for a receiver operating characteristic (ROC) plot (Hanley and McNeil 1982). The AUC ranges from 0.5 to 1, and, in this case, indicates the overall probability that, for a randomly selected set of binary observations (one in which fire stopped at a fuel break and the other in which fire did not stop), the model correctly identifies them.

After exploring the relationships among the explanatory variables through regression modelling and correlation analysis, we developed a structural equation model (SEM) to confirm hypotheses about the factors and interactions that were significant in explaining fuel-treatment outcome. We developed our hypotheses based on the regression analysis as well an exploration of correlations among all the variables. SEM has advantages over multiple-regression modelling because it can test whether our hypotheses are consistent with our data and can also test for indirect interactions (Grace and Pugesek 1998). Rather than a predictive modelling approach, SEM serves as a framework for interpreting relationships among a network of interrelated factors (Grace *et al*. 2010). We supplemented the multiple-regression analysis with SEM because our objective was to better understand the interactions among factors influencing the role of fuel breaks in controlling fires.

Because we were modelling categorical outcomes, we used the weighted least-squares with mean and variance adjustment (WLSMV) estimator, and evaluated model fit using chi-square and associated P values as well as other fit indices, including RMSE of approximation and weighted root mean square residual (Hooper *et al*. 2008). Owing to our limited dataset, we included paths that were significant at $P \leq 0.15$; however, we compared alternative models by removing one path at a time to ensure that, if a path were removed, the chi-square did not increase more than 3.84 points (the single degree-of-freedom test) (J. B. Grace, pers. comm.). We performed the structural equation modelling with *Mplus version 5.1*.

Results

There were ~550 km of mapped fuel breaks in the study area (Fig. 1), including fuel break backbones along ridgelines as well

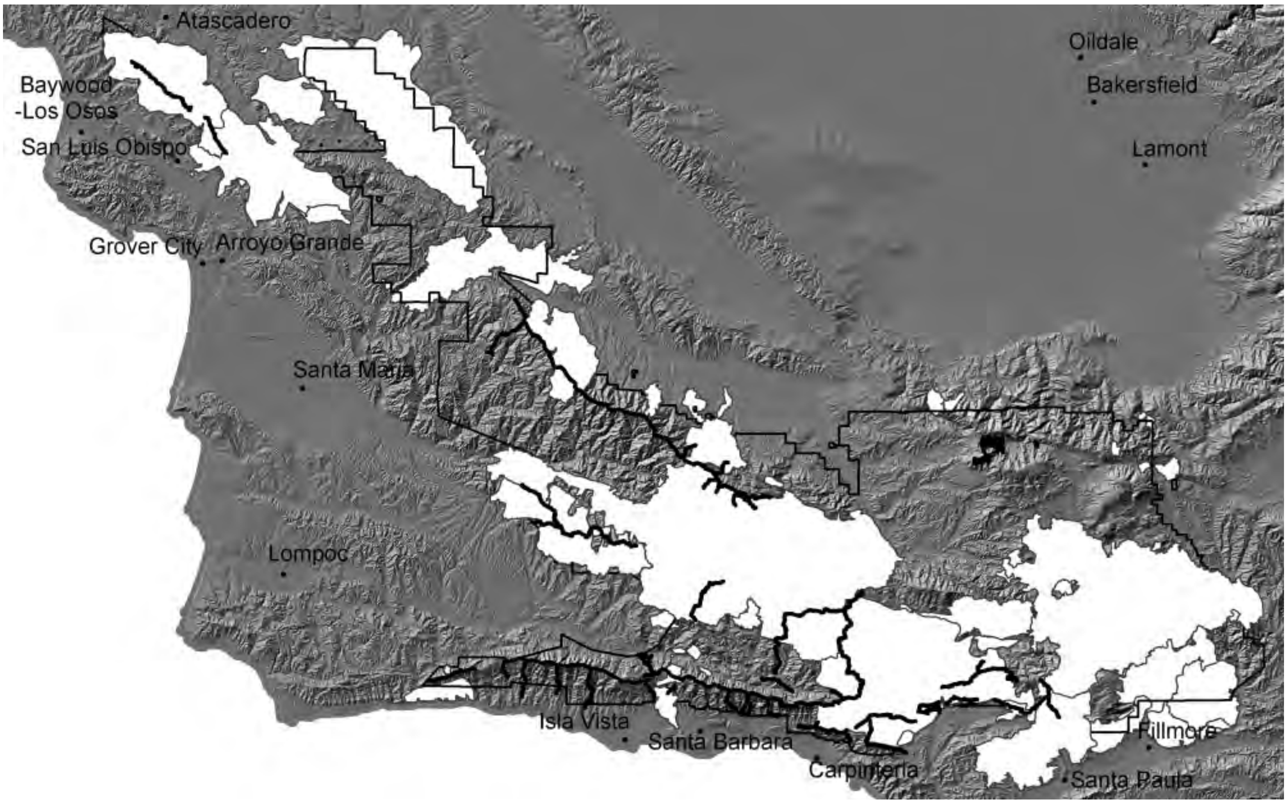

Fig. 1. Map showing location of fuel breaks (thick black lines) and fires (in white) that occurred between 1980 and 2007 in the Los Padres National Forest, CA. The thinner black line shows the study area.

as laterals. Most were constructed before 1980, but several were created within the last decade. Often, a combination of methods were used to create and maintain the fuel breaks, including dozers, discs, herbicide or spot herbicide, hand pile and burn, hand pile and chip, or mastication. These methods often varied along the length of individual fuel breaks, and maintenance methods changed over time. Although one fuel break (~28 km) was shaded, the rest of the fuel breaks were constructed similarly, as linear features on the landscape in which shrublands were converted primarily to grasslands.

From 1980 to 2007, 95 fires intersected the study area, with sizes ranging from 5 to almost 100 000 ha (the Zaca fire of 2007) (Fig. 1). Of these, 20 fires (21%) intersected at least one fuel break, and 8 of these 20 fires (40%) intersected more than one fuel break. Some portions of the fuel breaks never intersected any fires, but during the 28-year study period, some portions of fuel breaks intersected up to four fires (Fig. 2).

The GIS analysis identified 74 unique events in which fires intersected fuel breaks, but during personal interviews, 21 of those intersections were removed from the analysis owing to one of the following reasons: in one case, two fires were unnamed and nobody remembered them; in another, several fires did not spread into the fuel break, but rather spread away from it or parallel to it; and lastly, one of the fires in the database apparently never occurred. We did not consider fires spreading away from or parallel to the fuel break because the firefighters claimed in the interviews that the fuel break in those cases would have been irrelevant in the control of the fires. Therefore, the final number of fire and fuel break intersections was 53.

For 23 of the 53 events (46%), the fire was effectively constrained by the fuel breaks, and for 30 (54%) of the events, the fire spread across the fuel break. In all but one of the events in which fires stopped at the fuel breaks, firefighters had access to the treatment for suppression activities. For the events in which fires spread across fuel breaks, there were 11 occasions (37%) in which fire crews did not have access to the treatment and 19 events (63%) in which crews had access to the treatment, but the fire spread across it.

Results from the interviews with the firefighters revealed that the primary reasons that fires crossed fuel breaks were: (1) scarce resources were available if the fire was large or if other fires were burning simultaneously; (2) winds shifted during the event, making fire behaviour unpredictable; (3) the fuel break had not been maintained and was difficult to manoeuvre around; or (4) fire crews did not put suppression resources on the treatment.

During the interviews, the fire crews also described how they frequently ran dozers down the fuel breaks before the fires reached them. In wilderness areas, dozers are prohibited, so crews instead used hand-lines or hose-lay in preparation for the fire. If the fuel breaks were already type-converted to grass, the crews did not dozer them, but dropped retardant and water. If safe, firefighters waited for the fire with a hose-lay and hand-line to bare dirt. In many cases, substantial areas of the recorded fires

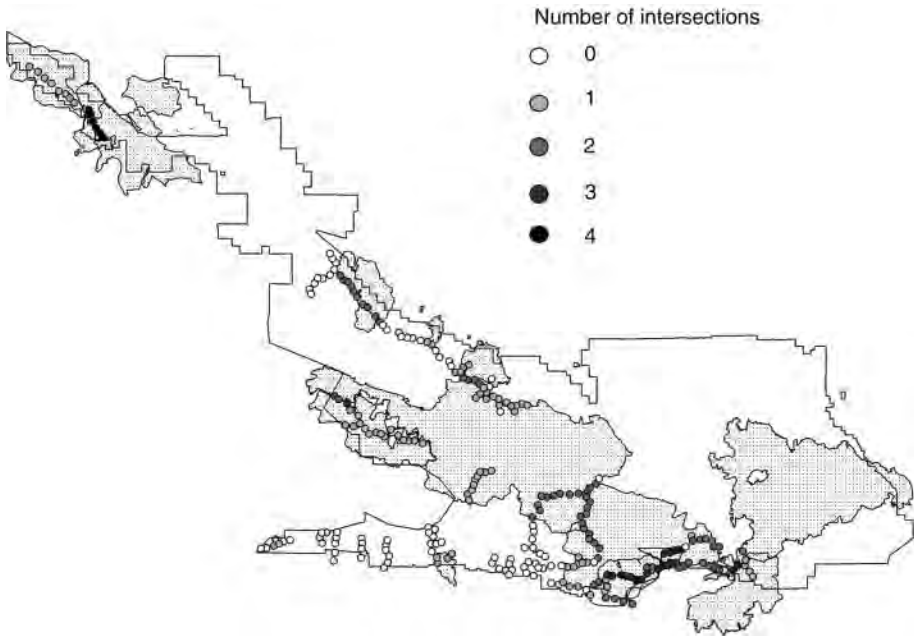

Fig. 2. Map of sample points on fuel breaks classified according to the number of times fires had intersected them from 1980 to 2007. Perimeters of fires that intersected fuel breaks are also shown.

had been burned through backfires to prevent the actively spreading fire from reaching the treatment. In one case (the ~100 000-ha Zaca fire), nearly 33 000 ha burned from backfire activity.

The crews described that they focussed most of their suppression efforts on the backbone fuel breaks, which are typically located along ridge lines. The lateral fuel breaks, running perpendicular to the backbone, were used to contain smaller fires that potentially were spreading within a drainage basin. The crews often put dozer lines down the laterals during the fire under those conditions.

For seven (13%) of the events cases, the fuel break changed the fire behaviour after the intersection such that crews could manoeuvre around the vicinity of the treatment and ultimately successfully suppress the fire.

Statistical analysis

Number of intersections

Almost 40% of the fuel treatments never intersected a fire, but ~30% of the treatments intersected two or more fires. Fires were most likely to intersect fuel breaks in areas where: historic fire frequency was high ($D^2 = 0.18$, $P < 0.001$); fuel breaks were in close proximity to trails ($D^2 = 0.07$, $P = 0.09$); distance to roads was intermediate ($D^2 = 0.04$, $P = 0.001$); historic ignition density was low ($D^2 = 0.02$, $P = 0.04$); and winter solar radiation was low ($D^2 = 0.02$, $P = 0.02$). None of the other variables explained significant variation in number of intersections.

All of these variables that were significant in the bivariate simple regressions were retained in the multiple-regression model explaining number of intersections; however, whereas the linear term and its quadratic were both significant for distance to roads in the simple model, only the linear term was retained in the multiple-regression model, which was highly significant ($D^2 = 0.28$, $P < 0.001$).

The map surface generated by applying the formula and coefficients of the multiple-regression model to the original GIS maps of the predictor variables showed the relative distribution of where fires are predicted to intersect fuel breaks most frequently (Fig. 3). The Pearson's correlation coefficient for the observed versus predicted observations was 0.57, and the RMSE was 0.74.

Fuel-treatment outcome

Five of the independent variables explained more than 5% of the residual deviance ($D^2 > 5$) in the bivariate simple regression analysis. Fires were most likely to stop at a fuel break when: there was firefighter access to treatment ($D^2 = 0.12$, $P = 0.01$); fire size was smaller ($D^2 = 0.11$, $P = 0.009$); vegetation age was younger ($D^2 = 0.10$, $P = 0.01$); fuel breaks were longer ($D^2 = 0.07$, $P = 0.03$); and there were adequate firefighting resources ($D^2 = 0.07$, $P = 0.12$). The fuel break outcome was not significantly explained by fire season, weather, any of the biophysical variables or distance to human infrastructure.

There was significant multicollinearity between access to treatment and vegetation age ($D^2 = 0.05$, $P = 0.09$). Access to treatment was also significantly related (again through simple bivariate regression) to the condition of the fuel break (better condition contributed to better access, $D^2 = 0.10$, $P = 0.05$) and fuel break width (wider fuel breaks contributed to better access, $D^2 = 0.06$, $P = 0.08$). These two variables were not considered in the multiple-regression model, but their effects were indirectly evaluated in the SEM.

After entering the significant variables in order of deviance explained and performing forward and backward stepwise regression, the final multiple-regression model for fuel-treatment outcome retained access, fire size and length of fuel break. The model was significant at $P = 0.006$, with a D^2

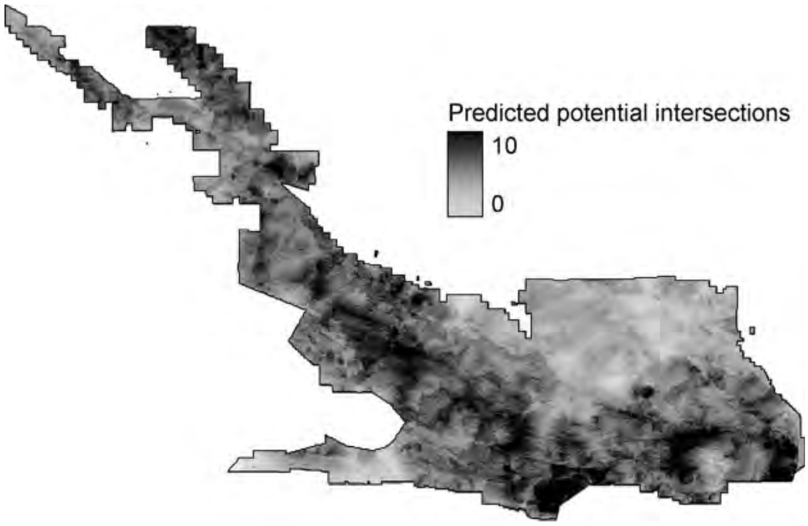

Fig. 3. Map showing predicted distribution of areas where fires and fuel breaks are most likely to intersect in the Los Padres National Forest, CA.

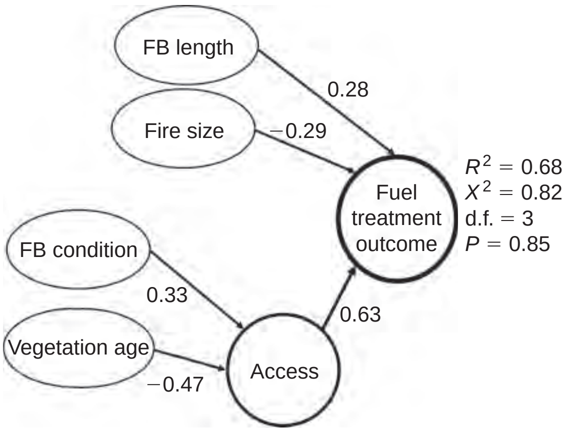

Fig. 4. Structural equation model of factors that directly and indirectly explain why fires stopped at fuel breaks (FBs) in the Los Padres National Forest. Coefficients shown along arrows are standardised values.

of 0.29. The leave-one-out cross-validation of the multiple-regression model resulted in an AUC of 0.84.

Based on exploration of the relationships among the variables, our structural equation model that explained why fires stopped at fuel breaks included the direct effects of the significant explanatory variables from the multiple regression (access, fire size and fuel break length) as well as indirect effects of vegetation age and fuel break condition based on their influence on treatment access (Fig. 4). The model chi-square was low (0.82), with a high P value (0.85) that indicated there was no significant difference between the data and our hypothesised model. The proportion of variance explained in fuel treatment outcome ($R^2 = 0.68$) was substantially higher than the generalised linear mode (GLM) multiple-regression model equivalent ($D^2 = 0.29$). Removal of any paths in the model resulted in an increase of chi-square that was greater than 3.84. The standardised coefficients in the SEM results indicated that fuel-treatment effectiveness was positively related to access to treatment and fuel break length and negatively related to fire size. There was a positive indirect effect of fuel break condition and a negative indirect effect of vegetation age on fuel-treatment outcome due to their direct effects on access to treatment.

Discussion

Because prefire fuel manipulation is one of the primary strategies used to manage wildfire, we evaluated the role that fuel breaks have played in controlling the extent of large fires in southern California. For a fuel break to function, it must: (1) encounter a fire, and (2) successfully function as expected, which in the WUI is to stop the spread of fire, either directly or by facilitating the alteration of fire behaviour. During the nearly three decades of our analysis, most of the fires that occurred (79%) burned without intersecting a fuel break, and many segments of fuel breaks never encountered a fire. However, certain fuel breaks intersected several fires, and our results showed that we can identify the factors that influence the likelihood of intersection and we can map where on the landscape treatments are likely to intersect fires. Our results also showed that the primary role of fuel breaks is to provide firefighters safe access to perform suppression activities. Only a few of the other variables that we considered as potentially influencing the role of fuel breaks were statistically significant.

A potential reason that some environmental variables did not significantly affect the fuel break–fire outcome is that they may have been relatively uniform across our study area relative to the sample size, which may have been too small to adequately explain substantial variation. In other words, there may be additional reasons that fires stop at fuel breaks, but there were not enough samples to adequately quantify these different effects. Regardless, the results strongly suggest that fires will generally not stop at fuel breaks in our study area unless firefighters are present to suppress the fire. There was only one event in our analysis in which a fire stopped at a fuel break without active fire suppression. With firefighter control, however, fuel breaks had a decent success rate (46%), which is the exact same success rate found in old (and one of the only other) analyses of fuel break effectiveness in the region (Cecil 1941).

It is important to keep in mind that our statistical analysis was based on a response variable describing whether the fire stopped at the fuel break and did not reflect the role of fuel breaks in changing fire behaviour. In seven cases, the treatments did change the behaviour of the fire that ultimately allowed subsequent control, and if these are included, the success rate increases to 56%. The key variables that may be most important to consider in fire management and planning, therefore, may be related to those that affect firefighting activities.

Our results showed that access to the fuel break was critical in the success of fire control, and this was echoed by firefighters who generally viewed access as a function of the spread rate of the fire relative to location of fire origin, the location of the fuel break and the location of the crews at the time of the fire. Also, if the fire started at night, there were fewer people available, so they would have to travel from home to work to get to the engine. The speed of response is an important component in successful fire control (Halsey 2005), and this has been recognised for many decades, particularly in the Los Padres National Forest, which has extensive roadless and trailless areas (Show *et al*. 1941).

Once firefighters were in the vicinity of the fuel break, vegetation structure played an important role in determining whether they could access the fuel break in time to stop the fire, and this is reflected in our SEM (Fig. 4). In the high-elevation chaparral of the Los Padres National Forest, as well as chaparral elsewhere, stand age and fuel loads play a limited role in stopping the spread of fire, particularly during extreme weather conditions when fires will readily spread through all age classes of vegetation (Moritz 1997; Moritz *et al*. 2004; Keeley and Zedler 2009). Therefore, whereas young fuels may constrain fire in other vegetation types, the primary relationship in the present study is with firefighter access to fuel breaks. Chaparral is composed of dense, woody shrubs that form a continuous cover that makes it difficult to manoeuvre and contributes to dangerous flame lengths (Conard and Weise 1998), and therefore, younger vegetation makes it easier for crews to access the fuel break and establish an anchor point. In many cases, the crews will re-establish the fuel break (e.g. through dozers or handlines) once they arrive. However, if the fuel break is close to a fast-moving fire, there may not be time to re-establish the break and to fully prepare. Therefore, the condition of the fuel break was significant in explaining access to treatment owing to the time required to restore a fuel break in poor condition, especially when fires were fast and near. This suggests that maintaining current fuel breaks may be an important component of effective fire management.

Although maintaining current fuel breaks may increase their success rate, the length of the fuel break was also important, although fuel break width was insignificant. A possible reason that fuel break width was insignificant is that the widths provided in the data may have been approximations, and we also needed to average the range of widths for several of the fuel breaks. We considered that fuel break length may have facilitated firefighter access, but those two variables were not correlated. Therefore, longer fuel breaks may potentially provide greater number of opportunities for fires to intersect fuel breaks. Another consideration is that we did not explore the relative difference of main fuel breaks versus secondary or lateral fuel breaks (which tend to be shorter in length), and other research in the region has shown that laterals are not as effective and do not substantially improve firefighting (Omi 1977).

Although interviews confirmed that the rate of fire spread and fire weather conditions play an important role in the efficacy of fuel breaks (e.g. they determine whether fire crews can access the treatment on time or whether conditions are safe enough to anchor at the break), the only variable related to fire spread rate that was significant in our study was fire size. Although fire size can be a function of multiple interacting factors, larger fires are generally associated with faster spread rates (Anderson 1983; Finney 2003), and faster, or erratic, spread rates are likely to vary as a function of fire–atmosphere couplings as well as fire-induced wind (Sun *et al*. 2009). We made the basic assumption that fire size is correlated with rate of spread at least during some point during the duration of the fire, and consistent with our expectations, small fires were more likely to stop at fuel breaks than large fires. Although there is also the possibility fire size is smaller when fuel breaks are effective because the fuel break played a role in constraining the fire, conversations with firefighters during the interviews confirmed that larger fires are typically associated with severe weather conditions and are much more difficult and dangerous to control.

Although we explored two different sets of weather data, and multiple weather indicators, the likely reason that we found no statistically significant relationships is that many of our fires burned over several days, and we had no way of knowing the exact date and time that the intersection with the fuel break actually occurred. Because weather is highly variable over space and time, we were therefore unable to assign exact weather conditions to the location or moment of intersection. One example of the effect of weather on fuel break outcome that we were unable to capture was the Wheeler Fire number 2 of 1985, which burned for 2 weeks. The weather conditions during the first 4 days were erratic and extreme; the only fuel breaks that were effective were those that intersected the fire after these first 4 days (Salazar and González-Cabán 1987).

Even in other forest types, the influence of fuel breaks on fire spread and severity can be variable and are likely to vary according to weather conditions and other variables (Schoennagel *et al*. 2004). A ‘one size fits all’ approach to fire management has been cautioned against in several recent papers (Noss *et al*. 2006; Reinhardt *et al*. 2008; Keeley *et al*. 2009*b*) and we reiterate the warning for chaparral. There is high variability and complexity in the circumstances leading up to the intersection of fires and fuel breaks and the outcome of what happens (Keeley *et al*. 2009*a*), and the effectiveness of the fuel break in our study could not be predicted by variables such as fuel type, elevation, slope or average climate conditions. Furthermore, our study only accounted for the final realisation of the fire event and not for finer-scale factors that change fire behaviour during the course of the fire event or firebrand production during the spread of the fire.

Although many of the biophysical variables we considered did not significantly explain the role of fuel breaks in stopping fires, a suite of biophysical and human variables was important for developing a model that can predict which parts of the landscape are likely to experience the highest number of fire and fuel break intersections, at least on the landscape from which the model was developed. It was no surprise that historic fire frequency was the strongest predictor of number of fire–fuel break intersections because some areas are inherently more fire-prone than others. The negative relationship between ignition density and number of intersections was unexpected, but may be because the relationship between humans and fire tends to be non-linear (Syphard *et al*. 2007, 2009), and different factors control fire ignitions versus fire occurrence or spread (Syphard *et al*. 2007, 2008). Aside from solar radiation (which varies slowly over time), the other significant variables (distance to trails and roads) tend to be spatially dynamic (as more roads or trails are constructed), which means that predictive mapping models may have to be refitted as landscapes change.

The fact that a substantial proportion of the fuel breaks never intersected a fire during the course of the study suggests that fuel breaks have not historically been placed in areas where fires are most likely to intersect them. Although it is possible that a fire may cross these fuel breaks in the future, fire managers might want to consider focussing maintenance and new construction in areas where fires and fuel treatments are most likely to intersect and thus provide greater opportunities for controlling fires. Construction of fuel breaks can be costly (Agee *et al*. 2000) and may lead to negative resource effects in the chaparral (Witter and Taylor 2005; Merriam *et al*. 2006). Therefore, mapping where fires are most likely to intersect fuel treatments could be part of the planning process to increase efficiency of new construction.

Although fuel breaks surrounding communities clearly serve an important role in creating a safe space for firefighting activities, fuel breaks in remote areas and in areas that rarely or never intersect fires have a lower probability to serve a beneficial function. It is important to consider strategic placement in terms of values at risk, near communities and the WUI, in shrubland ecosystems or other areas where the resource benefits of fuel treatments have not been demonstrated as they have been in forests. Despite strong arguments for locating fuel breaks near communities where protection is most needed (Winter *et al*. 2002; Halsey 2005; Keeley *et al*. 2009*b*), most fuel break proposals continue to be located in more remote wildland areas (Ingalsbee 2005; Schoennagel *et al*. 2009). Other finer-scale factors may also be important for strategic placement (e.g. placing them on ridgelines or other landscape features that offer tactical advantages; Ingalsbee 2005). It is also important to consider that many homes are not ignited owing to direct fire spread, but from firebrands, and more research is needed on the location of fuel breaks relative to firebrand production and structure exposure (Mell *et al*. 2010).

Although this study focussed on the role of fuel breaks in southern California, the increasing threat of fire to human lives and structures, as well as to natural resources, is far-reaching within the United States as well as many other regions in the world. As more fuel breaks are being constructed to mitigate fire risk, there is ongoing need to better understand their role in controlling wildfires. Our methods of systematically exploring the historic role of fuel breaks could be adopted anywhere, and indeed, the specific factors affecting the role of fuel breaks are likely to vary even within the southern California region. Controls over fire regimes vary at multiple scales (Falk *et al*. 2007). Although there are substantial differences in fire regimes between conifer forests and shrublands, southern California is also spatially diverse, and the relative importance of variables predicting fuel break effectiveness, and where fires intersect fuel breaks, may vary according to the scale of the analysis or across the region.

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Vegetation type conversion in the US Southwest: frontline observations and management responses

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Abstract

Background: Forest and nonforest ecosystems of the western United States are experiencing major transformations in response to land-use change, climate warming, and their interactive effects with wildland fire. Some ecosystems are transitioning to persistent alternative types, hereafter called "vegetation type conversion" (VTC). VTC is one of the most pressing management issues in the southwestern US, yet current strategies to intervene and address change often use trial-and-error approaches devised after the fact. To better understand how to manage VTC, we gathered managers, scientists, and practitioners from across the southwestern US to collect their experiences with VTC challenges, management responses, and outcomes.

Results: Participants in two workshops provided 11 descriptive case studies and 61 examples of VTC from their own field observations. These experiences demonstrate the extent and complexity of ecological reorganization across the region. High-severity fire was the predominant driver of VTC in semi-arid coniferous forests. By a large margin, these forests converted to shrubland, with fewer conversions to native or non-native herbaceous communities. Chaparral and sagebrush areas nearly always converted to non-native grasses through interactions among land use, climate, and fire. Management interventions in VTC areas most often attempted to reverse changes, although we found that these efforts cover only a small portion of high-severity burn areas undergoing VTC. Some areas incurred long (>10 years) observational periods prior to initiating interventions. Efforts to facilitate VTC were rare, but could cover large spatial areas.

Conclusions: Our findings underscore that type conversion is a common outcome of high-severity wildland fire in the southwestern US. Ecosystem managers are frontline observers of these far-reaching and potentially persistent changes, making their experiences valuable in further developing intervention strategies and research agendas. As its drivers increase with climate change, VTC appears increasingly likely in many ecological contexts and may require

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management paradigms to transition as well. Approaches to VTC potentially include developing new models of desired conditions, the use of experimentation by managers, and broader implementation of adaptive management strategies. Continuing to support and develop science-manager partnerships and peer learning groups will help to shape our response to ongoing rapid ecological transformations.

Keywords: Adaptive management, Alternative stable states, Forest management, High-severity fire, Post-fire recovery, Resilience, Vegetation type conversion, Community reorganization, Wildland fire

Resumen

Antecedentes: Los ecosistemas boscosos y no boscosos en el oeste de los EE.UU. están experimentando grandes transformaciones en respuesta al cambio de uso de la tierra, el calentamiento del clima y sus efectos interactivos con los incendios naturales. Algunos ecosistemas están en transición hacia tipos alternativos persistentes, a partir del ahora denominado "conversión del tipo de vegetación" VTC, por sus siglas en inglés. VTC es uno de los temas que más presión ejerce en cuestiones de manejo en el sudoeste de los EEUU, aunque las estrategias actuales para intervenir y abordar el cambio usan frecuentemente acercamientos de prueba y error ideados después del evento. Para entender mejor cómo manejar el VTC, reunimos gestores, científicos y practicantes de todo el sudoeste de los EEUU para recolectar sus experiencias con desafíos de la VTC, respuestas de manejo, y resultados.

Resultados: Los participantes en dos talleres proveyeron 11 casos descriptivos y 61 ejemplos de VTC de sus propios campos de observación. Estas experiencias demostraron la amplitud y la complejidad de la reorganización ecológica a través de la región. Los incendios de alta severidad fueron los conductores predominantes del VTC en bosques semiáridos de coníferas. Por un amplio margen, estos bosques se convirtieron en arbustales, con algunas conversiones a comunidades herbáceas nativas y no nativas. Áreas de chaparral y de artemisia casi siempre se convirtieron en pastizales no nativos a través de interacciones como el uso de la tierra, el clima y el fuego. Las intervenciones de manejo en áreas de VTC intentaron más frecuentemente revertir cambios, a pesar de que encontramos que estos esfuerzos cubrieron solamente una pequeña porción de áreas quemadas con alta severidad que experimentaron VTC. Algunas áreas tuvieron largos períodos de observación (>10 años), previos a iniciarse las intervenciones. Los esfuerzos para facilitar el VTC fueron raros, pero pudieron cubrir áreas amplias.

Conclusiones: Nuestros resultados ponen en relieve que este tipo de conversión es una consecuencia común de fuegos de alta severidad en el sudoeste de los EE.UU. Los que manejan los ecosistemas son observadores de primera línea de estos cambios de largo alcance y potencialmente persistentes, haciendo que sus experiencias sean además valiosas para desarrollar estrategias de intervención y en agendas de investigación. A medida que las causas se incrementan con el cambio climático, los VTC aparecen cada vez más probables en varios contextos ecológicos, y pueden requerir también paradigmas de manejo hacia la transición. Acercamientos al VTC incluyen potencialmente nuevos modelos de desarrollo con condiciones deseadas, el uso de la experimentación por parte de los gestores, y una amplia implementación de estrategias de manejo adaptativas. El continuo apoyo y desarrollo a las asociaciones científicas y de gestión y de grupos de aprendizaje entre colegas ayudará a formar nuestra respuesta a las transformaciones ecológicas rápidas que están ocurriendo.

Introduction

When disturbances overwhelm resilience mechanisms, vegetative communities change in composition, structure, and trajectory (Beisner et al. 2003; Millar and Stephenson 2015; Coop et al. 2020; Falk et al. 2022). If the new state is persistent and resilient to, or reinforced by, further disturbance, it can be considered a vegetative type conversion (VTC, Syphard et al. 2019; van Mantgem et al. 2020). Key drivers of VTC in the southwestern US are associated with climatic warming, land-use change, introductions of non-native species, and anthropogenically-altered fire regimes. Throughout semi-arid forests of the region, the widespread disruption of historical fire regimes in the late 19th century has led to increased stand densities (Covington and Moore 1994), increasingly large and severe fires (Miller et al. 2009; Singleton et al. 2019), and accelerating fire frequencies in shrub-dominated landscapes subject to high numbers of anthropogenic ignitions (Balch et al. 2017). Simultaneously, climate change facilitates VTC by producing "hotter droughts" that stress existing vegetation (Williams et al. 2013; Allen et al. 2015), increase fire severity (Mueller et al. 2020; Parks and Abatzoglou 2020), and limit the success of ecosystem re-establishment and recovery (Keeley 1991; Keeley et al. 2019; Stevens-Rumann and Morgan 2019; Davis et al. 2019). Novel drought effects are now emerging as a consequence of interactions between climate change, land-use change, and human-induced declines in water availability, particularly in arid environments with growing human populations (Crausbay et al. 2020). Acute moisture deficits are increasingly recognized as a driver of ecological transformation that may be irreversible (Crausbay et al. 2017; Batllori et al. 2020). As anthropogenic climate change continues to amplify these trends (Nolan et al. 2018; Williams et al. 2020), transitions to novel ecosystem types can be expected to become increasingly common.

Conifer-dominated, historically frequent-fire forests in the southwestern US are particularly vulnerable to VTC. Here, we focus on Arizona, California, Colorado, and New Mexico, but many events and trends we discuss are relevant elsewhere in western North America (Hessburg et al. 2019). Southwestern dry-conifer forests are defined as those dominated by ponderosa (*Pinus ponderosa*) or Jeffrey pine (*P. Jeffreyi*) and often include associated species such as Douglas-fir (*Pseudotsuga menziesii*), red fir (*Abies magnifica*), southwestern white pine (*P. strobiformis*), limber pine (*P. flexelis*), and white fir (*A. concolor*). Over the last century or more, these forests have undergone significant changes in structure and function, mainly due to the lack of recurrent fire activity (Allen et al. 2002; Hagmann et al. 2021). Throughout the region, loss of Native American burning practices, industrial logging, livestock grazing, and active fire suppression disrupted historical fire regimes (Swetnam et al. 2016). With climate warming, recent fires often include large areas of high-severity (stand-replacing) fire effects that can result in rapid post-fire transitions to hardwood-, shrub-, herb-, or grass-dominated ecosystems (Savage and Mast 2005; Airey Lauvaux et al. 2016; Tepley et al. 2017; Coop et al. 2020). Post-fire recovery depends largely on the extent of parent tree survival, understory composition, and local- to micro-scale temperature and soil moisture conditions. Recovery is most challenged in uncharacteristically large high-severity burn patches that include spatially extensive mortality of parent trees and potentially severe and long-lasting impacts to the soil (Shive et al. 2018; Safford and Vallejo 2019; Dove et al. 2020). In warm and semi-arid regions, higher elevation and north-facing localities within a species distribution tend to be more favorable for post-fire recovery (Collins and Roller 2013; Korb et al. 2019; Stevens-Rumann and Morgan 2019). Fire-catalyzed VTC may be most common at warm/dry ecotones or in areas experiencing drought events, where low moisture availability had already stressed or killed overstory trees prior to burning (Allen et al. 2015) and subsequently reduced post-fire regeneration rates (Rother and Veblen 2016; Young et al. 2019; Davis et al. 2019; Rodman et al. 2020). However, these same ecotonal forests are often resilient to recurrent low-severity fire, even with climate warming (Harris and Taylor 2020).

Recovery following stand-replacing disturbances in dry conifer forests can include successional pathways through aspen (*Populus tremuloides*), hardwood, or shrub-dominated stages, but current climatic and fire regime trends are enhancing the likelihood of permanent conversion and the spatial extent of hardwood and shrub dominance in many parts of the southwestern US. In portions of the Colorado Plateau and southern Rockies, ponderosa pine and mixed-conifer forests are converting to shrublands of Gambel oak (*Quercus gambelii*) and New Mexico locust (*Robinia neomexicana*) (Guiterman et al. 2015, 2018; Coop et al. 2016; Rodman et al. 2020). In the Sky Island ecosystems of southern Arizona and New Mexico, Madrean oak woodland species (e.g., *Q. arizonica* and *Q. hypoleucoides*) and *Ceanothus* shrubs are replacing conifers, even where a resprouting pine species (*P. leiophylla*) is common (Minor et al. 2017; Barton and Poulos 2018). In parts of southern Oregon and northern California, repeated high severity fires are helping to expand the colonization of knobcone pine (*Pinus attenuata*), a serotinous-cone species that is highly adapted to such a fire regime (Reilly et al. 2019). Elsewhere in California, severe fires typically induce a strong shrub response, often from *Ceanothus* or *Arctostaphylos* species, which compete intensively with conifer regeneration (Helms and Tappeiner 1996). Because they resprout, hardwoods—especially oaks—can benefit from conifer mortality, and their density has been generally increasing in California montane forests for decades due to interactions between forest disturbance and climate warming (Dolanc et al. 2014; McIntyre et al. 2015). Subsequent burning tends to reinforce hardwood and shrub response (Coppoletta et al. 2016; Haffey et al. 2018; Keyser et al. 2020), especially where other factors including sparsity of parent trees already inhibit conifer recovery. Reburning at low- to mixed-severity within decades of the initial high-severity fire may explain centuries-long persistence of shrublands in which fire was historically frequent (Iniguez et al. 2009; Guiterman et al. 2018; Roos and Guiterman 2021). As these examples illustrate, there is no intrinsic, single time scale that can be used to define when a type conversion has occurred without imposing an arbitrary standard. The distinction between transient and persistent reorganization depends more on the mechanisms at work, in particular, if the converted state is reinforced by altered climate or disturbance regimes (Falk et al. 2022).

The spread of non-native grasses and forbs (e.g., *Bromus* spp., *Avena* spp., *Erodium* spp.) due to interactions among land uses, climate, and changing fire regimes is generating substantial change in chaparral and sagebrush areas. These herbaceous species can support uncharacteristically frequent fire relative to historical intervals, resulting in positive feedback with fire that is driving extensive VTC (Balch et al. 2013; Syphard et al. 2019). The mechanism for woody decline and conversion is the relatively long period of recovery required to regenerate post-fire. Chaparral requires 10–15 years for recovery (Keeley et al. 2011; Keeley and Brennan 2012; Lippitt et al. 2013), while sagebrush may require several decades under favorable conditions (Shriver et al. 2018). These lapse periods are outpaced by the spread of non-native species such as cheatgrass (*B. tectorum*) that invade under and throughout shrub ecosystems, increase flammability, and set the stage for post-fire community reorganization (D'Antonio and Vitousek 1992).

Prevention of VTC is emphasized in forest and shrubland management in the southwestern US through measures that promote species or community resistance or recovery (e.g., Franklin et al. 2018). Current intervention strategies that include fuel reduction and repeated low-severity fire have a strong scientific foundation (Allen et al. 2002; Prichard et al. 2021) and are effective (Stoddard et al. 2021). These strategies often accord with the cultural burning activities of many Indigenous groups across the southwestern US (Kimmerer and Lake 2001; Roos et al. 2021), and, where they are conducted in diverse collaborations with tribes and other stakeholders, can have benefits to social systems that extend beyond ecosystem resilience (Lake et al. 2017).

Management after extensive high-severity fires is more challenging than prevention because we simply have not obtained adequate knowledge or experience. Research on VTC is relatively new, and we have yet to capture the scale of the phenomenon in space and time, including how many areas are undergoing VTC and how many areas might not experience VTC despite major post-fire changes. Studies on both natural and managed recovery following fires have yet to answer how future climate and disturbances interact with treatments to either promote recovery or reorganization.

To better understand the challenge of managing ongoing VTC, we held two multi-day workshops in 2019 that brought together managers, scientists, and practitioners to discuss their observations of, perspectives on, and experiences with VTC events (Gregg and Marshall 2020a, 2020b). Participants voiced a need for greater clarity on the regional extent of VTC and responses to it, felt that focusing on their own management units (though many are quite extensive) limited their understanding of others' experiences with similar challenges, and found limited resources in the scientific literature to help answer questions. In this paper, we address these concerns by presenting the firsthand experiences of the workshop participants through a series of 11 case studies and a summary of 61 VTC examples (Fig. 1). During the workshops and throughout this paper, we categorized management responses to VTC as (i) *Reverse change*: restore pre-fire conditions or manage recovery such that the affected ecosystem is brought to a recognizable (perhaps pre-fire exclusion) and ideally more resilient composition and structure; (ii) *Observe change*: exercise patience and monitor the system and its post-disturbance trajectory; and (iii) *Facilitate change*: push the system along a new, potentially novel, trajectory (Table 1). We recognize that these responses generally align with the resist-accept-direct (RAD) framework (Schuurman et al. 2020) and chose to maintain our classifications because many of the VTC examples lack a specific management response, which may or may not constitute intentional selection of "accept" as the desired future condition. Below, we summarize the VTC case studies and the individual examples, then synthesize these in the context of pressing management challenges and opportunities. The full case study descriptions and details regarding our approach are provided in the online Supplemental Information that accompanies this article.

Case studies

Participant-provided case studies of VTC demonstrate the profound complexity of ecological reorganization in the region. For example, the conversion of forests by high-severity wildfire illustrates that history and land-use changes are important. In each case, processes that led to VTC started a century or more earlier with the disruption of historical fire regimes and associated changes to composition and structure. This slow but profound change set the stage for multiple disturbance agents often acting in conjunction to fundamentally shift the ecosystem type or its dominant species. Management responses have been similarly diverse, reflecting individual situations, constraints, and goals. We note that in several case studies, more than one category of management response is described, representing the evolving nature of VTC management and its trial-and-error approach.

Reversing change

One possible management response to VTC is to actively attempt to reverse changes. Such responses are highlighted by recovery efforts on the *Klamath Reservation in southern Oregon* (case study #1) where long-term fire exclusion allowed tree encroachment into important

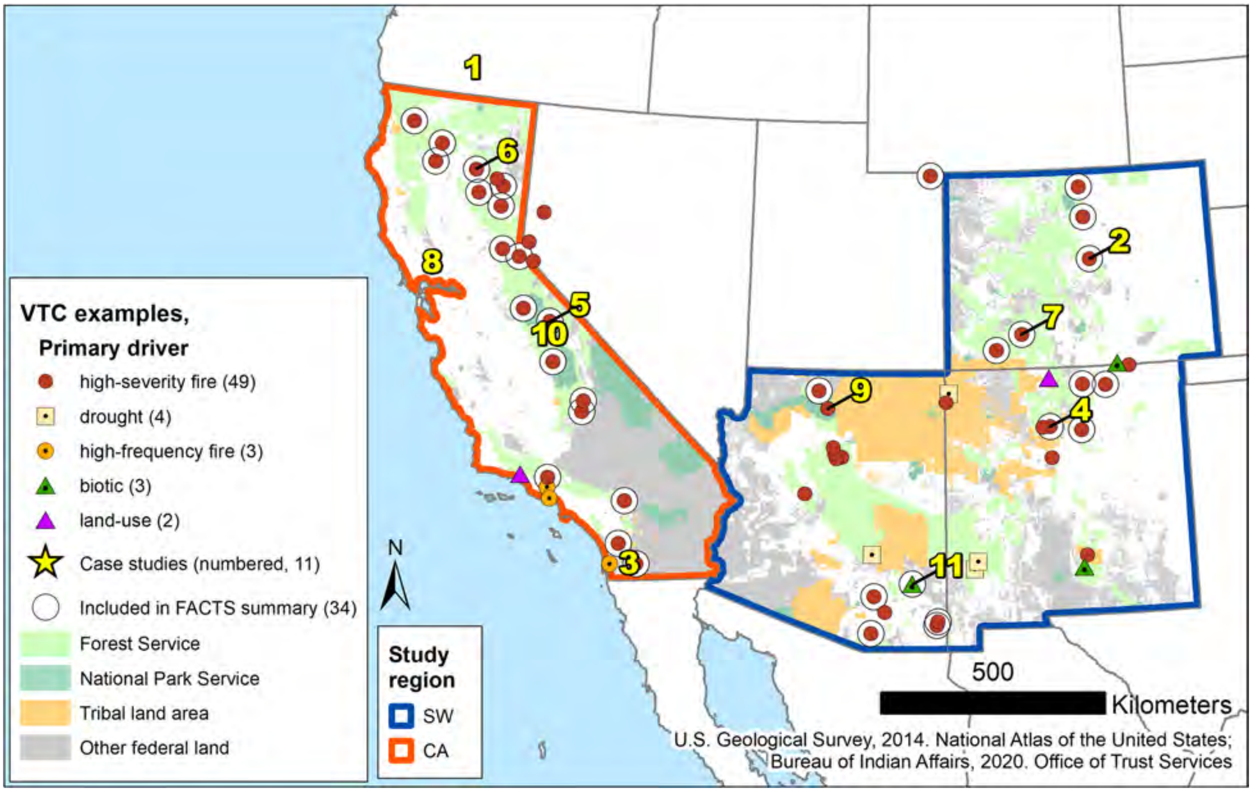

Fig. 1 Observations of vegetation type conversions (VTCs) and their primary drivers. Workshops focused on two subregions, California (CA) and three southwestern states (SW). Case study numbers refer to the individual descriptions provided in the online Supplemental Information

Table 1 Descriptions of management responses to VTC from workshop participants along with case study examples

Management response	Description	Case study examples
Reverse change	Actively try to reverse change via: • Coupled thinning and prescribed fire treatments to reduce fuel loads and fire severity and promote fire-dependent species and ecosystem recovery (Stephens et al. 2009) • Planting or seeding pre-VTC species • Removing or managing new or undesirable species (e.g., non-native grasses and shrubs that may increase fire frequency and/or severity) • Fire suppression to reduce fire extent and allow for recovery time • Preventing post-disturbance soil loss to sustain ecological functions	1. Klamath Reservation, southern Oregon 2. Southern Front Range, Colorado 3. Laguna Mountain, California
Observe change	Take no active intervention measures and adopt monitoring to assess ecosystem trajectory over time. This approach may be most appropriate where there is: • Limited management capacity (e.g., high upfront and maintenance costs of active intervention, limitations to access in sites such as those in wilderness or roadless lands) (Rother et al. 2015; Aplet and Mckinley 2017) • High uncertainty of unintended consequences of active intervention (e.g., one workshop participant noted that "sometimes doing something is worse than doing nothing") (Landres 2010). This approach is consistent with restoration paradigms emphasizing a spectrum of approaches to spread risk (Aplet and Mckinley 2017).	4. Eastern Jemez Mountains, New Mexico 5. Devils Postpile National Monument, California 6. Lassen Volcanic National Park, California 7. San Juan Mountains, Colorado 8. Inner Coast Range, northern California
Facilitate change	Actively direct system toward alternative and/or novel acceptable conditions by: • Planting or seeding with focus on more drought- and fire-tolerant species compared to pre-disturbance species (e.g., assisted gene flow; Young et al. 2020) • Follow-up wildfires with ecologically-credible fuel reduction activities	9. North Rim of the Grand Canyon, Arizona 10. Southern Sierra Nevada, California 11. Pinaleño Mountains, Arizona

wetland and moist forest areas, altering the hydrology of the ecosystem and triggering the loss of culturally-important plants and environments. Tribal forest managers are working to restore forest structure and composition, improve wetland habitats, and recover the historical forest resilience and ecosystem services of the area. These efforts will hopefully stave off the kind of high-severity fires that are affecting areas of the *southern Front Range in Colorado* (#2). There, managers are achieving relatively high survival of planted ponderosa pine and Douglas-fir seedlings in the footprint of the 2002 Hayman Fire, despite years of drought since the planting operations (Fig. 2A). The success to date is credited to early spring planting operations targeted to the most productive sites, often at higher elevations and on northerly slopes, and using coarse-woody debris or other objects for additional shade. On *Laguna Mountain in southern California* (#3), however, a series of droughts, fires, and bark beetles have slowed or stopped post-fire recovery efforts in Jeffrey pine forests (Fig. 2B). Years of drought following the 2003 Cedar Fire prevented any tree recruitment and all planting operations failed. As managers were accepting the conversion to shrubland and herbland with scattered black oak (*Q. kelloggii*) and Coulter pine (*P. coulteri*), the newly established non-native goldspotted oak borer (*Agrilus auroguttatus*) decimated mature oaks (Safford and Vallejo 2019).

Observing change

The complexity of compounding disturbances including fire, insects, and climate warming can incapacitate recovery efforts. In many cases, observing changes is necessary to gauge ecological trajectories, decide whether and how far outside of the natural range of variation the system has moved (Jackson 2012), and plan future management actions. In the *eastern Jemez Mountains of New Mexico* (#4), a series of high-severity fires culminating in the 2011 Las Conchas Fire left tens of thousands of hectares depleted of living conifers (Fig. 3A). Nearly 10 years post-fire, a coalition of stakeholders emerged with diverse plans to employ a variety of actions across the RAD framework based on variability in post-fire environments, community needs, tribal resources, and the risks of floods and debris flows originating from the burned area. Managers at the *Devils Postpile National Monument in California* (#5) found an array of post-fire trajectories in the decades following a mixed-severity fire. The prefire forest was recovering in lower-severity burn areas, but extensive shrublands were developing following complete overstory mortality in high-severity patches. Similar findings come from *Lassen Volcanic National Park in California* (#6) where mixed-conifer forests were widely transformed into shrublands, except where earlier prescribed fires reduced the intensity and severity of wildfire. In lodgepole pine (*P. contorta*) forests, low to moderate fire severity in 1984 generated legacy effects in a 2012 fire in which recent post-fire regeneration is abundant everywhere except for areas twice-burned at high-severity. The trajectory of these un-regenerated lodgepole pine forests is uncertain in light of warming temperatures, and may not return to pre-fire conditions. The same is true for subalpine forests in the *San Juan Mountains of southern Colorado* (#7) where a severe bark beetle outbreak and subsequent high-severity fire resulted in high aspen

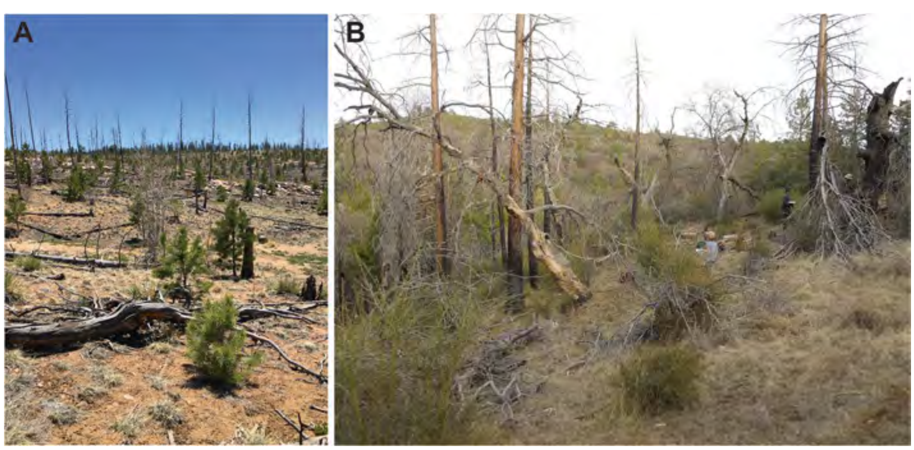

Fig. 2 Examples of reversing change. **A** The distribution of coarse woody debris around planted ponderosa pine seedlings following the 2002 Hayman Fire in Colorado is credited with helping to mitigate drought effects on the developing seedlings (credit: Paula Fornwalt). **B** Forest Service staff inventory stand conditions in a former Jeffrey pine-black oak forest on Laguna Mountain, Cleveland National Forest, eastern San Diego County, California (**B**). This site was impacted by multiyear drought, then severe wildfire, then drought again, Jeffrey pine beetle mortality, and most recently by an oak borer outbreak (credit: Hugh Safford)

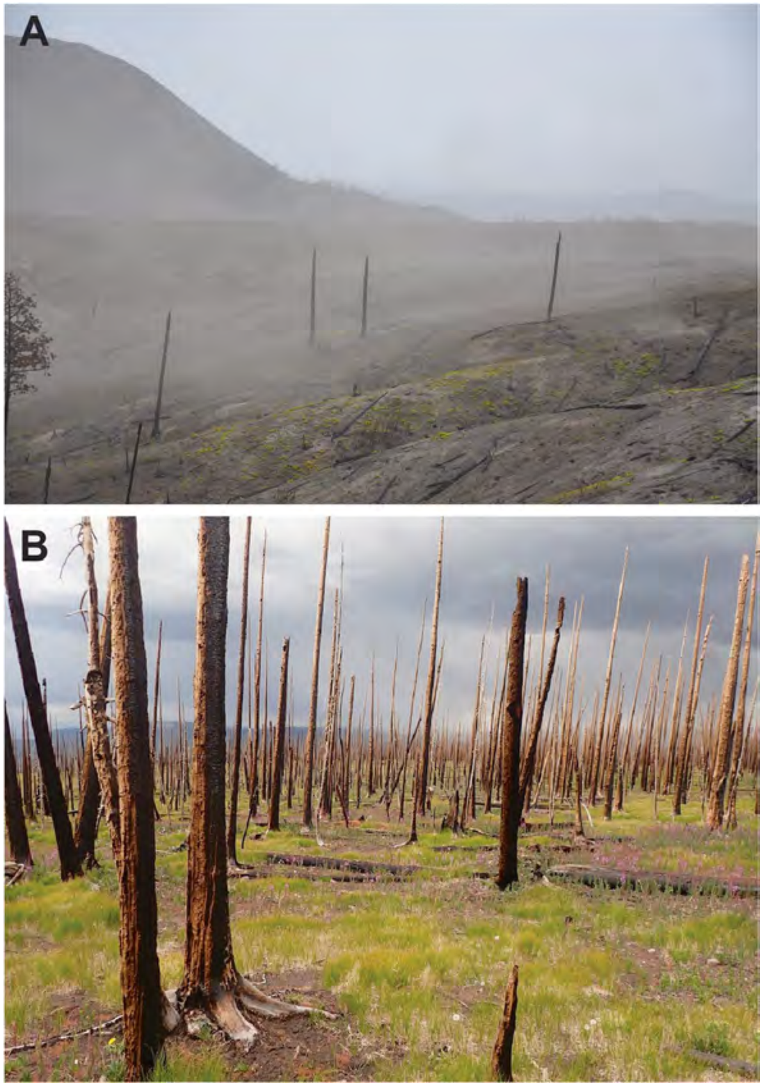

Fig. 3 Examples of observing change. **A** Light wind mobilizes ash and dried soil in a high-severity burn patch of the 2011 Las Conchas Fire, where it reburned an earlier high-severity patch. This photo was taken on April 26, 2012, nearly 1 year after the fire when only some herbaceous plants were growing (credit: Chris Guiterman). **B** Former Engelmann spruce-dominated forest impacted by spruce beetle and fire within the 2013 West Fork Complex Burn, Colorado. Matchstick-like snags are indicative that the trees were killed by beetles prior to the fire (credit: Jonathan Coop)

reproduction in some areas and a variety of herbaceous vegetation in others (Fig. 3B). That these VTC events occur in designated wilderness areas can limit management including fire suppression, prescribed fire, and tree planting. In one of the largest wildland-urban interface regions of the United States, the *Inner Coast Range of California* (#8), VTC has only recently emerged following the disruption of historical fire regimes and associated reduction in the spatial diversity of the grassland-woodland-forest mosaic. The devastating "wine country" wildfires in 2017 marked the return of fire to this coupled human-natural ecosystem. Some areas have now experienced four fires in the last 5 years. Beyond losses to human life and property, the entire ecological mosaic has been affected, with major loss of chaparral communities, fundamentally changing the landscape to non-native grasslands and leaving human infrastructure vulnerable to flooding and debris flows.

Facilitating change

Facilitation of VTC is the least common management response documented in our study, though ideas of when, where, and how to direct changes are becoming clearer (Millar and Stephenson 2015). The facilitation case studies we present include management actions that direct change knowingly but perhaps without the explicit intention of promoting type change. In the case of the *North Rim of the Grand Canyon in Arizona* (#9), fire managers successfully reintroduced fire in ponderosa pine forests following many decades of fire exclusion. However, with more recurrent fire activity, they noted higher-than-expected conifer mortality in surface fires, which is benefiting Gambel oak and slowly converting the forests to shrubby woodlands (Fig. 4A). Some of the small shrubland patches that are established in high-severity burn areas are expanding as large, downed fire-killed trees burn in subsequent fires with enough intensity to expand the shrubland gaps, sometimes merging into large patches. Frequent fire may be more in line with projected climate conditions but also threatens large, old trees. The management goal to maintain fire as an ecological process (https://www.nps.gov/grca/learn/management/upload/grca_fmp.pdf) is promoting this ecological transition. In the *southern Sierra Nevada of California* (#10), a decade of drought and recurrent fires is rapidly removing conifers from commercial forest areas where thinning has reduced relative mortality but progressed the transition from conifer-dominated forests to oak- and hardwood-dominated woodlands (Fig. 4B). Now, unthinned areas are vulnerable to fire due to their composition of dense fire-intolerant tree species and heavy loading of drought-killed trees, but thinned stands dominated by oak trees are vulnerable to the advance of goldspotted oak borers. Finding a balance between these options is challenging, so managers are utilizing new decision support tools to guide post-fire recovery efforts and the facilitation of VTC in some areas to be used as fuel breaks in generating a landscape mosaic. Along the

Fig. 4 Examples of facilitating change. **A** Tree mortality of ponderosa pines following two high-severity fire events on the North Rim of the Grand Canyon, AZ. This expanding gap is now dominated by forbs and New Mexico locust with no pine regeneration (credit: Chris Marks). **B** Tree mortality following a multi-year drought in a pre-drought thinned ponderosa pine and black oak stand on the Sierra National Forest, southern Sierra Nevada, California. The foreground illustrates the current open stand conditions dominated by black oak and canyon live oak with an understory of mountain misery (*Chamaebatia foliolosa*) following the cutting and piling of dead conifers (mostly ponderosa pine and sugar pine). The background shows post-drought stand conditions prior to conifer removal (credit: Marc Meyer)

high summit of *Pinaleño Mountains in Arizona* (#11) spruce-fir (*Picea engelmannii* and *Abies lasiocarpa* var. *arizonica*) forests are critical habitat for the endangered Mount Graham red squirrel (*Tamiasciurus fremonti grahamensis*) (USFWS 2011) but were decimated by two fires in 2004 and 2016 (Merrick et al. 2021). Managers recognize that re-planting a spruce-fir forest will neither rapidly re-establish habitat nor be resilient and productive given the changing climate. They have therefore opted to plant a native, but more drought- and insect-resilient, mix of conifer species (including spruce and fir) that could, once mature, potentially aid in the return of the spruce-fir type. The key idea here is to help push the system in a trajectory of conifer forest, rather than shrub or grassland conditions.

VTC examples

In order to capture the regional scope and diversity of VTC, workshop participants identified sites undergoing VTC on printed maps that we later geolocated in a geographic information system. Each workshop had a subregional focus (Fig. 1). The workshop in Tucson, AZ (March 2019) focused mainly on Arizona, New Mexico, and Colorado (Southwest (SW) study region). The workshop in Sacramento, CA (December 2019) focused on California and adjacent environments (CA study region). For each location they marked, participants described their observations on paper forms that included the (1) location of the VTC, (2) land ownership of the area, (3) ecosystem types before and after the VTC, (4) year of any precipitating event(s), (5) driving mechanism(s) of change, (6) species of interest in the area, and (7) management actions, if any, taken to address the VTC. We emphasize that these examples of VTC represent the site-specific knowledge and expert opinion of scientists and practitioners who attended the workshops and are not an attempt to identify or quantify the true extent of regional VTC. The examples were summarized in the context of two large-scale spatially explicit data sets, Monitoring Trends in Burn Severity (MTBS, Eidenshink et al. 2007) and the US Forest Service Activity Tracking System (FACTS) (https://data.fs.usda.gov/geodata/edw/datasets.php), to describe broad patterns in the VTC observations (see online supplemental information for details).

Workshop participants provided 61 examples of VTC across six southwestern US states (Fig. 1), with 26 in the CA study area and 35 in the SW (each example is provided in the online Supplemental Table). The vast majority (80%) of these examples related to high-severity fire (Fig. 5A). Drought, biotic agents, high-frequency fire, and land use each account for <10% of the identified VTC drivers. Some examples represent changes across vast areas that could not be accurately portrayed by our approach. For example, within the land-use category, only a single record in southern CA describes widespread fuel breaks in which repeated disturbances including bulldozing, prescribed fire, herbicide applications, and mastication of vegetation have converted chaparral within the fire lines to herbaceous dominance, predominantly non-native grasses. Although these actions were intentional, they were not necessarily intended for the establishment of non-native vegetation.

Trajectories of VTC underscore the commonality of forest-to-shrubland transitions (Fig. 5B). In total, 59% of the examples include conversion to shrubland. In the SW, both ponderosa pine and dry mixed-conifer forests (which often include ponderosa pine, Romme et al. 2009), are seen to almost always transition to shrublands. In CA, 54% of the examples include the shrubland trajectory, predominantly resulting from fire-driven conversions of mixed-conifer and Jeffrey pine forests. Grasslands dominated by mostly native herbaceous vegetation are the next most common post-VTC type, with non-native grass making up 15% of the examples, all of which were reported in CA. This latter group includes a variety of pre-VTC vegetation communities such as chaparral, Jeffrey pine forest, and sagebrush.

Reversing change was the most common management response to VTC (Fig. 5C). The second most common response was either no management (often written as "none") or was not provided. If we could not supplement the participant's entry with information from FACTS, we report what the participants provided, leaving 13 examples in which a management action was not provided. There were three examples that included observing change, and one example (the fuel breaks described above) of facilitate change. These examples show that interventions to reverse change were more common in CA than in the SW, and by contrast, observing change was more common in the SW than in CA. These subregional differences were notable in our analysis of the FACTS data (Fig. 6), in which we explored 34 examples of VTC that were within patches of high-severity fire, as recorded in MTBS. We identified 55 high-severity burn areas over the 34 individual sites, suggesting that repeated high-severity fire may have been a factor in some examples of VTC. FACTS data show that in CA, most post-fire management interventions occur within 5 years of the fire and aim to reverse change (commercial tree removal, fuel reduction, and tree establishment). Little observation of change was recorded for CA, and none occurred after 5 years, whereas in the SW, observation was more common than tree removal or fuel reduction, and could last as long as 20 years post-fire. The rate of tree establishment dwindled in CA after 15 years post-fire, while it only increased in the SW through 20 years

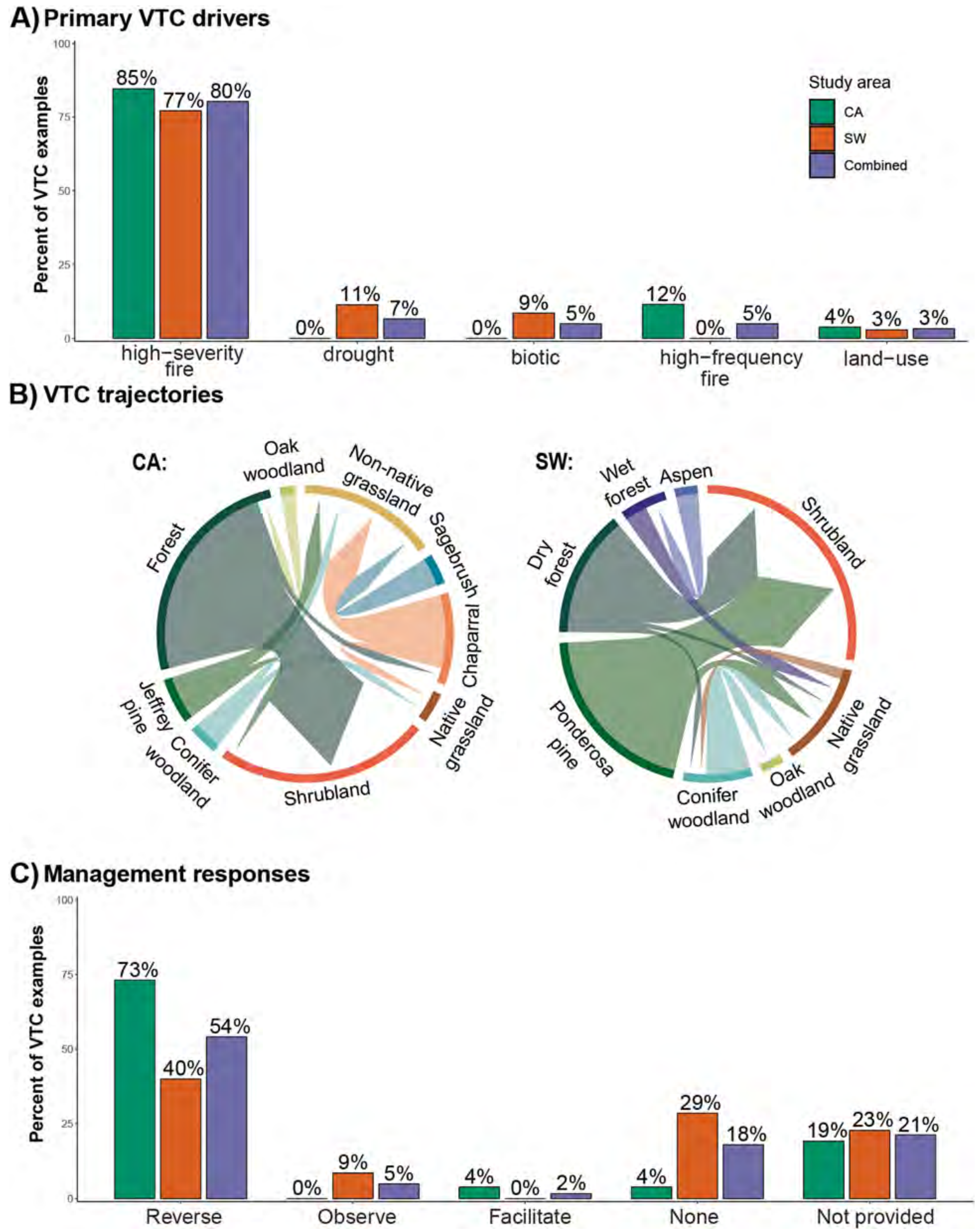

Fig. 5 Summary of 61 participant-provided VTC examples across the southwestern US. **A** Drivers, **B** trajectories, and **C** management responses. Legend colors are shared between the **A** and **C** panels. In **B**, broad arrows are unidirectional, and do not imply further transitions beyond a single workshop example. The "forest" classification in each region was usually provided as "mixed-conifer forest," with the difference between "wet" and "dry" in the SW pertaining to whether or not the sites were occupied by ponderosa pine (sensu Romme et al. 2009)

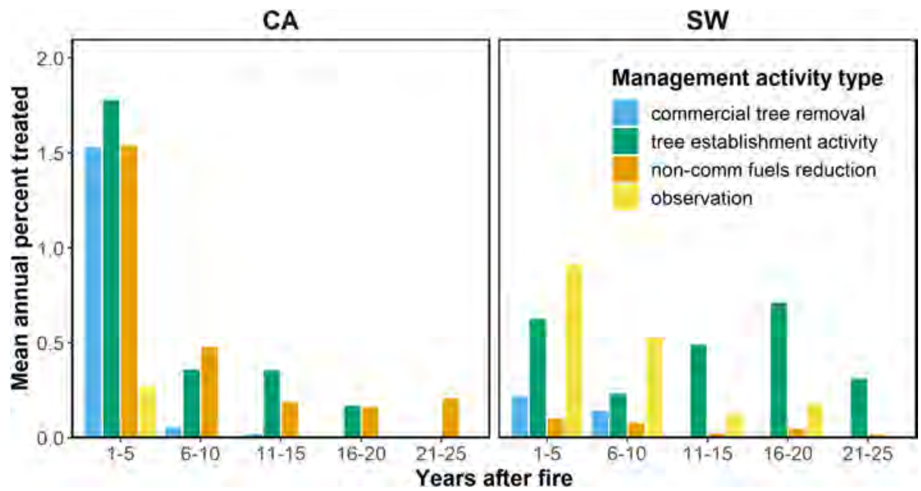

Fig. 6 US Forest Service Activity Tracking System management activity units completed by activity type within high-severity portions of named fires in CA and the SW

post-fire. Across all of these management responses, however, the spatial coverage of treatments recorded in FACTS shows that less than 25% of individual high-severity burn areas saw any treatment.

Synthesis

Across the breadth of ecosystems represented in our case studies and VTC examples, we found that forests typically convert to shrubland, and chaparral or sagebrush communities convert to herblands, often dominated by non-native grasses. The post-fire types represent transitions to vegetative states that are shorter in height, better adapted to disturbance and drought, and, as more areas are affected, reduce landscape-scale diversity in ecological structure. Our findings emphasize that altered fire regime characteristics, including frequency and severity, are likely to generate novel transitions. In general, these processes increase overstory mortality among trees and chaparral, which is the key trigger of a state transition, especially in larger patches (Chambers et al. 2016; Falk et al. 2022). Other mortality agents, such as insect outbreaks, often in combination with fire, further promote transitions. Recovery to the initial state is likely to be inhibited by a hotter and drier climate (Davis et al. 2019; Stewart et al. 2020). When all of these factors align, as they have in recent decades across most of the Southwest, VTC is the likely outcome.

Once converted, new vegetative states are highly persistent. This underscores the need for management to consider undertaking preventive strategies that capitalize on the persistence mechanisms of intact vegetative types (Falk et al. 2022), if these are the desired long-term communities (see Matonis and Binkley 2018). Effective prevention strategies often include fuel reduction and re-introduction of recurrent low-severity fire (Stoddard et al. 2021), which can be accomplished in diverse partnerships that promote important ecocultural products and values along with a suite of ecosystem services (Hessburg et al. 2021; case study #1). Treatments are ideally conducted at landscape scales, but smaller, targeted actions can be undertaken to promote refugia areas following future wildfires that would help recovery efforts by providing seed sources (Krawchuk et al. 2020).

While some prevention strategies are effective, they do not address all concerns regarding VTC. Participants in our workshops are frontline observers to ecological changes rarely witnessed until recent decades. As the case study descriptions echo, there is a palpable sense of futility when confronting the scale and uncertain ecological trajectories of VTC. Indeed, in many cases, little can be done to reverse changes wrought by multiple compounding disturbances and long-term drivers. The rapid and stubborn spread of non-native species further frustrates recovery and intervention strategies. This emphasizes the importance of management frameworks that have an option to accept rapid and profound change (Lynch et al. 2021) and calls on increasing research to evaluate a variety of approaches (Crausbay et al. 2021).

Reversing change is often resource intensive. To expand recovery efforts and maximize often limited resources, it may be critical for managers to prioritize particular sites. Recovery via planting conifers has received mixed success (Ouzts et al. 2015; case studies #2, 3, 11), and thus more focus is currently being placed on targeted planting operations that have the highest potential for survival through drought and subsequent fire (Dumroese et al. 2016; North et al. 2019). Recovery efforts will have to rely on appropriate seed sources and planting stock, but the necessary infrastructure has declined in recent decades (Fargione et al. 2021), as has the availability of appropriate species. Opting to plant more drought-tolerant or more commercially-desired species could represent a choice to facilitate change rather than resist it (case study #3). Federal support and local efforts are needed to re-establish nursery production capacity, and doing so could present an opportunity to invest in underrepresented groups such as Native American communities and tribal forestry programs that have the capacity but may lack market demand to re-establish their nurseries. Open Source tools are also emerging that help to identify potential seed sources for planting operations (e.g., https://seedlotselectiontool.org/sst/, https://climaterestorationtool.org/csrt/) as well as where natural regeneration after disturbance may be insufficient (https://code.usgs.gov/werc/redwood_field_station/poscrptr) and when and where planting operations may be most efficacious (e.g., https://reforestation.shinyapps.io/preset/).

The option of observing change may be determined by a desire to "wait and see," a lack of the resources needed to take more deliberate intervention measures to reverse change or by constraints in land designations, such as in wilderness areas. Uncertainties regarding unintended consequences of active intervention (e.g., moving towards "undesired" conditions, "sometimes doing something is worse than doing nothing") may also delay or prevent other actions. Allowing managers time to observe change is a valid approach to informed adaptive management (Sagarin and Pauchard 2010; Halofsky et al. 2018; Chazdon et al. 2021), especially given highly variable seasonal climates of recent years. Observing an ecosystem's trajectory and understanding the dynamics of the developing community will help managers gain a general sense of the probability of type conversion, and whether the site risks invasion by problematic non-native species. However, institutional constraints may limit the ability to experiment with different approaches, particularly with wildfire management (e.g., Abrams et al. 2021). For example, most agency mandates and funding streams are directed toward fire suppression rather than prevention or recovery, leading to a mismatch between policy directives and ecological needs in some cases. In other cases, the number of agency staff available to support fire prevention or recovery may be limited by budgetary constraints.

Choosing to facilitate or direct change depends on agency mandates, site objectives, individual managers' risk tolerance, and values. While examples of and research on intentional on-the-ground facilitation of VTC are generally lacking to date, more flexibility in management directives would allow for opportunities to better understand the dynamics of novel systems (Millar and Stephenson 2015). Findings from other efforts to facilitate change (e.g., assisted gene flow, assisted range expansion), while not specific to fire-driven VTC, may be useful for inspiration and lessons learned (McLane and Aitken 2012; McPherson et al. 2017; Richardson and Chaney 2018; Crotteau et al. 2019).

Trepidation in confronting the scale of VTC stems in part from the uncertainty of its trajectory given slow and variable recovery processes. Insights from Indigenous knowledge can aid in understanding the degree of a possible departure from historical ranges of variability, whether changes are undesirable from an ecocultural perspective, and options for management that proved effective in the past (Lake et al. 2017). Paleoecological and historical studies are helpful in gauging the long-term dynamics and persistence of various ecological communities (Jackson 2012). Our understanding of the mechanisms and drivers of VTC is improving apace, with critical reviews on resilience and its properties (Falk et al. 2019; Syphard et al. 2019; Coop et al. 2020; Falk et al. 2022) that provide a basis for comparison among events, and a focused language by which managers can compare events and areas (Stevens et al. 2021). Efforts are also underway to estimate landscape resilience or lack thereof, and thus the probability of VTC ahead of disturbance (Walker et al. 2018; Marshall and Falk 2020).

As management paradigms shift to accommodate impending change (e.g., Truitt et al. 2015; Schuurman et al. 2020), decisions around whether and how to accept or direct change will require new datasets and detailed models of plausible future ecological scenarios. Defining "desired conditions" may necessitate new models of collaboration that deeply engage stakeholders including local communities, tribes, and the broader public to better incorporate social and economic considerations in ecological management discussions. Manager-scientist collaborations such as the Fire Science Exchange Networks (https://www.firescience.gov/JFSP_exchanges.cfm) provide opportunities for workshops and field gatherings, peer-to-peer efforts such as the Burned Area Learning Network (https://www.conservationgateway.org/ConservationPractices/FireLandscapes/FireLearningNetwork/RegionalNetworks/Pages/BALN.aspx), and regional and place-based nongovernmental group initiatives help to promote awareness and readiness for VTC events. These efforts are changing the perceptions of managers, scientists, and the public, helping to incorporate VTC into the planning and decision making of agencies and land managers as they strive for "desired conditions" in a changing climate. Developing and assessing the capacity for management to achieve these conditions will require abundant experimentation within a co-production framework and social license for less-than-certain success.

Opening the door to accepting and directing VTC has potentially far-reaching and long-lasting implications for species, ecosystems, and society. Managing for change represents a potentially dramatic departure from traditional land management philosophy, especially in areas designated as natural areas or wilderness. Engaging with VTC may require more intensive intervention in ecosystem processes in many cases, but foundational principles for how to do this do not exist as yet. New and shared ethical frameworks drawing on science, Indigenous knowledge, and social consensus will be needed to guide this transition.

Future directions

VTC is among the most pressing issues for ecosystem management in the southwestern United States. Although the phenomenon eludes a simple definition (van Mantgem et al. 2020), land managers "know it when they see it," and there is a strong sense of alarm at what they have been witnessing in recent years. The experiences and stories captured in 11 case studies presented here underscore that VTC is occurring at broad spatial and temporal scales (e.g., large patches to regional ecological ranges, from decadal land-use changes to rapid post-fire transitions) across most southwestern forest and woodland types to grasslands, shrublands, and chaparral. The rising sentiment among many managers appears to be that VTC at some scales and across many sites is a foregone conclusion following many high-severity fires in the study region. As VTC areas grow larger and more common, managers will increasingly need to shift their focus from persistence measures to recovery efforts in type-converted areas (Falk 2016). And as our collective understanding of VTC drivers, trajectories, and persistence mechanisms grow, options for its management will expand. Some may prove to be ineffective, such as traditional plantation layouts in large patches far from parent trees, while others may emerge that provide multiple benefits but might be considered acceptance or facilitation of VTC by current standards. More systematic collection and analyses of observations and on-the-ground experiences will be important to provide clarity and direction for research efforts that will help guide management. Land managers, practitioners, and scientists share many of the same trepidations regarding VTC, and the pace at which land management agencies are adapting to current conditions, but may also find strength in the collective experience and freedom to discuss experiences. Future adaptive management of VTC-prone areas and areas that are undergoing VTC depends on co-production and collaboration among managers, scientists, and stakeholders, particularly as we contend with rapid environmental changes.

Abbreviations

VTC: Vegetative type conversion; RAD: Resist-adapt-direct management framework; SW: Southwestern US study area, encompassing Arizona, Colorado, and New Mexico; CA: California and adjacent ecosystems study area; MTBS: Monitoring Trends in Burn Severity data set; FACTS: US Forest Service Activity Tracking System.

Supplementary Information

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Additional file 1. Supplemental text describing 11 case studies and methods used to evaluate the VTC examples.

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Authors' contributions

PvM, RMG, JEK, and DAF acquired funding. CHG, DAF, PvM, RMG, and LAEM designed the study. CHG, JJB, RMG, and LAEM carried out the research. CHG, DAF, PvM, JEK, JJB, and RMG interpreted the findings and wrote the initial draft. CHG, ACC, JDC, PJF, CH, RKH, AML, CM, MDM, HS, and AHT wrote the case studies. All authors validated the findings, contributed to revisions, and read and approved the manuscript.

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Availability of data and materials

All data used in this manuscript was derived from publicly available sources. Materials consisting of observations from the workshops are provided in SI Table 1.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Consent for publication not applicable as we did not use data from individual people.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ARTICLE

ECOLOGICAL APPLICATIONS
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Fire-driven vegetation type conversion in Southern California

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Abstract

One consequence of global change causing widespread concern is the possibility of ecosystem conversions from one type to another. A classic example of this is vegetation type conversion (VTC) from native woody shrublands to invasive annual grasslands in the biodiversity hotspot of Southern California. Although the significance of this problem is well recognized, understanding where, how much, and why this change is occurring remains elusive owing to differences in results from studies conducted using different methods, spatial extents, and scales. Disagreement has arisen particularly over the relative importance of short-interval fires in driving these changes. Chronosequence approaches that use space for time to estimate changes have produced different results than studies of changes at a site over time. Here we calculated the percentage woody and herbaceous cover across Southern California using air photos from ~1950 to 2019. We assessed the extent of woody cover change and the relative importance of fire history, topography, soil moisture, and distance to human infrastructure in explaining change across a hierarchy of spatial extents and regions. We found substantial net decline in woody cover and expansion of herbaceous vegetation across all regions, but the most dramatic changes occurred in the northern interior and southern coastal areas. Variables related to frequent, short-interval fire were consistently top ranked as the explanation for shrub to grassland type conversion, but low soil moisture and topographic complexity were also strong correlates. Despite the consistent importance of fire, there was substantial geographical variation in the relative importance of drivers, and these differences resulted in different mapped predictions of VTC. This geographical variation is important to recognize for management decision-making and, in addition to differences in methodological design, may also partly explain differences in previous study results. The overwhelming importance of short-interval fire has management implications. It suggests that actions should be directed away from imposing fires to preventing fires. Prevention can be controlled through management actions that limit ignitions, fire spread, and the damage sustained in areas that do burn. This study also demonstrates significant potential for changing fire regimes to drive large-scale, abrupt ecological change.

KEYWORDS
aerial photograph, annual grass, chaparral, drought, fire regime, grass-fire cycle invasive species, human development, predictive mapping, VTC, wildfire

INTRODUCTION

Rapid global change, such as shifts in fire regimes, has the potential to greatly disrupt ecological functioning and cause dramatic transformations. For example, once-dominant vegetation types may transition to different types and lead to cascading ecological impacts. A classic example of this is vegetation type conversion (VTC) from native woody shrublands to invasive annual grasslands in Southern California, one of the five Mediterranean-climate ecosystems in the world (Underwood, Franklin, et al., 2018). Chaparral shrublands provide a wide range of ecosystem services, and their support of exceptional species richness in one of the world's biodiversity hotspots makes their decline an issue of global significance (Rundel, 2018; Underwood, Hollander, et al., 2018).

The vulnerability of chaparral to high fire frequency—specifically, short fire return intervals—has been recognized in the literature and observed in field studies for many decades (e.g., Cooper, 1922; Haidinger & Keeley, 1993; Jacobsen et al., 2004; Keeley & Brennan, 2012; Zedler et al., 1983). However, the role of short-interval fire in driving type conversion has also been questioned in some studies (Meng et al., 2014; Storey et al., 2021). Once chaparral has been replaced with invasive grass, its recovery becomes unlikely, at least on human time scales (Anderson & Keeley, 2018; Zedler, 1995). Thus, better understanding of the rate, drivers, and potential locations of vulnerability is critical for identifying the most efficient and effective ways to prevent further decline.

Until recent years, empirical documentation on landscape scales of where and to what extent chaparral is being locally extirpated and replaced with herbaceous vegetation has been lacking. The few landscape-scale studies that have been conducted have only covered parts of chaparral's range in Southern California and have used different methodologies (e.g., Lippitt et al., 2012; Lucero et al., 2021; Meng et al., 2014; Storey et al., 2021; Syphard, Brennan, & Keeley, 2019a & b). Complicating our understanding is that these studies have found variation in the relative importance of factors most strongly correlated with woody chaparral decline and conversion to grass, particularly the role of short-interval fire.

For example, Meng et al. (2014) found a weak association between fire history and a remotely sensed index of vegetation cover. More recently, Storey et al. (2021) also reported that little evidence existed on the role of short-interval fire in effecting VTC, concluding that earlier studies demonstrating VTC were not typical of what was occurring over broad portions of the landscape. Lucero et al. (2021) found dynamic but generally weak evidence for the effect of a single, short interval between two successive fires on VTC, but they acknowledged the potential for spatial and temporal variation. On the other hand, landscape-scale studies by Lippitt et al. (2012), Syphard, Brennan, and Keeley (2019a & b) demonstrated that short-interval fire was an important factor separating sites of woody decline and VTC from those that did not change. Several factors likely play a role in accounting for the different conclusions about the role of short-interval fires in producing VTC. These studies examined different chaparral associations, and it is clear from field studies that shrub species are markedly different in terms of resilience to short-interval fires (Keeley et al., 2008; Schumann et al., 2020). The only VTC studies where species composition was considered was in the aforementioned field studies that followed species changes before and after short-interval fires.

An equally important factor are the different methodologies in landscape-scale VTC studies. Landscape studies that have implicated fire interval in explaining VTC were time-series studies of vegetation changes following a sequence of fires on a particular site; Lippitt et al. (2012) used field observations and Syphard, Brennan, and Keeley (2019a & b) used a time-series approach incorporating airphoto imagery to demonstrate changes in woody cover at particular sites in response to short-interval fires. In contrast, Meng et al. (2014) failed to find a fire-interval connection using Landsat remote-sensing indicators of plant biomass and took a so-called space-for-time approach in which, instead of demonstrating VTC at a single plot over time, they inferred it based on comparisons of paired plots with different fire histories. Lucero et al. (2021) also used paired plots, but instead of using Landsat data, they used fine-scale aerial imagery. These space-for-time studies assume that the only important difference between sites is the fire history; they control for certain types of environmental variation but cannot discern species composition. This is important in chaparral remote-sensing studies because of the complex mosaic of different species dominants (Peterson & Stow, 2003; Roberts et al., 1998), fine-scale environmental heterogeneity, and species distributions (Keeley, 2004). This chronosequence approach is fraught with problems and is not recommended for phenomena that can be studied by following changes on a site over time (Walker et al., 2010).

Understanding landscape changes requires a multivariate approach that considers factors other than fire interval. For example, Meng et al. (2014) found a reduction in vegetation cover after a short interval between fires at low elevations, and this likely was due to changes in community composition (i.e., chaparral is replaced at lower elevations by the smaller-stature sage scrub), as revealed by Lucero et al. (2021) and Syphard et al. (2006) and by the fact that human ignitions are inversely correlated with elevation (Keeley & Syphard, 2018a). Additionally, given the association of elevation with different plant communities and a range of physiological factors associated with plant growth or postfire recovery (Franklin, 1996), there could be multiple reasons for this pattern. Lippitt et al. (2012) observed a similar topographic effect with low elevation. Syphard, Brennan, and Keeley (2019a & b) found that other variables most strongly associated with VTC were indicators of soil moisture, which is consistent with Park et al. (2018), who found that the spatial distribution of herbaceous cover in chaparral communities was most strongly correlated with low soil moisture.

There are several ways that soil moisture availability may facilitate vegetation change. For example, drought-related plant mortality may drive chaparral decline and lead to VTC because dead shrubs open the canopy and allow for the establishment of sage scrub or invasive grasses (Jacobsen & Pratt, 2018). Drought may limit postfire recovery of chaparral and shift the competitive balance in favor of invasive grasses (Park et al., 2019). Also, the interaction between soil moisture and short-interval fires may play a role because obligate-seeding shrubs are most sensitive to short-interval fire and are also strongly favored on more arid sites (Keeley & Syphard, 2018b). Soil nitrogen is another factor that could increase the competitive ability of invasive species (Fenn, Allen, & Weiss, 2010); however, previous studies found it not to be a significant factor in postfire VTC (Keeley et al., 2005; Syphard, Brennan, & Keeley, 2019b).

An additional consideration is geographical differences in factors driving VTC. Understanding such variation might identify the variables of most concern in different regions; additionally, identifying the subregions most vulnerable could facilitate setting priorities in terms of where to focus decision-making and management. In this study, we expanded the geographical extent of previous empirical studies conducted with aerial photography to document and explain the relative extent and drivers of woody shrubland decline and conversion across Southern California. Our approach was spatially hierarchical, with separate analyses conducted across the entire area, by northern and southern regions, and by four subregions. This extended and hierarchical analysis enabled us to answer the following questions:

1. How much VTC has occurred across the entire Southern California region, and are there geographical differences in the amount of woody decline and conversion that are occurring?
2. What are the most important drivers or correlates to woody decline and conversion, and how do they vary across regions?
3. Do the geographical differences among regions result in different predictive model output maps of woody decline and conversion?

METHODS

Study region

The coastal region of Southern California is a hotspot of biodiversity that has already lost more than half of its area of natural vegetation due to habitat loss and fragmentation from urban development (Underwood et al., 2009), which continues apace (Radeloff et al., 2018). The region has a Mediterranean climate with cool, wet winters and hot, dry summers, and the most extensive vegetation types include the largely summer-deciduous sage scrub and taller-stature evergreen chaparral shrublands. Throughout the region these shrublands form a mosaic with oak woodlands, grassland, and, at higher elevations, montane conifer forests. The region is environmentally diverse with strong climatic and topographical gradients that vary from the coast to the interior and from the south to the north (Keeley & Syphard, 2018b).

The natural fire regime in the region is one of periodic high-severity crown fires that tend to be most destructive when driven by strong, dry, offshore Santa Ana winds (Faivre et al., 2016). Humans are responsible for at least 95% of fire ignitions, with lightning fires primarily restricted to the highest elevations in the interior mountain ranges (Keeley & Syphard, 2018a). Given the exponential population growth in the last century, wildfires have become uncharacteristically frequent, with extensive areas of chaparral having experienced fire return intervals much shorter than those from presettlement fire regimes (Safford & Van de Water, 2014). Although the area has a semiarid climate, prolonged periods of extreme drought can result in substantial vegetative effects (Dong et al., 2019).

To delineate the full study area, we selected two ecoregion provinces, California Coastal Chaparral Forest and Shrub and California Coastal Range Open Woodland

(Cleland et al., 1997), and constrained them to fall within San Bernardino, Santa Barbara, Ventura, Los Angeles, Riverside, and Orange Counties. We then subdivided the study area into northern and southern regions and four subregions. First, we used the ecoregion province boundaries to separate coastal from interior plots. However, there were no clear ecoregional or other boundaries separating the region into north and south. The metropolitan area of Los Angeles, California, however, creates a large gap between the sample plots to the north and south; we used this gap as a general dividing line, with State Route 330 creating the separation in the narrow interior area, where the northern and southern plots are relatively close together.

Airphoto imagery and random sampling

We previously created vegetation plots to analyze the drivers of VTC in San Diego County (Syphard, Brennan & Keeley, 2019b) and the Santa Monica Mountains (Syphard, Brennan, & Keeley 2019a). For the latter subregion, estimates of the amount of vegetation change could potentially have been biased by the intentional selection of plots in which woody cover had declined. Therefore, to estimate vegetation change across the entire study region considered here, we started with plot data from San Diego County ($n = 656$) and, using the same methodology, added new plots across the rest of the region, including the Santa Monica Mountains.

To generate the new plots, we selected and georeferenced the earliest available historical aerial photos ($n = 195$) from the University of California Santa Barbara Map and Image Library (http://mil.library.ucsb.edu/ap_indexes/FrameFinder) to cover the entire region (except for San Diego County). The historical photos were at the scale of 1:20,000, with dates ranging from 1943 to 1959. We subsequently acquired georeferenced overlapping contemporary photos (year 2019) with a resolution of 60 cm from the National Agriculture Imagery Program (NAIP) (https://gis.apfo.usda.gov/arcgis/rest/services) to pair with the historical photos for change analysis. Thus, the number of years between photos ranged from 60 to 76.

Across the photo coverage footprints, we generated 3411 random points spaced a minimum of 90 m apart in areas mapped as shrub in a historical vegetation map (Kelly et al., 2005). After deleting points overlapping imagery that was too poor to interpret, we generated 30-m buffers around the remaining points to create 0.28-ha plots for interpretation and analysis.

For all plots on both historical and contemporary images, we manually interpreted and recorded in four equal-interval numeric classes from 1 to 4 (corresponding to 0%–25%, 26%–50%, 51%–75%, and 76%–100%) the percentage cover of woody chaparral vegetation, herbaceous vegetation, and human disturbance (e.g., urban, agriculture, road, trail, or fuel break). We additionally recorded whether there were pure stands of each class (95%–100% cover) or whether the cover type was absent (0%–5% cover). We documented the type of human disturbance present in the plots for a summary of types of vegetation change overall. Although woody cover is easily distinguished from herbaceous cover in the imagery, we could not discern the condition of the chaparral in terms of drought-related dieback. However, even had there been dieback, the skeletons remained visible and were recorded as woody cover until the next fire. To ensure that postfire recovery was not mistaken for VTC, we deleted any plots that had experienced a partial or complete burn within 5 years of either image date, which is sufficient time for chaparral biomass to recover (Guo, 2001).

For all plots in which there was no recent fire, we recorded both gain and loss of woody cover over the study duration to show summary statistics of overall vegetation change (Table 1a). For statistical analysis of woody vegetation decline and conversion, we deleted plots in which there was less than 75% cover of woody vegetation or human disturbance in the earliest image date. This ensured that all plots started in the same condition and that our analysis was appropriately focused on decline or conversion. Also, because the focus of the statistical analysis was conversion of woody cover to herbaceous cover, we removed all plots that had become disturbed by human land use during the contemporary period. This ensured that the changes analyzed were vegetative changes only. We created two binary dependent variables. Woody decline included any plot in which chaparral had experienced at least a 25% conversion to grass (i.e., a cover decline of at least one class). For *type conversion*, the plot must have experienced more than 50% decline (i.e., a decline of at least two classes) such that herbaceous cover occupied more than half of the plot.

Explanatory variables

To determine the relative importance of potential drivers and environmental correlates with woody vegetation decline and type conversion to herbaceous cover, we used a suite of variables similar to prior studies (Syphard, Brennan, & Keeley, 2019a & b) (Table 1b). Previous work identified soil characteristics and water balance as important correlates with VTC and herbaceous expansion (e.g., Park et al., 2018; Syphard, Brennan, & Keeley, 2019a & b), in part because

TABLE 1 Description and native scale of (a) dependent and (b) explanatory variables used in statistical analysis of vegetation type conversion in Southern California from ~1950 to 2019

	Description	Native scale and units
a) Vegetation change (dependent variables)		
Woody decline	Plot that was fully chaparral in historical period and experienced at least a 25% conversion to grass by contemporary period	30-m buffers around points (0.28 ha), binary
Woody conversion	Plot that was fully chaparral in historical period and converted to at least 75% grass by contemporary period	30-m buffers around points (0.28 ha), binary
b) Explanatory variables		
Soil and drought		
Actual evapotranspiration (AET)	Total annual water evaporated from surface and transpired by plants, assuming unlimited water, summed annually and averaged from 1981 to 2010	270-m raster, mm
Soil available water storage (SOIL_AWS)	Maximum amount of water available for plant use that soil can provide	30-m raster, mm
Nitrogen deposition	Annual deposition of reduced and oxidized nitrogen	Polygon converted to raster
Topography		
Elevation	US Geological Survey digital elevation model	30-m raster, m
Slope	Degree slope derived from elevation	30-m raster, degrees
Fire frequency		
Fire count	Total no. fires since 1878	Regions polygon converted to raster, count
Minimum fire return interval	Shortest no. years between any two fires on record or between contemporary image date (2019) and 1878, the first year in record	Regions polygon converted to raster, years
Fire departure	Estimated departure of contemporary fire return interval from median reference fire return interval of pre-Euroamerican settlement	Polygon converted to raster, percentage departure
Proximity to development or disturbance		
Distance to roads	Proximity to all TIGER line file roads, excluding 4WD and OHV roads. TIGER Roads 2015, US Department of Commerce, US Census Bureau	30-m raster, m
Distance to Wildland Urban Interface (WUI)	Euclidean distance to interface or intermix WUI in 2010	30-m raster, m
Terrestrial intactness	Relative natural condition of landscape as function of multiple types of human disturbance using input data from 2011 to 2015	Converted from polygon to raster, unitless (−1 to 1)

they mediate plant development and productivity. Therefore, we evaluated available soil water storage provided by the Natural Resources Conservation Service (https://www.arcgis.com/home/item.html?id=e66bffd8e4614cc9bf3c770fe6a4d4fc) and actual evapotranspiration (AET), calculated from topography, soil, precipitation, and temperature data produced by Flint and Flint (2012) using the California Basin Characterization Model (https://ca.water.usgs.gov/projects/reg_hydro/basin-characterization-model.html). Because nitrogen deposition can moderate soil fertility and enhance the growth rates of invasive grasses (Fenn, Allen,Weiss, Jovan, et al., 2010), we used a 2002 map representing total annual deposition of reduced and oxidized nitrogen (kilograms of nitrogen per hectare per year) at 4-km resolution (Tonnesen et al., 2007). Topographical variables also have the potential to regulate energy and moisture balance (Franklin, 1995), in addition to mediating wildfire behavior directly, so we included elevation and slope as explanatory variables.

We considered two explanatory variables to capture the effect of fire frequency on vegetation change. For the first, minimum fire interval, we used the wildfire perimeter database from Cal Fire (https://gis.data.ca.gov/datasets/e3802d2abf8741a187e73a9db49d68fe_0), with overlapping fires mapped from 1878 to 2018. We overlaid all plots with the fire perimeters and calculated the minimum fire return interval as the shortest number of years between any two fires in the record that occurred before the contemporary image date (i.e., 2019). If no fire occurred in the record, we subtracted 1878 from the contemporary data year and used that as the minimum interval; if one fire occurred, we calculated the minimum interval to be the smaller of the interval in years been the fire date and either the beginning of the fire record or the contemporary data year. We considered, but ultimately did not use, the total count of fires as an explanatory variable because it was highly correlated with minimum interval. For the other variable, we used the USDA Forest Service fire return interval departure (FRID) map layer (https://www.fs.fed.us/r5/rsl/projects/gis/data/FRID/FRID_Metadata.html) to quantify the degree of difference between contemporary median fire return intervals at a site and the estimated fire return intervals that occurred in pre-Euroamerican settlement times. Although fires are burning less frequently than historical times in coniferous forests in California, the trend for much of the Southern California study area is for fires to be burning more frequently (Safford & Van de Water, 2014).

Because expansion of invasive grasses often results from their dispersal from disturbed areas (Fusco et al., 2021), we considered three metrics of human disturbance. Two of these, distance to roads (https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.2015.html) and Wildland Urban Interface (WUI) (http://silvis.forest.wisc.edu/data/wui-change/), were included in previous studies of type conversion in Southern California (Syphard, Brennan, & Keeley, 2019a & b) (Table 1). Here we also included a map that reflects the overall footprint of human disturbance on the landscape through a metric of terrestrial intactness (https://databasin.org/datasets/e3ee00e8d94a4de58082fdbc91248a65/).

We constrained the extent of all mapped variables to the study region and resampled all grids to the finest-resolution data at 30 m using the ArcMap (version 10.6.1) Resample tool with the Bilinear resampling technique (https://desktop.arcgis.com/en/arcmap/latest/tools/data-management-toolbox/resample.htm). We also converted all polygon layers to raster using the same extent and cell size. Around all plot points, we created a 30-m buffer, then extracted the mean value of all explanatory variables and assigned them to the plots. To simplify interpretation for evaluating variable importance, we charted results based on the variable with the highest percentage contribution to the model out of these groups: terrain (elevation and slope), disturbance (distance to roads and WUI and terrestrial intactness), soil (available soil water storage, AET, and nitrogen), and fire (minimum fire interval and fire departure).

Analysis

To quantify vegetation change, we summarized the number of plots in different woody and herbaceous cover classes for the historical and contemporary image dates. In addition to summarizing change across the entire study area, we also stratified the study region geographically to determine whether there were differences in the extent and drivers of vegetation change and whether those differences affected mapped predictions. Thus, we calculated these numbers and performed analyses separately for the northern and southern regions and for four subregions representing the combinations of north, south, coastal, and interior. Because sample sizes of full type conversion were small for the northern and southern coastal subregions ($n = 6$ and 9 respectively), we merged them with the interior regions in the north and south for inferential statistical analysis. For woody decline, however, we performed separate analyses for the four separate regions. For all explanatory variables, we quantified descriptive statistics, including minimum, maximum, average, and range of values for the explanatory variables for the four subregions (Phillips et al., 2006) of the study area to assess their relative environmental differences.

To quantify the relative importance of explanatory variables, we used two types of statistical analysis—one that estimated each variable's independent importance (hierarchical partitioning) using presence-absence data, and a presence-only multivariate analysis that accounted for variable interactions (MaxEnt, version 3.4.3, https://biodiversityinformatics.amnh.org/open_source/maxent/). Hierarchical partitioning is a statistical algorithm that calculates the isolated effect of each explanatory variable on the response, which in this case was binary, indicating either woody decline or woody conversion as presence and plots that did not change or decline as absence; for the MaxEnt modeling, we only used the presence data. The relative contribution of each variable is determined by running a hierarchical decomposition of a goodness-of-fit measure from regression models using all variable subsets (in this case a log-likelihood goodness-of-fit test for logistic regressions) (MacNally & Walsh, 2004). We used the hier.part package version 1.0–6 in RStudio (R Core Team, 2020).

For mapping and comparison of variable importance within a multivariate framework, we used the MaxEnt statistical software program (Phillips & Dudık, 2008) that was originally developed for species distribution modeling but has recently been used for a range of other ecological applications (Elith et al., 2010) and for mapping fire or ignition probability (e.g., Syphard, Rustigian-Romsos et al., 2019). One of the benefits of MaxEnt is its known high performance for spatial mapping, which is why we used that method for the mapping part of our work. MaxEnt performs well with small sample sizes (Hernandez et al., 2006; Oppel et al., 2012; Wisz et al., 2008), has high predictive accuracy compared to other modeling methods (Elith et al., 2006; Guisan et al., 2007; Shabani et al., 2018), and allows versatile and flexible settings that can account for model interactions and nonlinear relationships (Elith et al., 2006; Merow et al., 2013).

MaxEnt is a presence-only machine-learning algorithm that iteratively compares the differences in explanatory variables between locations of the response variable (here, the plot location of either woody decline or conversion) and the locations of a randomly generated sample of 10,000 background plots, located at least 30 m apart. Through these iterative comparisons, the model estimates the best approximation of the response variable environmental distribution as the one with maximum entropy. The model outputs a raster map in which an exponential function is used to assign each cell a value between 0 and 1 representing relative suitability. The model also generates metrics of variable importance and performance accuracy from the area under the curve (AUC) of receiver operating characteristic curves (Fielding & Bell, 1997).

For the MaxEnt modeling, we used the same predictor variables as in the logistic regression models and evaluated differences in variable importance in the different regions and subregions. We initially ran the models with all variables included to record their relative importance. The MaxEnt program produces two alternatives (Phillips et al., 2006) for assessing variable importance in this multivariate framework. The percent contribution reflects each variable's influence as the algorithm is fitting the model, whereas the permutation importance reflects the importance of each variable within the final model—done by iteratively removing each variable from the model and quantifying the decrease in model accuracy that results from the omission of that variable. In the models run with all variables, we focused on percent contribution as the metric of relative importance and provide permutation importance in the Supporting Information Appendix S1. After running the variable selection process, described in what follows, we focus on the permutation importance for the variables retained because these represent the final selected models used for mapping. MaxEnt used with default parameterization has been shown to result in overly complex models (Anderson & Gonzalez Jr., 2011; Moreno-Amat et al., 2015; Warren et al., 2014). Therefore, it is recommended that MaxEnt settings be tuned to optimize model complexity and performance (Merow et al., 2013). We took the following steps to reduce potential model overfitting: limited potential model complexity by constraining the feature types to linear, quadratic, and product; excluded correlated predictors from entering the same models; utilized an iterative stepwise variable selection process to increase model parsimony; and optimized the regularization multiplier.

Because we wanted to capture the spatial signature of vegetation change and not urban development, we restricted the training extent of the maps to all vegetated areas except medium-intensity developed, high-intensity developed, and cultivated crops, using the National Land Cover Database from 2016 (https://www.mrlc.gov/). Before running the models, we used ENMTools (version 1.4.4) (Warren et al., 2010) to calculate correlation coefficients between pairs of all variables, and none were correlated $r >= 0.7$.

After recording variable importance in the full models, we proceeded to conduct an iterative stepwise process of variable selection. For each iteration, we removed the variable contributing the least information to the model fit (highest mean training gain without the variable) to decrease model complexity and increase performance (Warren et al., 2014) and ran the model again with the remaining predictors. This was repeated until only one variable remained. The model with the fewest variables having a mean training gain not significantly different than the full model was selected for each. Significance was defined as a lack of overlap between 95% confidence intervals for training gain means (R Core Team, 2020). After variable selection, we then altered the regularization multiplier from 0.5 to 5 at 0.5 increments and used the Model Selection function in ENMTools to calculate the Bayesian information criterion (BIC) for each of the models (run with no replication and raw output). The final model was the one with the regularization multiplier producing the lowest BIC score. Finally, we ran a fivefold cross validation of the final model to assess model performance.

After completing this MaxEnt modeling process for the full region using both woody decline and woody conversion as the response variables, we repeated the process for the northern and southern regions. We also ran separate models for the four subregions, but only for woody decline due to the small sample size for full type conversion. Finally, we overlaid maps at these different spatial extents and then calculated and mapped the differences in predicted suitability for woody decline and conversion.

RESULTS

Extent of vegetation change

The total number of plots randomly sampled across the paired dates of air photos, including plots from the San Diego region (Syphard, Brennan, & Keeley 2019a), was 4067. From those we deleted 168 whose imagery was too poor to interpret, 326 that had had a fire within 5 years of either image date, and 833 plots that had had some type of human disturbance on either date. This resulted in a total of 2740 plots for which we analyzed vegetation change.

In terms of human disturbance, 741 out of 3899 (19%) plots were converted from vegetation to human land use over the study period. The reasons for natural vegetation conversion to human land use, from most to least common, included mechanical vegetation management (removal, thinning, and crushing of woody vegetation for linear fuel breaks) (31%), road development (26%), urban development (20%), trail construction (10%), miscellaneous agriculture (e.g., orchards, grazing, cropland) (8%), and undetermined (6%).

Most plots experienced no change in woody cover, and woody cover increased in some plots, particularly in the southern interior portion of the study area (Figure 1). Overall, there was a substantial net loss of

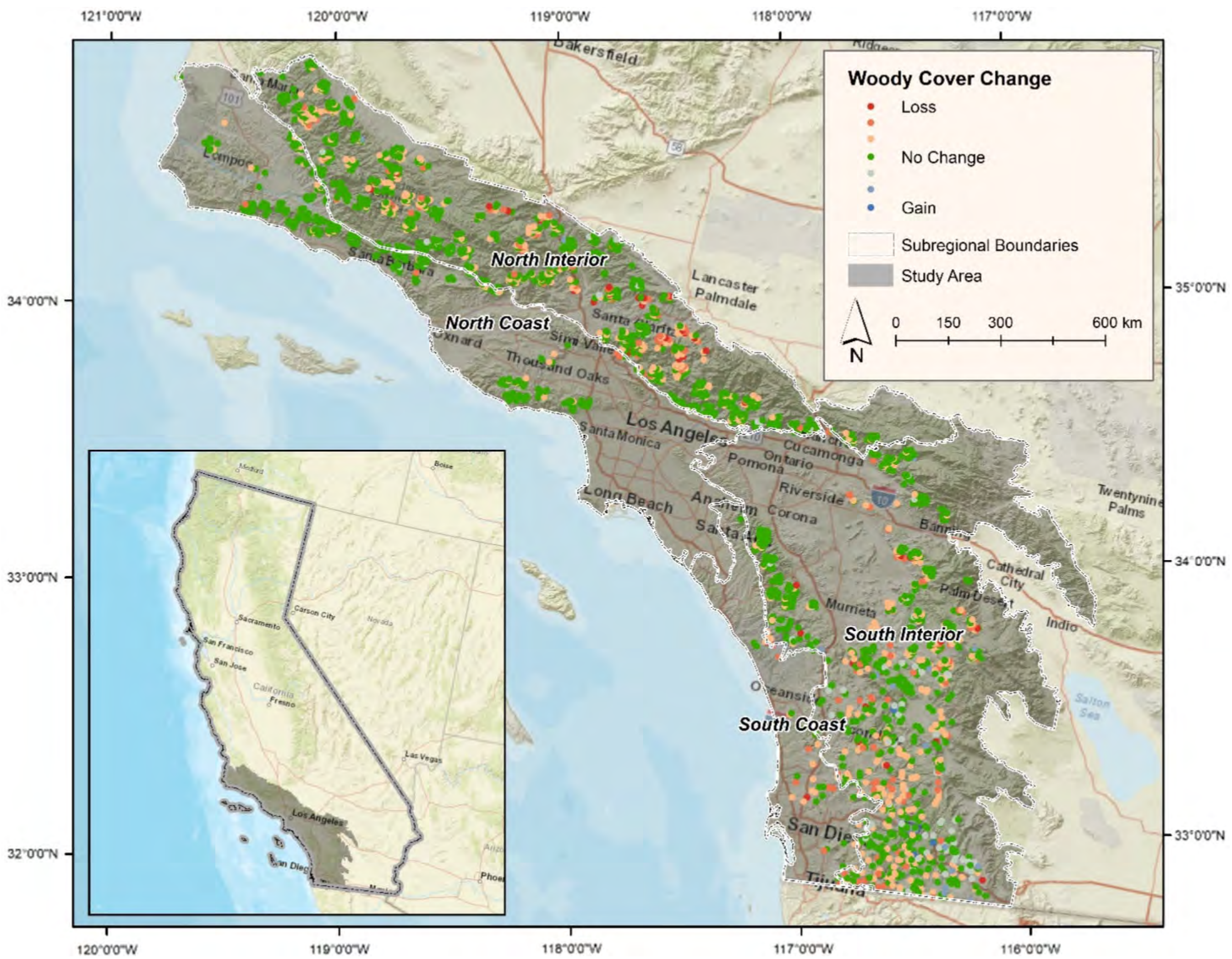

FIGURE 1 Study area map showing change in percentage woody cover from earliest to most recent image dates (~1950–2019) in Southern California. The middle value (green) indicates no change; the progressively warm colors display four classes of cover loss in 25% increments, with *woody decline* represented by all warm colors and *woody conversion* represented by the two darkest warm colors. The cool colors represent 25% increments of woody cover gain. The inset shows the study area location divided into four subregions.

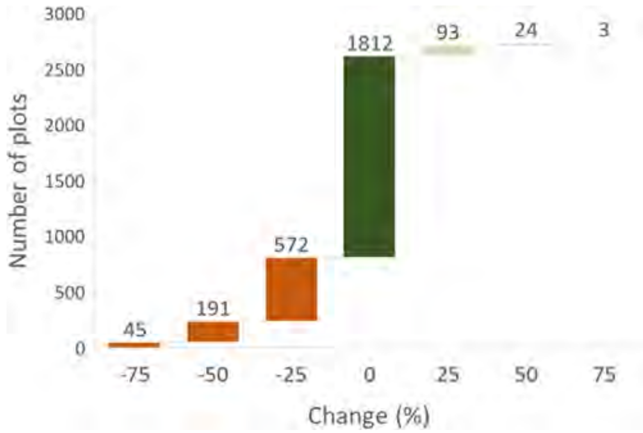

FIGURE 2 Net change in woody cover from earliest to most recent image dates (~1950–2019) in Southern California. Negative values indicate woody cover decline, and positive values indicate woody cover increase.

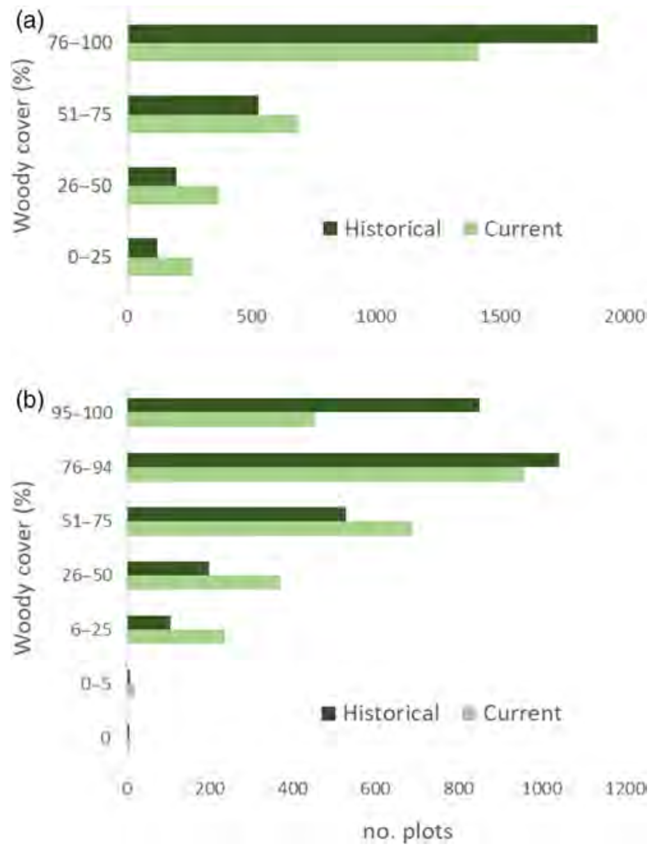

FIGURE 3 Number of vegetation plots distributed within woody cover classes in historical and current image dates show in (a) equal-interval classes of 25% cover and (b) equal-interval classes plus classes of pure woody (95–100%) and pure herbaceous (0–5%) vegetation

woody cover across the study region (Figures 1 and 2), along with herbaceous expansion (Appendix S1: Figure S1). The most dramatic decline was in the cover of originally pure stands of chaparral (i.e., 95%–100% woody cover) (Figure 3). When separated into subregions, both southern areas experienced the largest proportion of woody decline and conversion, most in the south coast (Figures 1 and 4), although the south coast had the smallest number of plots in the four regions. In the northern region, the interior experienced more woody vegetation decline and conversion than the coastal area (Figures 1 and 4).

Drivers of vegetation change

There were differences in the distribution of explanatory variables among the regions and subregions of the study area (Table 2, Appendix S1: Table S1). The coastal regions were less rugged and lower in elevation than the interior regions. The southern region showed the highest presence of human development, with shorter overall proximity to roads and the WUI, and both coastal regions were more highly disturbed than the interior regions. Available soil water storage and AET were generally higher in the north than the south, although soil water storage was lowest in the northern interior region. Nitrogen content in the soils was highest in the coastal regions. The shortest minimum fire interval was in the northern interior, but the largest departure in fire intervals was by far in the southern coastal area. In all areas, the average fire departure was negative, indicating that fires are overall more frequent than they have been historically.

Across the full region and in the north and south, fire was most frequently ranked as the most important variable (Figure 5, Appendix S1: Figures S2–S13) for woody decline and conversion. This was true both in terms of independent contribution through hierarchical partitioning and in terms of percent contribution in multivariate MaxEnt modeling. However, in the hierarchical partitioning models, the independent contribution of fire in the full region was less important than AET for both woody decline and conversion; and fire was also less important than slope for woody decline (Figure 5b, Appendix S1: Figure S2). In the MaxEnt models in which all variables were compared, both minimum fire interval or fire departure were the most important variables regionwide as well as in the north and south (Figure 5b, Appendix S1: Figures S2 and S3). Variable rankings among the other three classes of variables showed no clear trends and shifted slightly depending on whether the model was for woody decline or conversion or depending on the measure of variable importance.

In models fit with all explanatory variables in the subregions, fire again was ranked highest most frequently, but terrain and soil-related variables were more important compared to the models fit at larger extents (Figure 6a,b, Appendix S1: Figures S2–S13). In the hierarchical partitioning models, terrain (in this case slope [Appendix S1: Figure S1]) was ranked almost equally as fire for the coastal areas; and for the south interior, both slope and AET were more important than fire, albeit only slightly (Figure 6a, Appendix S1: Figure S2). In the multivariate MaxEnt models, soil (in this case nitrogen deposition [Appendix S1: Figure S3]) was nearly as important as fire interval in the north coast; and in the south coast, potential soil moisture in terms of available water storage and elevation were both slightly more important than fire (Figure 6b, Appendix S1: Figure S3). In the subregional models, human disturbance variables were generally less important than the other variable types (Figure 6a,b), although there was substantial variation among individual variables (Appendix S1: Figures S2 and S3).

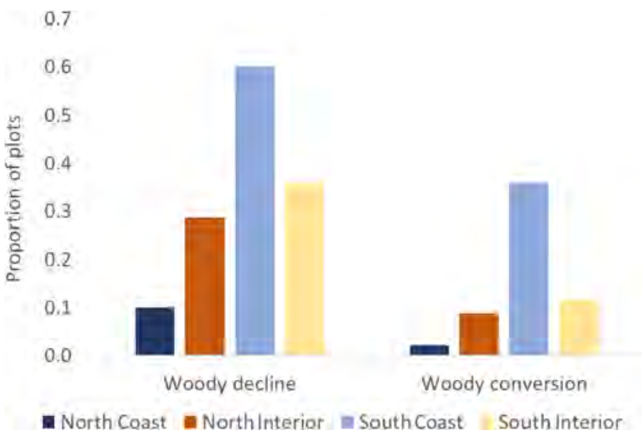

FIGURE 4 Proportion of plots experiencing woody decline and conversion from earliest to most recent image dates (~1950–2019) in four subregions of Southern California

After variable selection and model fitting, all multivariate MaxEnt models for woody decline and conversion and across all regions and subregions retained minimum fire return interval as the highest-ranking variable (Tables 3 and 4). For the full region, elevation and AET were both retained for both woody decline and conversion, and for woody decline, terrestrial intactness was the second-ranking variable in permutation importance. Terrestrial intactness was also the second-ranking variable for woody decline in the north and south but was only retained in the model for the northern region for woody conversion. For woody decline, distance to WUI was retained for the north and distance to roads was retained for the south. Distance to roads was also the third-ranking variable for woody conversion in the south.

For the subregional MaxEnt models of woody decline after variable selection, fire interval was the only variable retained in the best models for the two coastal regions. In the northern interior, elevation, terrestrial intactness, distance to WUI, and nitrogen were also retained. In the southern interior, terrestrial intactness, AET, distance to roads, and slope were retained.

The AUC for both training and test data sets ranged from 0.7 to 0.79 for all models except the model on test data for woody conversion in the south, which was 0.52, with the training AUC at 0.79 (Tables 3 and 4). The regularization multiplier that resulted in the lowest BIC score varied across the models from 0.5 to 4.5.

TABLE 2 Average values for predictor variables explaining woody decline and conversion in Southern California

	Unit	Full region	North	South	North coast	South coast	North interior	South interior
Elevation	m	726.6	693.6	758.7	230.0	166.8	1137.0	876.9
Slope	Degrees	13.5	14.9	12.2	9.1	8.7	20.4	12.9
Distance to roads	m	793.9	817.0	771.5	253.2	278.2	1356.4	870.1
Distance to Wildland Urban Interface (WUI)	m	3239.4	4294.7	2213.1	3412.4	1551.7	5138.8	2345.2
Terrestrial intactness	Metric, −1 to 1	0.1	0.1	0.1	−0.4	−0.4	0.5	0.2
Available soil water storage	mm	102.6	113.9	89.3	149.4	97.5	81.3	87.4
Actual evapotranspiration	mm	316.5	330.6	302.8	346.0	302.7	315.9	302.9
Nitrogen	kgN_ha_year	9.7	10.0	9.4	12.7	10.6	7.5	9.1
Fire count	Sum	1.1	1.2	1.0	0.8	1.0	1.7	1.0
Fire interval	Years	74.9	70.5	79.2	99.2	85.1	43.0	78.1
Fire departure	Percentage	−10.9	−11.6	−10.3	−13.0	−32.2	−11.0	−8.1

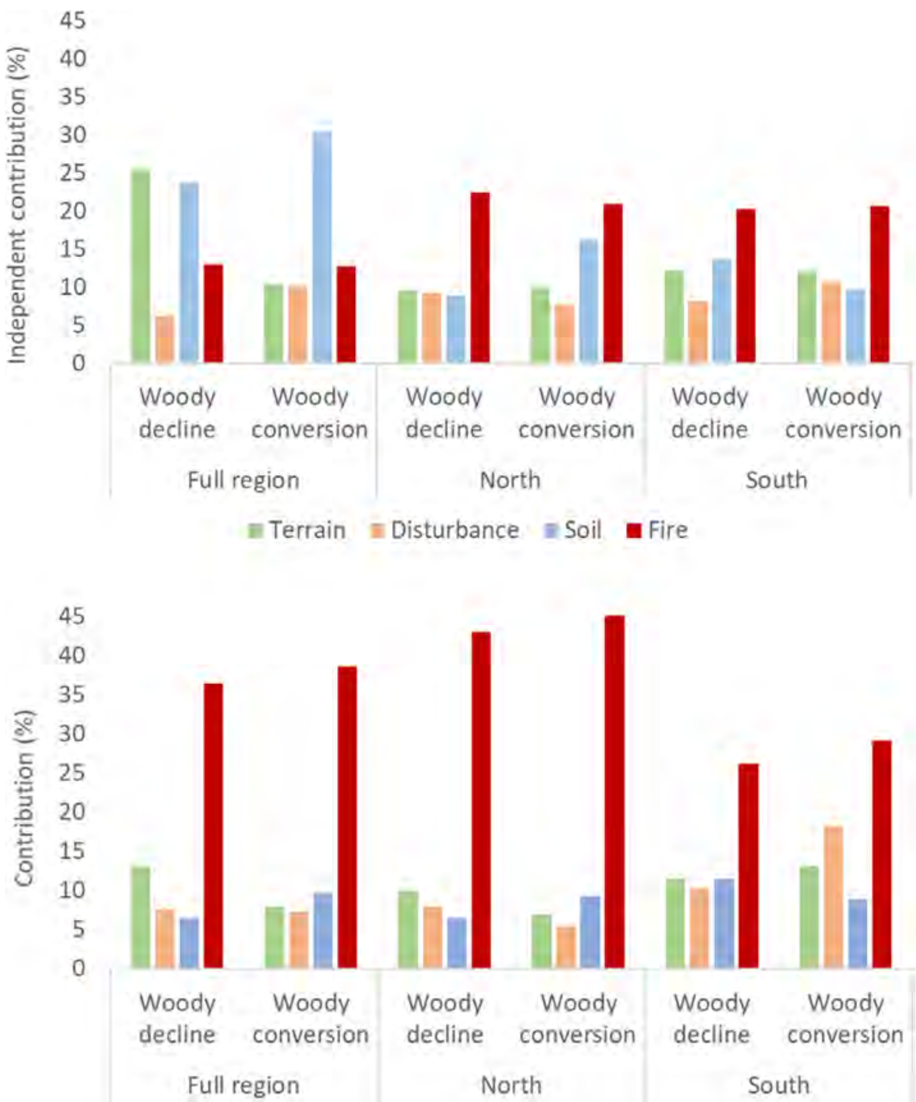

FIGURE 5 Relative importance of variable classes explaining woody decline and conversion in north, south, and full Southern California regions using (a) hierarchical partitioning and (b) MaxEnt models (for ungrouped variable results, see Appendix S1: Figure S1)

Distribution maps of suitable conditions for woody decline and conversion

Across the entire region, the areas mapped as having the highest potential for woody decline were similar to those with the highest potential for woody conversion. Areas of the highest likelihood of vegetation type change were distributed in the same general locations with slight discrepancies in probability (Figure 7).

When comparing maps from regionwide models to maps developed separately for the north and south, there was better correspondence with maps of woody decline (mean $r = 0.91$) than conversion (mean $r = 0.86$), and there was better correspondence with maps developed for the north ($r = 0.97$ for woody decline and $r = 0.91$ for woody conversion) than for the south and regionwide (0.85 for woody decline and 0.81 for woody conversion) (Figure 8a,b, Table 5). The differences in the maps of woody conversion were most extensive in the southern coastal part of the landscape, where the maps developed at smaller spatial extents predicted a higher probability of conversion than the regionwide map. For woody decline, the differences between maps showed no clear spatial trends, although the smaller-extent maps generally predicted higher probabilities near the coast and the regionwide map generally predicted higher probabilities in the interior (Figure 8a,b).

When maps developed for the four subregions were compared to maps developed regionwide (Figure 8c) or to maps developed for the north and south (Figure 8d), there was overall better agreement between subregional maps and the north and south maps than there was between subregional maps and the regionwide map (Figure 8c,d, Table 5). There was also a stronger

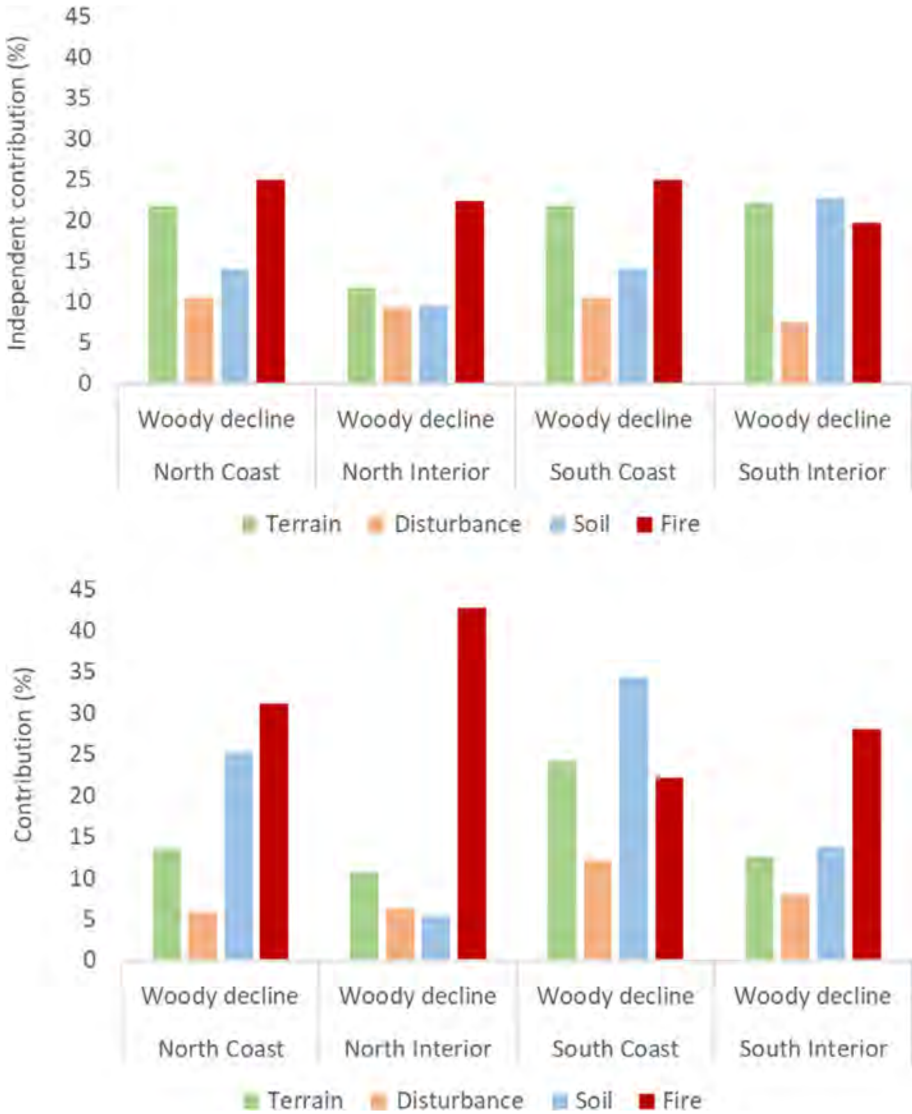

FIGURE 6 Relative importance of variable classes explaining woody decline and conversion in four Southern California subregions using (a) hierarchical partitioning and (b) MaxEnt models (for ungrouped variable results, see Appendix S1: Figures S2–S3)

correlation in the interior regions than in the coastal regions (Table 5), with coastal subregions tending to predict higher probabilities of vegetation change than interior regions (Figure 8c,d).

DISCUSSION

Widespread decline of woody chaparral shrubland vegetation and replacement with invasive grass has the potential to dramatically reduce ecological functioning and provision of ecosystem services in Southern California, with global implications in terms of rapid vegetation shifts in other fire-prone regions. Although previous work across shorter spatial or temporal extents has generated disagreement over the extent of this change and the reasons for it, our analysis across Southern California shows that decline of woody shrubs and conversion to grass has occurred extensively, with highest proportions of change in the northern interior and southern coast. Variables related to short-interval fire were most frequently ranked highest in predictive importance, but there was geographical variation across regions, as reflected in mapped output from distribution models.

We used several ways of quantifying variable importance in explaining woody decline and conversion, including independent contributions from binomial regressions and joint contributions from multivariate MaxEnt models—for seven different spatial extents and for both woody decline and conversion. For 16 out of the 20 different models comparing independent variable contributions (Figures 5 and 6), fire-related

TABLE 3 Explanatory variables giving their permutation importance and evaluation statistics for multivariate MaxEnt models of woody decline and conversion for regionwide models and models for north and south. The permutation values range from 0 to 100, with higher values representing greater importance in explaining vegetation change

	Woody decline			Woody conversion		
	Full region	North	South	Full region	North	South
Fire interval	58.1	60.7	41.8	73.6	87.2	58
Terrestrial intactness	23.7	19.1	25.1	...	4.2	...
Elevation	11.3	17.5	...	13.2	8.6	...
Actual evapotranspiration (AET)	6.8	...	20.5	13.2	...	22.8
Distance to Wildland Urban Interface (WUI)	...	2.7	...	...	...	...
Distance to roads	...	...	12.6	...	...	19.1
Sample size	539	295	244	173	89	84
Regularization multiplier	4.5	4	2	2.5	2.5	2
Mean test area under curve (AUC)	0.74	0.76	0.76	0.76	0.74	0.52
Mean train AUC	0.74	0.77	0.77	0.77	0.76	0.79

TABLE 4 Explanatory variables, permutation importance, and evaluation statistics for multivariate MaxEnt models of woody decline for subregional models in Southern California

	North coast	North interior	South coast	South interior
Fire interval	100	60.5	100	41.6
Elevation	...	17.9	...	...
Terrestrial intactness	...	8.5	...	20.8
Distance to WUI	...	6.7	...	...
Nitrogen	...	6.5	...	...
Actual evapotranspiration (AET)	...	...	...	19.9
Distance to roads	...	...	...	12.5
Slope	...	...	...	5.1
Sample size	28	267	15	230
Regional multiplier	0.5	4.5	0.5	1.5
Mean test area under curve (AUC)	0.72	0.7	0.74	0.76
Mean train AUC	0.72	0.71	0.74	0.78

variables were ranked as more important than other variables. The exceptions were the regression models performed regionwide for woody decline and conversion, where soil water storage (woody decline and conversion) and terrain (woody decline) were higher ranking; the regression model for woody decline in the southern interior, where soil water storage and terrain both ranked slightly higher; and for woody decline in the southern coast, where again soil water storage and terrain ranked slightly higher. In the multivariate models, not only was fire interval retained in all models after variable selection, but it was also the top-ranking variable in all models, with it being the only variable retained for the northern and southern coast models of woody decline.

Although both Meng et al. (2014) and Storey et al. (2021) have questioned the role of short-interval fire in explaining VTC in chaparral, and Lucero et al. (2021) found weak evidence for it, the results here overwhelmingly point to short-interval fire and the degree of departure from historical fire return intervals as most important—regardless of the modeling method used or spatial extent of analysis. It is noteworthy that we used here a variable that has not been explored in other work, including our own previous studies—the measure of fire interval departure (vs. minimum fire interval). Estimates of departure in this metric are mapped as a function of current fire return intervals compared to historical estimates for 28 different vegetation types (Safford & Van de

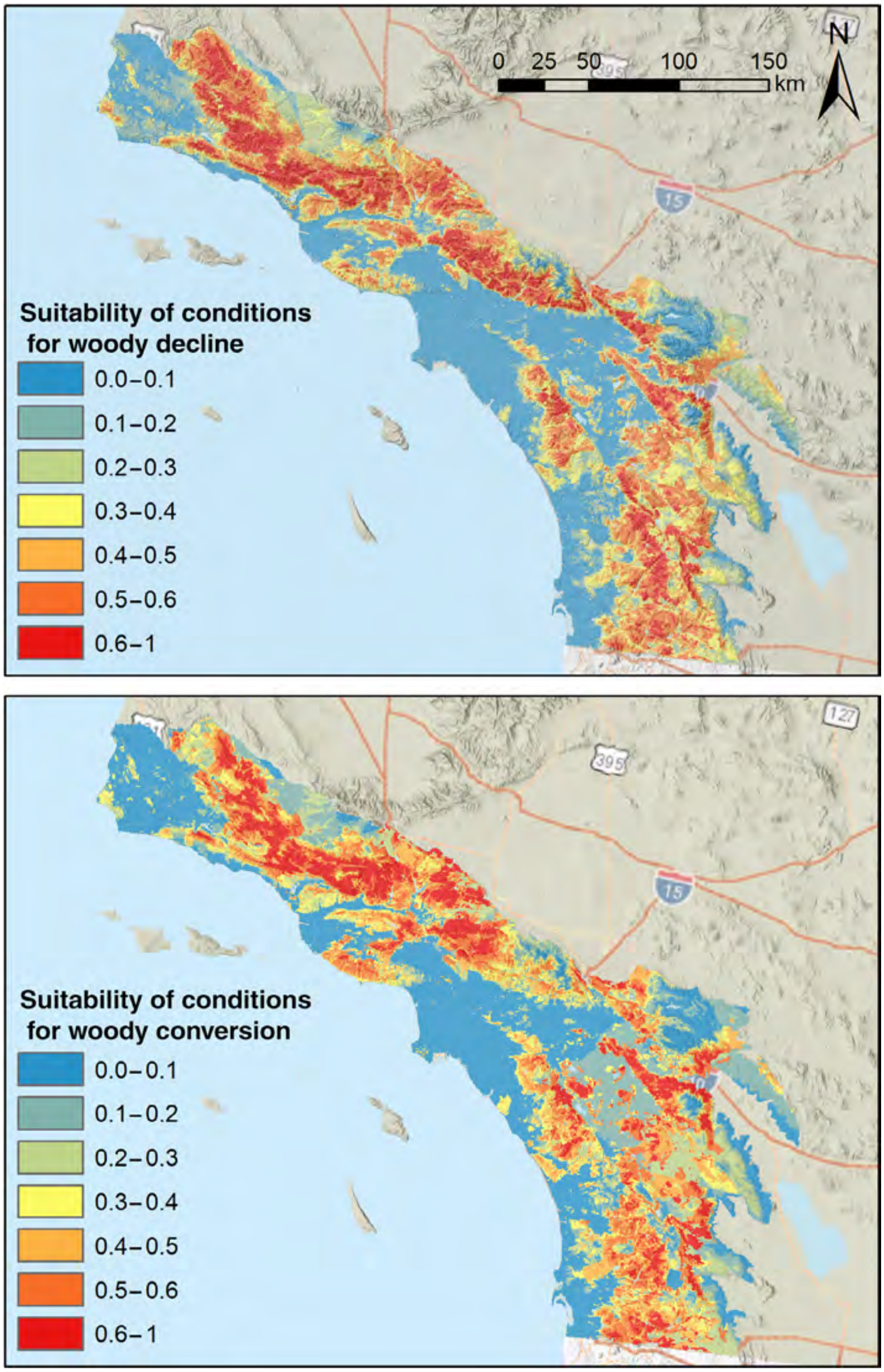

FIGURE 7 Distribution of areas with most potential for woody decline or conversion across Southern California

Water, 2014). This variable was frequently more important than minimum fire interval in the independent measures of variable importance (Appendix S1: Figures S1 and S2). Given its association with vegetation type, therefore, it is possible that in some cases it reflects species composition and picks up a stronger correlation with vegetation change than fire-related variables used in other studies. Species composition plays a large role in vulnerability to frequent fire owing to the nature of regeneration. For example, obligate seeding species, which depend on building a seed reserve in the soil that is sufficient to ensure postfire survival, pass through a prolonged growth period of up to 20 years in which seed production is minimal or zero. They are therefore vulnerable to short periods between fires, which can kill them before they have established a sufficient seed reserve (Haidinger & Keeley, 1993; Keeley, 1991; Keeley & Brennan, 2012).

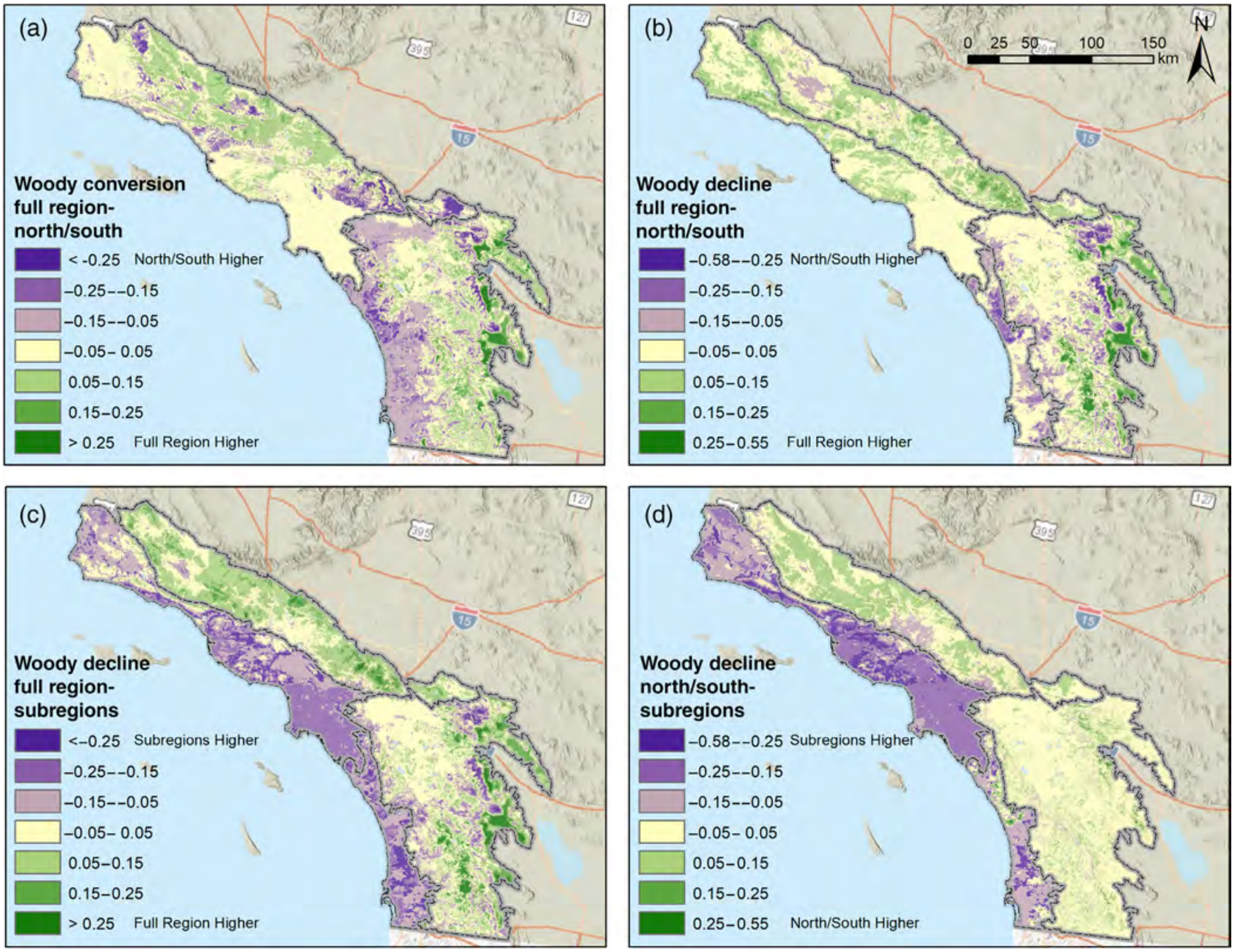

FIGURE 8 Differences in suitability for potential (a) woody conversion to herbaceous between MaxEnt models developed across full region versus models developed separately for northern and southern areas, (b) woody decline between MaxEnt models developed across full region versus models developed separately for northern and southern areas, (c) woody decline between MaxEnt models developed across full region versus models developed separately for four subregions, and (d) woody decline between MaxEnt models developed for northern and southern areas versus models developed separately for four subregions

TABLE 5 Correlation coefficients among maps produced from models of woody vegetation decline and conversion developed across different spatial extents in Southern California

	Woody decline			Woody conversion
	Regionwide	North	South	Regionwide
North	0.97	...	...	0.91
South	0.85	...	...	0.81
North coast	0.87	0.85	...	...
North interior	0.91	0.95	...	...
South coast	0.83	...	0.81	...
South interior	0.84	...	0.98	...

Another potential reason that other research found weaker relationships between fire and chaparral decline is that those studies isolated areas that had reburned a set number of times (i.e., once or twice) within a shorter temporal extent of analysis. In this study, fires could have burned frequently over a longer period across a larger geographical area, and that may be important in terms of the process of type conversion. Type conversion is a gradual, long-term process that often occurs as a function of multiple disturbance events over time in areas that are environmentally vulnerable to this change. That is, it may take more than one or two short fire-interval events for significant change to occur, and the number of events that trigger this change likely vary by region as a function of species composition and environmental context.

For type conversion to occur, several processes are involved. Initially, the aboveground portions of adult shrubs are killed, typically via wildfire, but potentially also because of drought. Subsequently, another fire may kill the seedlings or resprouts before they fully recover, which is why the immediate driver is often short intervals between fires. In addition to having sufficient time for regeneration, environmental context is important relative to successful recovery, and this is the most likely explanation for the strong correlation of woody decline and conversion with factors such as drought and topography–and for the geographical variation in relative variable importance. Soil aridity, which is perhaps best captured by AET, was a very significant factor in both woody cover decline and conversion to herbaceous vegetation (Appendix S1: Figures S1 and S2), although the relationship was nonlinear, with VTC most likely at intermediate to high levels of AET but then dropping at the highest AET values. This is likely operating in conjunction with fire because increased soil aridity in the immediate post-fire years is detrimental to shrub seedling survival and favors annual grasses, which can further deplete soil moisture (Davis & Mooney 1985). Soil aridity also favors obligate seeding shrubs (Davis & Mooney 1985), and this functional type is highly sensitive to short-interval fires; thus, the association of VTC with soil aridity may in reality be a result of frequent fires.

Another possible reason for the differences in results between our studies and those of Meng et al. (2014) and Lucero et al. (2021) is that our approach used a historical view of changes over time and theirs relied upon paired plots and a space-for-time substitution. That is, we directly tracked change at one site over time, whereas the other studies inferred change by comparing two sites with different fire histories and then attributed the change to the fire. Though the other studies attempted to control for environmental differences between plots, resource gradients and species composition are highly heterogeneous in many parts of Southern California, particularly in rugged areas where topoclimate variability may be as fine scale as <10 m (Ackerly et al., 2010). Given the strong influence of topoclimatic diversity on plant species' distribution and abundance (Franklin, 2010), this is an additional source of uncertainty in determining whether one plot in a pair can accurately substitute for another (Walker et al., 2010).

Geographical variation in factors that influence species distribution, composition, and abundance also potentially explains why it has been difficult to assess the extent and drivers of VTC in Southern California. Although the high ranking of fire interval was consistent across regions and spatial extents, its relative importance in combination with other environmental variables did vary, and these variations were reflected in the mapped predictions of potential VTC hotspots. In other words, maps created at smaller spatial extents reflect the unique geographical combination of factors best explaining the footprint of vulnerability in that region. When models are conditioned at larger geographical extents, they average the regional or subregional relationships, resulting in more generalized models.

Maps illustrating areas with the highest potential for vegetation change could be critical for determining management or restoration priorities; thus, mapped differences may have important consequences. The largest discrepancy in maps was in the southern part of the region, particularly along the coast. The maps developed in the northern coastal area also differed substantially from the maps conditioned at larger spatial extents. Overall, the southern part of the region experienced more decline and conversion than the north, which may partly explain the larger disagreement in mapped model output. On the other hand, the northern coast experienced the smallest vegetation change of the four subregions.

At least for the coastal areas, the most likely explanation for map differences is that the most accurate and simple subregional models only retained fire interval as the explanatory variable. Although our model selection approach is widely advocated for balancing goodness of fit with the potential for overfitting models, in this case the models may be underfit. In terms of decision-making, it may be desirable to have some balance between capturing regionally specific relationships (i.e., the subregions) with some of the generality reflected in maps at larger extents. The maps developed separately for the north and south may therefore serve most effectively for guiding decisions, although new maps could be developed for other geographies of interest, such as coastal or interior. While these maps illustrate the conditions that most closely approximate those where VTC has occurred, there is uncertainty inherent in where change may occur in the future. Also, the performance of the models was only slightly above average (AUCs mostly ranging from 0.7 to 0.8) (Fielding & Bell, 1997). Although fires do tend to recur within the same geographical areas (such as wind corridors) in Southern California, it is possible that short fire return intervals may occur in different types of areas in the future. Accounting for species composition is also critical for assessing VTC potential in Southern California, and these maps do not account for that.

Of the three general types of variables—fire, terrain, and proximity to human infrastructure—proximity to human infrastructure was never the top-ranking variable, despite its significance in many models. The spread of invasive grasses throughout the landscape often occurs unintentionally along roads, trails, powerlines, or other human land uses (Vila & Ibáñez, 2011). Thus, while these anthropogenic variables would not directly contribute to chaparral decline or recovery, they could account for the proximal source for grass dispersal and establishment (Fusco et al., 2021). Contrary to this expectation, however, the relationships here were counterintuitive such that VTC was more likely to occur at longer distances to roads or the WUI and in areas that were relatively more intact. The likely reason for this is that, given the strong association with wildfire, VTC may be more likely to occur in remote or continuous vegetation because these places are where larger fires are able to spread. Other research has shown that, though ignition probability is highest adjacent to human infrastructure, area burned tends to have an inverse relationship and tends to be largest far from roads or populated places (e.g., Syphard, Rustigian-Romsos, et al., 2019). This suggests that the detrimental effect of short-interval fire on chaparral overrode the positive effect of human adjacency as a source of grass.

In conclusion, this study shows the overwhelming importance of changes in fire regimes in causing VTC from shrublands to grasslands. Abrupt changes in fire regimes have the potential to upset ecological structure and function across a wide range of ecosystems and are considered a major global problem (Pausas & Keeley, 2014). In fact, VTC among diverse vegetation types is occurring globally as a result of sudden fire regime shifts (e.g., Coop et al., 2020; Fernandes, 2013). In Southern California, where the primary issue is frequent fire, the management approach of prescribed fire could exacerbate this vegetation shift with little effect on subsequent burning (Price et al., 2012). On the other hand, given that the primary cause of short-interval fires is human ignitions (Keeley & Syphard, 2018a), fire prevention has the potential to be the most cost-effective management approach.

CONFLICT OF INTEREST

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US government.

DATA AVAILABILITY STATEMENT

Data are available in Data Basin at https://databasin.org/galleries/aea3ce47dd874848a69bec856400bba3/#expand=297919%2C297920.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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ATTACHMENT F

Hydrology | Hydraulics | Geomorphology | Design | Field Services

September 26, 2022

Via Email Only

Mr. Brian Oh
Comprehensive Planning Manager
Permit Sonoma County of Sonoma
2550 Ventura Avenue
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Brian.Oh@sonoma-county.org

Subject: Review of Draft Environmental Impact Report (DEIR) (SCH# 2022020222)
Sonoma Developmental Center Specific Plan, Sonoma County, California

Dear Mr. Oh:

I am a hydrologist with over thirty years of technical and consulting experience in the fields of hydrology, geology, and hydrogeology. I have been providing professional hydrology and geomorphology services in California since 1989 and routinely manage projects in the areas of surface- and groundwater hydrology, water supply, water quality assessments, water resources management, and geomorphology. Most of my work has been in the Coast Range watersheds of California. My areas of expertise include: characterizing and modeling watershed-scale hydrologic and geomorphic processes; evaluating surface- and ground-water resources/quality and their interaction; assessing hydrologic, geomorphic, and water quality responses to land-use changes in watersheds and causes of stream channel instability; assisting and leading in the development of CEQA environmental compliance documents and project environmental permits; and designing and implementing field investigations characterizing surface and subsurface hydrologic and water quality conditions. I earned a Master of Science degree in Geology, specializing in sedimentology and hydrogeology as well as an A.B. in Geology from Miami University, Oxford, Ohio. I am a Certified Hydrogeologist (CHG #360) and a registered Professional Geologist (PG #5737) in the state of California. A copy of my resume is attached.

I have reviewed the Draft Environmental Impact Report (DEIR) for the Sonoma Developmental Center Specific Plan in Sonoma County, California, and evaluated if the project may impact surrounding properties and the environment. Specifically, I have reviewed the DEIR and technical appendices. Based on my review of these materials, it is my professional opinion that the DEIR is inadequate in evaluating the potential significant impacts of project actions on hydrology, water quality and biological resources. The rationale for this opinion is based on multiple findings presented below.

1. There are several local and state regulations applicable to the SDC Specific Plan that are not included in the Hydrology/Water Quality Regulatory Setting section (3.9.1 on pg. 270) of the DEIR. These include the following.

    a. Sonoma County General Plan 2020 Policy C-WR-2f, which states, "*Discretionary projects in Urban Service Areas, where the density of development thus extent of impervious surface area is greater than in Rural Communities, shall be required to maintain the site's pre-development recharge of groundwater to the maximum extent practicable/feasible. Develop voluntary guidelines for development in Rural Communities that would accomplish the same purpose. (GP2020 Revised)*".
    b. Sonoma County General Plan 2020 Policy C-WR-4b, which states, "*Use water effectively and reduce water demand by developing programs to: (1) Increase water conserving design and equipment in new construction, including the use of design and technologies based on green building principles; (2) Educate water users on water conserving landscaping and other conservation measures; (3) Encourage retrofitting with water conserving devices; (4) Design wastewater collection systems to minimize inflow and infiltration; and (5) Reduce impervious surfaces to minimize runoff and increase groundwater recharge. (GP2020)*".
    c. Sonoma County General Plan 2020 Policy C-WR-4f, which states, "*To minimize generation of wastewater and encourage conservation of Coastal water resources, require use of water saving devices as prescribed by the local water provider in all new developments. (New)*".
    d. California statutes and regulations (e.g., California Code, Division 3. Dams and Reservoirs) related to dam safety.

    As elaborated below, the missing County policies and state regulations are directly relevant to the water supply and flood hazard assessments for the project as elaborated below.

2. The DEIR Project Description is not detailed enough to evaluate potential impacts on hydrology and the environment. The DEIR does not contain a project plan with sufficient detail about land use change to complete the necessary hydrologic and water quality assessments to determine impacts from the project. Due to the lack of an adequate Project Description, I don't agree with the DEIR determinations that potential hydrologic and water quality impacts are less than significant and that no mitigation measures will be required for the following reasons.

a. Impact 3.9-1 - The DEIR states that potential impacts to federal, state, and local water quality standards are less than significant. However, the DEIR has not analyzed how changes in site runoff and associated erosion potential will change. Based on my experience, this analysis would require detailed hydrologic and hydraulic modeling that incorporates all changes in land use (esp. impervious surfaces) and runoff estimates to determine where and by how much flow rates (and erosion potential) may impact receiving waterways both on- and off-site. BMPs and other measures would then be designed correctly to mitigate these impacts. This is the primary way the DEIR can address the significance of the impact before and after mitigation.

b. Impact 3.9-2 - The DEIR states that the project will not interfere with groundwater recharge such that the project may impede sustainable groundwater management of the basin and associated potential impacts are less than significant. However, the DEIR does not contain any detailed technical analysis of how the project development will alter groundwater recharge. The DEIR has an obligation to describe any potential changes in recharge. Simply stating that BMPs that support groundwater recharge will be integrated into the Project does not demonstrate that they will be sufficient to mitigate potential impacts.

c. Impact 3.9-3 - The DEIR states that Project development would not substantially alter the existing drainage patterns or result in substantial erosion and flooding on- or off-site or contribute runoff that would exceed the capacity of existing or planned storm drain systems. Thus, the DEIR concludes that associated impacts are less than significant. These conclusions are not substantiated as the DEIR does not present results from any hydrologic on hydraulic analyses to demonstrate to what degree the project may increase runoff rates and erosion potential from new or improved development. The assumption that adhering to County mandated BMPs will reduce flooding and erosion impact to below significant has not been demonstrated. Instead, the DEIR defers analysis and mitigations for hydrologic and water quality impacts.

d. Impact 3.9-4 – The DEIR states that the potential to expose people and structures to significant risk or loss, injury or death involving flooding from dam failure is less than significant. However, this is completely contrary to the California Division of Safety of Dams (DSOD) conclusions about Project dam safety presented in Section 3.9.2.5 (Flooding – Flooding from Dam Failure, pg. 286-287) of the DEIR. Page 286 of the DEIR states, "The DSOD has classified the downstream hazard of a failure at Fern Lake as high". On page 287, the DEIR states, "*The DSOD has classified the downstream hazard of a failure at Suttonfield Lake as extremely high*." These statements alone suggest this potential impact is not "less than significant". The DEIR does present inundation maps associated with these failures but provides no further analysis on how these potential impacts will be mitigated apart from the statement (pg. 287) "*Specific geotechnical investigations of the dams at Fern and Suttonfield Lakes would need to be conducted to determine their potential for failure*." However, this is a deferred analysis, which does not support the findings of "less than significant" impacts and "not applicable" mitigations.

e. Impact 3.9-5 - The DEIR states that implementation of the Project would not conflict or obstruct implementation of a water quality control plan or sustainable groundwater management plan. Thus, the DEIR concludes that associated impacts are less than significant. However, for the same reasons presented above (items 2a. – 2c.), the DEIR does not present any technical justification for this determination and should be considered inadequate and incomplete.

3. An important analysis of the SDC project is the determination if there are sufficient water supplies to meet proposed project water demands. Appendix D of the DEIR presents the results of this analysis. Based on my review of Appendix D, I've identified several mistakes and other issues that suggest the DEIR does not demonstrate there is sufficient water supply to meet future (2045 full buildout) demands.

   Table 2 (pg. 14) of Appendix D indicates that estimated Project annual water demands by the year 2045 will be 342 acre-feet per year (AFY). Table 9 (pg. 31) of Appendix D indicates that available annual supply that will be 100% reliable for the period 2030-2045 is 356 AFY. Comparison of available and reliable water supply (356 AFY) to full buildout demands (342 AFY) suggest there is very little margin for error in terms of future water supply management. The DEIR supply estimate is also concerning to me in that the historic (1969-2007) water use (demands) for the SDC averaged 622 AFY and peaked at 1,143 AFY in 1986 (pg. 12, Appendix D). I'm suspect that the historic SDC water use is nearly twice the volume of estimated future full buildout (2045) Project water demands, especially when the Project proposes to build an additional 1000 residential units and hotel and reoccupy and/or expand the commercial and industrial uses (see Table 1, pg. 13 of Appendix D). Even with conservation measures, I would expect that Project water demands would be similar to if not larger than historic use. The next paragraphs elucidate this opinion.

   In reviewing and cross-checking the data and information presented in Tables 1 and 2 of Appendix D, I identified several questionable results that suggest the DEIR water demands are significantly underestimated. These findings are as follows.

   a. Table 2 (pg. 16 of Appendix D) only provides employee water use estimates for the proposed hotel. Water use by guests staying in the 100,000 square foot hotel is not accounted for in the annual water demand estimate. Incorporating guest water use into the demand estimate could easily result in total annual project demands greater than reliable supply.

   b. To better evaluate the DEIR demand estimates, I created Table A (below), which merges data from Tables 1 and 2 in DEIR Appendix D. In doing this exercise, I identified a significant math error in the DEIR demand estimates for General Commercial, Office, Public/Industrial, and Research & Development land uses presented in Table 2 of

Appendix D. When independently calculating water demands using the 2045 land use areas and Water Use Factors provided in Appendix D, the respective 2045 water demands for the General Commercial, Office, Public/Industrial, and Research & Development land uses result in values that are two orders of magnitude higher than those reported, which results in an increased annual Project water demand of 9846 AFY (see Table A).

c. The Permit Sonoma website[1] provides guidelines (8-2-1 Water Supply, Use and Conservation Assessment Guidelines) for the preparation of Water Supply Assessments. The purpose of this policy is to provide guidance to applicants and their representatives on how to prepare a Water Supply, Use, and Conservation Assessment (henceforth, the "Assessment"). The Assessment may be a standalone document, or supplemental to a hydrogeologic study, Zero Net Use report, or other water supply related report. These guidelines are intended for discretionary and ministerial projects. Discretionary projects that are dependent on groundwater or surface water will typically require an Assessment with the use permit application. The Assessment will inform the environmental review process and conditions of approval. The authority of the Assessment falls under Sonoma County General Plan, Water Resource Element Goals WR-2 and WR-4, Objective WR-4.1, WR-4.2, and WR-4.3, and Policies[2] WR-2c, WR-2d, WR-2e, WR-4b, and WR-4f. Therefore, the DEIR Water Supply Assessment (Appendix D) should adhere to County Guidelines. Appendix A to the County's Guidelines has water use estimates for residential, landscape, agricultural, and Commercial and Industrial uses that are greater than those factors presented in Table 2 of Appendix D (see Table B). Applying the Sonoma County water use estimates to Project water demand estimates results in higher residential and irrigated area water demands than presented in the DEIR (see Table B below).

In summary, correcting math errors and applying the Sonoma County guidelines water use estimates to the DEIR demand estimate tables results in a total annual Project water demand of 10,231 AFY, a values three times higher than reported reliable supply (356 AFY). This annual total demand will be even higher when hotel guest water use is considered.

[1] https://permitsonoma.org/policiesandprocedures/8-2-1watersupplyuseandconservationassessmentguidelines

[2] Note: these policies are not included in Hydrology/Water Quality Regulatory Setting section (3.9.1 on pg. 270) of the DEIR. See Comment 1 above.

TABLE A: Corrected DEIR Water Demand Estimates

Land Use	Total Land Use	Land Use Units	Water Use Factor	Water Use Factor Units	DEIR Est. Water Use (AFY) - 2045	Corrected DEIR Est. Water Use (AFY) - 2045
Single Family Residential	250	du	244	gpd/du	68	68
Multi-Family Residential	500	du	100	gpd/du	56	56
"Missing Middle" Residential	250	du	172	gpd/du	48	48
Hotel	100,000	sf	0.16	AFY/employee	28.0	26.7
General Commercial	40,000	sf	1.79	AFY/100 sf	7.2	716.0
Office	127,500	sf	1.79	AFY/100 sf	23	2282
Public/Institutional	155,000	sf	1.79	AFY/100 sf	28	2775
Research & Development	127,500	sf	2.35	AFY/100 sf	30	2996
Total Open Space	3,116,000	sf				
Irrigated Park Area	488,000	sf			21	21
Other Irrigated Common Space Areas (e.g., landscaped medians)	148,000	sf			2.9	2.9
System Water Losses			9.5%		30	854
				Total	**342**	**9846**

TABLE B: Corrected DEIR Water Demand Estimates using selected Sonoma County Water Use Factors

Land Use	Total Land Use	Land Use Units	Water Use Source	Water Use Factor	Water Use Factor Units	Estimated Water Use (AFY) - 2045	DEIR Est. Water Use (AFY) - 2045
Single Family Residential	250	du	Sonoma County	0.5	AFY/du	125	68
Multi-Family Residential	500	du	Sonoma County	0.5	AFY/du	250	56
"Missing Middle" Residential	250	du	Sonoma County	0.5	AFY/du	125	48
Hotel	100,000	sf	Original EIR	0.16	AFY/employee	28	28
General Commercial	40,000	sf	Original EIR	1.79	AFY/100 sf	716	7.2
Office	127,500	sf	Original EIR	1.79	AFY/100 sf	2282	23
Public/Institutional	155,000	sf	Original EIR	1.79	AFY/100 sf	2775	28
Research & Development	127,500	sf	Original EIR	2.35	AFY/100 sf	2996	30
Total Open Space	3,116,000	sf	Original EIR	-	-	-	-
Irrigated Park Area	11	acres	Sonoma County	3.6	AFY/acre	40	21
Other Irrigated Common Space Areas (e.g., landscaped medians)	3	acres	Sonoma County	1.8	AFY/acre	6.1	2.9
System Water Losses	-	-	Original EIR	9.5%	-	888	30
					Initial Sum	9343	312
					Total	**10,231**	**342**

Please feel free to contact me with any questions regarding the material and conclusions contained in this letter.

Sincerely,

Greg Kamman, PG, CHG
Senior Ecohydrologist

Greg Kamman, PG, CHG
Senior Ecohydrologist

Education

MS, 1989, Geology, Sedimentology and Hydrogeology, Miami University, Oxford, OH

BA, 1985, Geology, Miami University, Oxford, OH

Professional Registration

1993, Professional Geologist, California, #5737

1995, Certified Hydrogeologist, California, #360

Professional Experience

cbec, inc., eco-engineering, West Sacramento, CA, Senior Ecohydrologist, 2020-present

Kamman Hydrology & Engineering, Inc., San Rafael, CA, Principal Hydrologist/Vice President, 1997-2020

Balance Hydrologics, Inc., Berkeley, CA , Sr. Hydrologist/ Vice President, 1994-1997

Geomatrix Consultants, Inc., San Francisco, CA, Project Geologist/Hydrogeologist, 1991-1994

Environ International Corporation, Princeton, NJ, Sr. Staff Geologist/Hydrogeologist, 1989-1991

Miami University, Oxford, OH, Field Camp Instructor and Research Assistant, 1986-1989

Greg Kamman is a professional geologist and certified hydrogeologist with over 30 years of technical and consulting experience in the fields of geology, hydrology, and hydrogeology. He specializes in directing and managing projects in the areas of surface and groundwater hydrology, stream and tidal wetland habitat restoration, water supply and water quality assessments, water resources management, and geomorphology. Mr. Kamman has worked extensively throughout California's coastal watersheds and estuaries, and on multiple projects in Oregon and Hawaii.

Mr. Kamman's experience and expertise includes evaluating surface and groundwater resources and their interaction, stream and wetland habitat restoration assessments and design, characterizing and modeling basin-scale hydrologic and geologic processes, assessing watershed hydraulic and geomorphic responses to land-use change , and designing and conducting field investigations characterizing surface and subsurface hydrologic and water quality conditions. Greg commonly works on projects that revolve around sensitive fishery, wetland, wildlife, and/or riparian habitat enhancement within urban and rural environments. Mr. Kamman performs many of these projects in response to local, state (CEQA) and federal statutes (NEPA, ESA), and other regulatory frameworks. Mr. Kamman frequently applies this knowledge to the review and expert testimony on state and federal water operation plan EIR/EIS reports, Groundwater Sustainability Plans, Habitat Conservation Plans, and biological assessments.

Mr. Kamman is accustomed to working multi-objective projects as part of an interdisciplinary team including biologists, engineers, planners, architects, lawyers, and resource and regulatory agency staff. Mr. Kamman is a prime or contributing author to over 360 technical publications and reports in the discipline of hydrology, the majority pertaining to the protection and enhancement of aquatic resources. Mr. Kamman has taught the following courses: stream restoration through U.C. Berkeley Extension (2001-2008); wetland hydrology through San Francisco State University's Romberg Tiburon Center (2007 and 2012-2014); and presented webinars (2020) to California Water Boards staff on hydrologic and hydraulic modeling. He has devoted his career to the protection, enhancement and sustainable management of water resources and associated ecosystems.

SELECTED EXPERIENCE

Floodplain Management Projects

Flood Reduction, Mitigation Planning, and Design on Yreka Creek, Siskiyou County, CA
City of Yreka as subcontractor to WRA, Inc., 2008-2010

Mr. Kamman completed a series of field and hydraulic model investigations for restoration planning and design along Yreka Creek to reduce flood hazards and potential damage to the City's water treatment plant and disposal field infrastructure. This work also addresses and satisfies dike repair mitigation conditions stipulated by state resource agencies. While achieving these goals, Mr. Kamman tailored analyses and study objectives to assist the City in: enhancing the ecological floodplain restoration along Yreka Creek; providing opportunities for expanded public access and trail planning consistent with the goals of the Yreka Creek Greenway Project; and improving the water quality of Yreka Creek.

Key elements of this work included: review and synthesize existing information; identify and analyze the feasibility for three conceptual alternatives; and conceptual design and report preparation. Funding for implementation of restoration work over such a large area was a significant concern to the City. Therefore, designs identify and define phasing in a fashion that gives the City flexibility in implementation.

SELECTED EXPERIENCE *(CONTINUED)*

West Creek Drainage Improvement Assessment, Marin County, CA
Marin County Flood Control, 2006-2008

Mr. Kamman prepared a study focused on characterizing existing flood conditions and developing and evaluating flood reduction measures along West Creek in Tiburon. The work was completed through the implementation of hydrologic and hydraulic feasibility and design assessments. The conceptual design and analysis of potential flood reduction strategies (alternatives) was completed through the development of a HEC-RAS hydraulic model that simulates historic, existing and proposed project flood conditions. It was intended that the conceptual design developed under this scope of work would be of sufficient detail and quality to initiate project permitting and the environmental compliance process and documentation. Opportunities for riparian corridor and aquatic habitat enhancement were also considered and integrated into the conceptual design. Mr. Kamman also developed and assessed six alternative flood hazard reduction measures. The hydraulic model results for each alternative were compared against baseline conditions in order to evaluate their ability to alleviate flood hazards.

Gallinas Creek Restoration Feasibility Assessment, Marin County, CA
San Francisco Bay Institute, 2003-2005

Mr. Kamman completed a feasibility assessment for restoration of Gallinas Creek in northern San Rafael. Restoration will require removal of a concrete trapezoidal flood control channel and replacement with an earthen channel and floodplain in a "green belt" type corridor. Work included the collection of field data and development of a HEC-RAS hydraulic model to evaluate and compare existing and proposed project conditions. Designs must continue to provide adequate flood protection to the surrounding community. The study also includes and evaluation of existing habitat values, potential habitat values, and restoration opportunities and constraints.

Hydrologic and Hydraulic Evaluation for Trinity County Bridge Replacement, Trinity County, CA
Trinity County Planning Department, 2002

Mr. Kamman completed technical peer review of peak flow estimates and hydraulic design parameters associated with the replacement of 4 bridges across the upper Trinity River in Trinity County, California. A primary study component was accurately predicting the magnitude and frequency of flood releases from Trinity Dam. Numerous flood frequency analytical approaches were evaluated and used throughout this study.

Restoration of Lower Redwood Creek Floodway and Estuary, Humboldt County, CA
California State Coastal Conservancy and Humboldt County DPW, 2002-2003

Mr. Kamman provided technical review for the development of a hydraulic model to evaluate river and estuary restoration alternatives along the lower portions of Redwood Creek between Orrick (Highway 1) and the Pacific Ocean. This work was completed to evaluate the feasibility for creek/estuary restoration alternatives developed by the County, and effects on flood hazards along this flood-prone reach.

In order to better address and evaluate the current flood hazards along the entire floodway and identify potential flood hazard reduction measures, Mr. Kamman was retained to update HEC-2 models previously prepared by the Army Corps, and to evaluate the impacts of vegetation encroachment (increased roughness) and sediment deposition on floodway conveyance. Mr. Kamman expanded the Corps hydraulic model with newly completed channel surveys and channel roughness observations. The impetus for this work was to assist the County in identifying mutually beneficial strategies for ecosystem restoration and flood hazard reduction. Technical work was completed under close coordination and communication with county engineers. Study results and findings were presented at public meetings of local area landowners and stakeholders.

Tembladero Slough Small Community Flood Assessment, Monterey County, CA
Phillip Williams & Associates, Ltd., 1997

Mr. Kamman completed a flood information study of Tembladero Slough near Castroville on behalf of the San Francisco District Corps of Engineers. The purpose of this work was to identify and document local flood risks existing in the community and propose potential floodplain management solutions as part of the Corps 1995/1997-flood recovery process. Work centered on conducting a field reconnaissance, reviewing available historical data, and conducting discussions/interviews with local landowners and agency personnel.

Fluvial Projects

Muir Woods National Monument Bank Stabilization Plan for Conlon Creek, Marin County, CA
Golden Gate National Parks Conservancy (GGNPC), 2018-present

Mr. Kamman developed a grading and drainage plan for the Conlon Avenue Parking Lot, located adjacent to Redwood Creek and sensitive Coho salmon habitat. More recently, he has assisted GGNPC and the NPS in assessing the planning and design for creek bank stabilization and ecological enhancement at a failed culvert on a tributary channel at the project site. This work includes constructing a HEC-RAS model to evaluate: culvert removal and channel design; fish passage; and water quality impacts. Work is currently in development of 50% engineering design.

Hydrology and Hydraulic Assessments for Design of Butte Sink Mitigation Bank Project, Colusa County, CA
WRA, Inc., 2017-2018

Mr. Kamman was retained to provide hydrology and hydraulic modeling support in the development of design and Draft Prospectus for the Butte Sink Mitigation Bank (Bank). This work entailed developing the necessary hydrology information, hydraulic model and documentation to support further design, environmental compliance and agency approvals/permitting of the Bank. The main objective of work was to develop a design that provides the necessary ecological conditions and functions for successful establishment and operation of the Bank.

Lagunitas Creek Salmonid Winter Habitat Enhancement Project, Marin County, CA
Marin Municipal Water District, 2013-2018

Mr. Kamman designed and led a study to evaluate opportunities to enhance winter habitat for coho and other salmonids in Lagunitas Creek and its largest tributary - Olema Creek. This work was done as a two-phase assessment and design effort. The first phase (completed in 2013) included a winter habitat assessment to evaluate existing juvenile salmonid winter habitat in Lagunitas Creek and lower Olema Creek. The results of this assessment were used to prioritize winter habitat needs, and identify opportunities for winter habitat enhancement to increase

SELECTED EXPERIENCE *(CONTINUED)*

the winter carrying capacity of coho salmon and steelhead. The second phase (completed in 2017) consisted of a designing winter habitat enhancements. These enhancements focused on restoring floodplain and in-channel habitat structures. Winter habitat enhancement work also needed to consider potential impacts to or benefits for California freshwater shrimp (Syncaris pacifica), a federally endangered species.

This work included field reconnaissance, topographic surveys and the preparation of final design drawings at nine different project sites. An overall self-maintaining design approach was developed to guide individual project plan, with minimal earthwork and disturbance to existing riparian and wetland habitat. Self-sustained, natural evolution of a multi-thread channel within a more active floodplain is a desired outcome of project actions. Design elements and structures are intended to enhance or restore natural hydrologic processes to promote geomorphic evolution of more active high flow (side) channels and floodplain. Design elements include construction of 24 individual log structures.

Lower Miller Creek Management and Channel Maintenance, Marin County, CA
Las Gallinas Valley Sanitary District, 2013-2015

Mr. Kamman was commissioned to formulate and implement a plan for sediment removal and improved flood flow conveyance in the Lower Miller Creek channel. The need for improved flood and sediment conveyance is driven by the following factors. Progressive accumulation of course sediment in the project reach had reduced area wide discharge efficiencies along Miller Creek and at District outfalls. The District had an immediate need to dredge Lower Miller Creek to protect existing operations and facilities. Miller Creek supports a population of federally listed Steelhead, and adjacent wetland areas potentially support other state and federally listed special status species. Therefore, permitting requirements and cost efficiency required minimizing the extent and frequency of channel excavation/maintenance that may adversely impact habitats in the wetland and riparian corridor.

The design objective of the project was to define and optimize an integrated channel maintenance, flood, and sediment management plan, that protects existing facilities from stream and coastal flood hazards. The plan's objective was to minimize costs and ecological impacts of future anticipated and designed maintenance activities required under District operations. Working with District Staff, Mr. Kamman developed a suite of potential project alternatives and identified a preferred approach. Mr. Kamman completed all CEQA compliance (IS/MND) and permitting. Mr. Kamman also managed and directed development of engineered drawings and assisted in bid document preparation.

Mr. Kamman provided site assessment, long term management planning and channel maintenance support to the Sanitary District to maintain flood conveyance, manage sediment aggrading at District outfalls, and improve ecological values in the intertidal Bayland reaches of Miller Creek. The creek supports multiple federal and state listed endangered species. Initial work included completing hydraulic and geomorphic assessments to characterize causes of channel aggradation, and quantify sediment yields. Assessments included evaluation of climate change impacts on habitat and flood hazards, and water quality modeling of District outfalls to quantify tidal exchange and dilution. Based on this analysis and supporting biological resource assessments, Mr. Kamman identified alternatives for channel maintenance, performed a cost benefit assessment of dredging alternatives, and is assisted the District in developing short and long term management objectives. Mr.Kamman also led a multidisciplinary design team in the preparation of engineering plans and specifications as well as permits and environmental compliance documents.

Vineyard Creek Channel Enhancement Project, Marin County, CA
Marin County Department of Public Works, 2007-2013

Mr. Kamman managed the preparation of designs and specifications for a flood conveyance and fish habitat and passage improvement project on Vineyard Creek. Creek corridor modifications included replacing the box culvert at the Center Road crossing with a free span bridge or bottomless arch culvert (civil and structural design by others), providing modifications to the bed and bank to eliminate erosion risks to adjacent properties and improve water quality, promoting active channel conveyance of both water and sediment, and providing improved low and highflow fish passage, improved low flow channel form and enhanced in-stream habitat, repairing eroding banks, and expanding/enhancing adjacent channel floodplains. The riparian corridor was replanted to provide a low-density native understory, "soft" bank erosion protection, and increased tree canopy along the tops of banks. Mr. Kamman prepared the JARPA for the project and conducted permit compliance and negotiations with all participating resource agencies. Designs and permitting also address the known presence of Native American artifacts. This work was contracted under an expedited design schedule and phased construction was initiated the summer of 2008 and continued the summer of 2009.

Bear Valley Creek Watershed and Fish Passage Enhancement Project, Marin County, CA
The National Park Service and Point Reyes National Seashore Association, 2005-2013

Working on behalf of the NPS and PRNSA, Mr. Kamman completed a watershed assessment and fish passage inventory and assessment for Bear Valley Creek. Work included a geomorphic watershed assessment and completing field surveys and hydraulic modeling (including flood simulations) of ten road/trail crossings to identify and prioritize creek and watershed restoration efforts while considering and addressing current flooding problems at Park Headquarters – a major constraint to channel restoration efforts that would likely exacerbate flooding. Mr. Kamman also completed a suite of conceptual restoration designs (Phase 1) including: the replacement of two county road culvert crossings with bridges; channel creation through a ponded freshwater marsh (former tidal marsh); and replacement of 4 trail culverts with prefabricated bridges; and associated in-channel grade control and fishway structures. Engineered drawings and specifications were also developed for some of these sites to assist PORE with emergency culvert replacements after damages sustained during the New Year's Eve flood of 2005. Mr. Kamman also directed geotechnical, structural and civil design of project components.

Two projects were completed in 2006 on emergency repair basis resulting from flood damages suffered during the New Year's Eve storm of 2005. The two most recent projects were constructed in 2013, consisting of a large bank repair and adjacent to main access road/trail and culvert replacement further upstream on same road. The bank repair utilized bioengineering approaches including engineered log revetments and log diversion vanes.

SELECTED EXPERIENCE *(CONTINUED)*

Kellogg Creek Restoration Project, Contra Costa County, CA
Olberding Environmental on behalf of the Contra Costa County Water District, 2012-2013

Mr. Kamman led the development of PS&E to restore 3,000 linear feet of riparian and associated creek corridor habitat. Project was designed as compensatory mitigation for direct and indirect impacts to jurisdictional waters from the Los Vaqueros Reservoir Expansion Project that Contra Costa Water District. Work included field investigations and data analysis to characterize hydrologic/ geomorphic conditions and numerical modeling to optimize desired inundation and hydroperiods. Work was completed under subcontract to.

Miller Creek Sanitary Sewer Easement Restoration, Marin County, CA
Las Gallinas Valley Sanitary District, 2010

Working on behalf of the District, Mr. Kamman completed field surveys and technical feasibility studies to develop engineering plans and specifications for a stream bank restoration project to protect an exposed sanitary sewer pipeline, stabilize incised banks, and promote an ecologically healthy stream corridor along an approximately 50 linear foot damaged reach of Miller Creek. The design includes backfill and materials to accommodate construction of a vegetated stabilized slope. The eroded bank repair included design of a 1:1 Envirolok vegetated slope with geogrid reinforced soil lifts extending eight to ten feet back from the slope face. One-quarter-ton rock will be placed in front of the Envirolok wall at the toe of the reconstructed bank to provide added scour protection. In order to perform the work, the project site will be dewatered. An existing felled tree perpendicular to the creek flow will be relocated and secured into the right creek bank with root wad remaining in active channel. All work on the bank and within the creek bed must be completed pursuant to project permits due to presence of steelhead trout.

California Coastal Trail Planning and Design at Fitzgerald Marine Reserve, San Mateo County, CA
WRA, Inc., 2008-2009

Mr. Kamman provided hydrology and hydraulics expertise in the planning and design for the 0.25-mile segment of the California Coastal Trail at the Fitzgerald Marine Reserve. The project was overseen by the San Mateo County Parks Department. This segment of Coastal Trail provides improved access from the trailhead to the beach as well as a free span bride over Vicente Creek. Greg completed the field surveys and hydraulic modeling to assist an interdisciplinary team to design the project. Understanding the hydrology of Vicente Creek and quantifying flood conditions was critical to successfully designing and constructing the free span bridge. He also evaluated how creek hydrology and coastal wave processes interact at the beach outfall in order to identify opportunities and constraints to beach access improvements (which will include crossing the creek on the beach) during both wet and dry season conditions in order to evaluate both permanent and seasonal crossing design alternatives.

Hydrologic Assessment and Conceptual Design for Conservation and Wetland Mitigation Bank Project, Stanislaus County, CA
WRA, Inc., 2009

Working as a subcontractor to WRA, Inc., Mr. Kamman provided hydrology, geomorphology and engineering support for the planning and design for a Conservation and Wetland Mitigation Bank on the San Joaquin River, in the Central Valley near Newman, California. The property is currently owned by the Borba Dairy Farms. The primary objective of the study was to characterize the hydrologic and geomorphic controls on the spatial distribution of habitat types. To meet this objective, Mr. Kamman's assessment included: (1) collecting and synthesizing hydrologic data to characterize existing and historic streamflow, geomorphic and shallow groundwater conditions; (2) filling a data gap by collecting topographic data of hydrologic features; (3) developing a hydraulic model capable of predicting water surface profiles for a range of design flows; and (4) quantifying the linkage between surface water/groundwater conditions and specific vegetation communities and habitat types through implementation of reference site assessments. Mr. Kamman also provided conceptual design and permitting support in evaluating habitat enhancement and creation opportunities on the site.

Redwood Creek Floodplain and Salmonid Habitat Restoration, Marin County, CA
Golden Gate National Recreation Area and Golden Gate Parks Conservancy, 2005-2008

Mr. Kamman lead development of a preferred project alternative and final project design drawings and specifications for a floodplain and creek restoration and riparian corridor enhancement effort on lower Redwood Creek above Muir Beach at the Banducci Site. A primary objectives of the project was to: improve salmonid passage/rearing/refugia habitat; riparian corridor development to host breeding by migratory song birds; and wetland/pond construction to host endangered red-legged frog. The preferred design includes: excavation along the creek banks to create an incised flood terrace; engineered log deflector vanes; removing and setting back (constructing) approximately 400-feet of levee; creating in- and off-channel salmonid rearing and refugia habitat; reconnecting tributary channels to the floodplain; and creating California red-legged frog breeding ponds. Designs were completed in 2007 and the project constructed in the summer of 2007.

Considerable hydraulic modeling was completed to evaluate and develop means to help reduce chronic flood hazards to surrounding roadways and properties. Alternatives that included set-back levees and road raising were developed and evaluated. Detailed and careful hydraulic (force-balance) analyses and computations were completed as part of engineered log deflector designs. These were unique and custom designed structures, building on past project efforts and in consultation with other design professionals.

This project demonstrates Mr. Kamman's ability to work closely with the project stakeholders to develop a preferred restoration alternative in a focused, cost-effective and expedited fashion. This was achieved through close coordination with the NPS and the effective and timely use of design charrette-type meetings to reach consensus with participating stakeholders. Conceptual through full PS&E were completed on-time and on-budget in 2007 and was project constructed in the fall of 2007. Mr. Kamman worked closely with NPS staff to "field fit" the project, by modifying grading plans to protect existing riparian habitat. Mr. Kamman also provided construction management and oversight to floodplain grading and installation of engineered log structures. Based on field observations, the project is performing and functioning as desired.

Pilarcitos Creek Bank Stabilization Project, San Mateo County, CA
TRC Essex, 2006-2007

Mr. Kamman directed field surveys and technical modeling analyses to develop restoration design alternatives for a Bank Stabilization Project on Pilarcitos Creek

SELECTED EXPERIENCE *(CONTINUED)*

in unincorporated San Mateo County, California. This work included hydrology and hydraulic design and preparation of plan sheets and technical specifications as well as a revegetation plan. Due to the importance of protecting an existing gas mainline, the design package will be completed in close coordination with TRC Essex geotechnical staff and revegetation subcontractor and PG&E civil staff. Design feasibility analyses focused on developing hydraulic design criteria for the project, including: estimates of design flood flow magnitudes (2-, 5-, 10-, 25-, 50- and 100-year floods); water surface elevation estimates for a suite of design floods; associated average channel velocities and shear stresses; and estimates for riprap sizing for channel bank toe protection. Plan sheets, technical specifications and cost estimates were provided for review and approval.

Watershed Assessments

Evaluation of Project Impacts on Oregon Spotted Frog, Klamath County, OR
Oregon Water Watch and Earthjustice, 2016-2019

Mr. Kamman designed a suite of hydrologic, hydraulic and geomorphic studies to evaluate proposed change operations of the Crane Prairie, Wickiup and Crescent Lake dams and reservoirs as related to harm to Oregon spotted frogs. Work began with analyzing impacts associated with proposed water delivery operations and developing a proposed alternative prioritizing protection and enhancement of frog habitat. This work followed with a technical review and critique of the USFWS's Biological Assessment. Work included preparation of four declarations for the clients.

Tennessee Hollow Creek Riparian Corridor Restoration, San Francisco County, CA
Presidio Trust, 2001-present

Mr. Kamman has been leading and assisting the Trust and Golden Gate National Recreation Area (GGNRA) in the planning and design on over a dozen multi-objective riparian corridor restoration and watershed management projects in the Tennessee Hollow/Crissy Marsh watershed since 2001. Specific project objectives include: daylighting creeks; riparian corridor restoration; expanding Crissy Marsh; enhancing recreation, education, archeological, and cultural resource opportunities; improving water quality discharges to San Francisco Bay; and remediation of numerous landfills within the watershed. Typical initial phases of work focus on characterizing surface and groundwater conditions within each project area and identifying opportunities and constraints to restoration of natural wetlands and creek/riparian corridors. Notable challenges of this work include restoring heavily disturbed natural resources in an urban setting while integrating designs with recreation, archeology/cultural resources, education and remediation programs. Mr. Kamman has acted as lead hydrologist and designer on eight separate reaches in the 271-acre Tennessee Hollow Creek watershed and several other projects within and in the vicinity of Mountain Lake.

All task authorizations under these on-call and individual design contracts and included hydrology and water quality assessments and conceptual restoration planning and design. The project areas overlapped both the Presidio Trust and NPS-GGNRA management areas. Preliminary construction cost estimates for project alternatives within the Tennessee Hollow watershed range from $10- to $20- million. Several restoration projects are also tied to providing mitigation for the current San Francisco Airport expansion and Doyle Drive Seismic Improvement projects. Several projects have been constructed since 2012 (Thompson's Reach, El Polin Loop), two projects (East Arm Mtn. Lake and YMCA Reach) were constructed in 2014, and MacArthur Meadow restoration in 2016.

This work illustrates the Mr. Kamman's ability to complete a broad variety of hydrologic analyses, including: multiple years of rigorous and thorough surface water and groundwater hydrologic and water quality monitoring throughout the entire watershed to characterize and quantify existing hydrologic conditions; development of a detailed watershed-scale water budget for existing and proposed land-used conditions (capturing existing and proposed vegetation cover types and land use activities) to calculate groundwater recharge estimates input into the numerical watershed model; preparation of EA sections on water resources and water quality (NEPA compliance) regarding Environmental Conditions, proposed Impacts, and Proposed Mitigations associated with the project; preparing detailed alternative plans; and coordination and preparation of engineered plans/specifications for construction. All work was completed on budget and in a timely fashion.

Mountain Lake Water Budget, San Francisco County, CA
Presidio Trust, 2012-2017

Mr. Kamman was retained to develop a water balance model for Mountain Lake in the Presidio of San Francisco. Through development of a water balance model, the Trust seeks to understand: the major source(s) of inflow to both Mountain Lake; anticipated seasonal (monthly) changes in water level relative to various outflow assumptions; and the relationship of surface and groundwater interaction. This information gained from this study will be used to: 1) better understand and manage lake levels for ecological habitats; 2) identify flood storage capacity of Mountain Lake and fluctuations in lake level under various storm conditions; 3) better understand and maintain wetland habitat in the east arm; and 4) complete mass balance calculations to assess water quality in and feeding into the lake.

To implement this study, Mr. Kamman developed a water budget model to identify and quantify the primary water inputs and outputs to the lake and determine major controls over water storage. Primary water budget variables analyzed includes: precipitation; evaporation/evapotranspiration; groundwater exchange; and surface runoff. This study also included a long-term field investigation completed between 2012 and 2016 to: identify all point source inputs such as culverts and drainage outlets; identify diffused surface runoff inputs from surrounding lands, including a golf course; better characterizing the function and performance of the primary lake outfall structure; monitor groundwater levels surrounding the lake; and continuously monitor lake water level and storage over a mult9i-year period. These data were used to quantify water budget variables used to build the water budget model. Precipitation and barometric pressure data used in the model was provided by the Trust maintained weather station. Model daily evaporation estimates came from a variety of local area gauges maintained by state agencies.

The water budget model developed for this study is successful in accurately simulating historic water level conditions. The model using a daily time-step appears more accurate than model using a weekly time-step, but both provide reasonable agreement with observed conditions. The model is highly sensitive to groundwater exchange with the lake. The water budget is also a proven useful tool for the design and analysis of improvements to the lake outfall structure and establishing flood storage needs to protect the adjacent highway.

SELECTED EXPERIENCE *(CONTINUED)*

Cordilleras Creek Hydrologic Assessment, San Mateo County, CA
City of Redwood City, 2002-2003

Mr. Kamman assisted the Cordilleras Creek Watershed Coordinator in planning, seeking funding, and implementing a hydrologic and biologic assessment of the Cordilleras Creek watershed. Work completed included completing a full creek reconnaissance and channel stability assessment, preparation of a watershed assessment work plan, presentations at public meetings, and study/review of flooding issues in the watershed. Challenges faced in this predominantly privately owned watershed include removal of numerous fish passage barriers and educating/coordinating property owners.

Capay Valley Hydrologic and Geomorphic Watershed Assessment, Yolo County, CA
Yolo County RCD, 2008-2010

Mr. Kamman designed and supervised a hydrologic, geomorphic watershed assessment, and conceptual restoration design for the Capay Valley segment of Lower Cache Creek . Funding for the project was from a CALFED Watershed Program grant. The Capay Valley reach of Cache Creek experiences considerable stream bank erosion, which contributes to downstream sedimentation. The channel instability also threatens adjacent homes and can negatively impact the riparian habitat along the creek that functions as an important wildlife corridor from the Western Coastal Range to the Yolo Bypass. Additionally, a significant proportion of methylmercury transported into the Bay-Delta originates from the Cache Creek watershed. The main goal of this proposed study is to address both the causes and the aforementioned consequences of bank erosion.

The assessment was designed to evaluate and quantify changes in hydrologic and geomorphic conditions in response to historical changes in land-use and water development (e.g., diversions, reservoir construction, groundwater pumping, etc.). This assessment also evaluated how historic human induced changes in hydrologic and geomorphic conditions affect riparian ecology in terms of the lost or altered floodplain area, character, and inundation frequency. A key product of this assessment was to distinguish between "natural" and "accelerated" bank erosion, and to identify the underlying causes (both natural and anthropogenic) so that appropriate solutions can be developed. Desired outcomes of the study included: reduce bank erosion by developing restoration designs for typical trouble sites; produce a ranking system to prioritize sites for stabilization and restoration; contribute to community education through watershed science education and the Yolo STREAM Project outreach program; improve water quality through reduction in accelerated erosion; and contribute to riparian corridor restoration and support the RCD's Wildlife Conservation Board funded efforts to remove non-native tamarisk and around from the creek corridor. Work was completed through a broad spectrum of field and analytical investigations that received close review by the RCD, stakeholders, and a Technical Advisory Committee.

Ventura River Unimpaired Flow and Habitat Assessment, Ventura County, CA
City of Buenaventura and Nautilus Environmental, 2006-2007

Mr. Kamman completed a hydrology feasibility assessments as part of evaluating the reuse of Ojai Valley Sanitary District (OVSD) effluent for other beneficial uses. Currently, OVSD discharges treatment plant effluent to the lower Ventura River. The City and OVSD recognize that the reduction in the discharge of treated effluent to the Ventura River could have an environmental effect on sensitive and endangered species. In light of these concerns, this study was conducted to determine if a reuse project is feasible without significant environmental harm.

The assessment included hydrologic and geomorphic field and analytical assessments of past (unimpaired), current and proposed surface and groundwater flow conditions over a wide range of dry- through wet water year-types. The main objective if these analyses was to determine the linkage to water quality and aquatic habitat conditions including: flow durations; extent of gaining vs. losing reaches; low flow inundation/wetted area; and influence on barrier beach dynamics. Mr. Kamman collaborated with a team of other professionals to prepare a facility plan documenting the analyses and conclusions of respective water recycling investigations.

Hydrologic Analysis of FERC Minimum Flows on Conway Ranch Water Rights, Mono County, CA
Law Office of Donald Mooney, 2001-2002

Mr. Kamman completed a hydrologic analysis to evaluate if FERC's proposed Minimum Flow Plan for Mill Creek would interfere with the exercise of the Conway Ranch's water rights from Mill Creek. The approach to this analysis was to quantify the duration of time the Conway Water right was met under historic gaged and simulated proposed Minimum Flow Plan conditions. The primary objective of the analysis was to evaluate impacts during the winter period when flows are typically limited due to water storage as snow pack. Minimum Flow Plan conditions were simulated by developing a spreadsheet model that redistributes actual (historic) Lundy Lake releases in a fashion that maintains a minimum flow of 4 cfs to Mill Creek to accommodate the downstream Southern California Edison's (SCE) power plant. The analysis period for both historic and simulated Minimum Flow Plan conditions consisted of water years (WY) 1990 through 1998 to capture an exceptionally diverse range of wet and dry year-types.

The primary method used to quantify changes in flow between historical and simulated Minimum Flow Plan conditions was to prepare and compare flow duration curves for each condition during both the winter and summer periods during a variety of water year types. Model results were tabulated for each conditions to determine the differences in the percentage of time target flows were equaled or exceeded. Based on these findings, Greg was contracted to complete more in-depth monthly modeling.

Groundwater Management Projects

Assessments of Groundwater-Surface Water Interaction, Stanislaus County, CA
The Law Offices of Thomas N. Lippe, APC and California Sportfishing Protection Alliance, 2015-present

Since 2015, Mr. Kamman has been assessing groundwater conditions within Stanislaus County and evaluating potential impacts of groundwater pumping on surface water flow and aquatic habitat of the Stanislaus, Tuolumne and San Joaquin Rivers. Mr. Kamman completed a comprehensive review and synthesis report of available groundwater and interconnected surface water (ISW) reports and data. Using available soils, geology and hydrology information, Mr. Kamman also delineated and mapped subterranean streams and Potential Stream Depletion Areas (PSDAs) to identify stream corridors susceptible to adverse impacts from groundwater pumping. This information is intended to help Groundwater Sustainability Agencies identify potential impacts to ISW.

SELECTED EXPERIENCE *(CONTINUED)*

Most recently, Mr. Kamman has been retained to review and comment on 7 Groundwater Sustainability Plans (GSPs) for critically overdraft groundwater subbasins within or adjacent to Stanislaus County. This review focused on how GSPs address Groundwater Dependent Ecosystems (GDE) and ISW. Comments included recommendations on monitoring and study plans to identify and quantify impacts of groundwater pumping on stream flow rates and associated ecological habitats.

Assessment of Surface Water-Groundwater Interaction, Humboldt County, CA
Friends of the Eel River (FOER), 2020-present

Mr. Kamman is currently providing technical assistance in understanding surface water-groundwater interactions in the Lower Eel River Valley. Work includes reviewing and synthesizing available reports and hydrologic data and providing a science-based opinion on the role groundwater plays in supporting stream flow and aquatic habitats. This analysis addresses conditions and changes associated with seasonal and long-term wet-dry cycles. Data gaps will be identified and documented during the analysis.

This work is being completed to support FOER efforts at protecting aquatic resources within the framework of current water management practices and the public trust doctrine under California law. Additionally, this work includes providing hydrologic and hydrogeologic review, comment and recommendations during development of the basin's Groundwater Sustainability Plan (GSP) under the California Sustainable Groundwater Management Act (SGMA).

Scott Valley Subbasin Technical Hydrogeologist Assistance, Siskiyou County, CA
Klamath Tribal Water Quality Consortium and Quartz Valley Indian Reservation, 2019-present

Mr. Kamman is providing technical review and comment on the groundwater models and associated studies in the Scott Valley groundwater subbasin under the Sustainable Groundwater Management Act (SGMA) process. Work includes: review of groundwater models; synthesis and review of available groundwater quality data; assisting to identify constituents of concern; and review of the planning and technical studies being used to develop a basin Groundwater Sustainability Plan (GSP).

Middle Russian River Valley Shallow Groundwater Storage Enhancement Study, Sonoma County, CA
Friends of the Eel River, 2016

Working on behalf of Friends of the Eel River, Mr. Kamman completed a study to identify and quantify the volume of recoverable aquifer storage along two independent 6-mile reaches within the alluvial fill valley of the Russian River. The approach to this study was to quantify how channel incision has reduced shallow groundwater levels and quantify how much aquifer storage can be increased if channel bed elevations are restored to historic levels. The goal of this investigation was to identify feasible approaches to increase groundwater storage that would off-set losses associated with the termination of out-of-basin diversions from the Eel River. This work was completed through: intensive review and mapping of available groundwater level data; quantification of aquifer hydraulic properties; and calculating the shallow aquifer storage volume. In total, reclaiming the shallow aquifers within these two areas yield a total added storage volume of over 20,000 AF.

Green Gulch Farm (GGF)/Zen Center Water Resources Investigation, Marin County, CA
Green Gulch Farm, 1998-2019

Mr. Kamman completed a multi-phase study to evaluate the short- and long-term water uses and resources at GGF. Work was initiated by developing comprehensive water usage/consumption estimates and assessing available water resources, including spring, surface water, and ground water sources. Water demand estimates included quantifying potable and agricultural water usage/demands. Once reliable water supplies were identified and water usage/demand figures calculated, Mr. Kamman provided recommendation for improvements to water storage and distribution systems, land-use practices, conservation measures, treatment methods, waste disposal, and stream and habitat restoration. The initial phase of work included: in-depth review of available reports and data; review of geology maps and aerial photography; review of water rights and historic land use records; field reconnaissance including year-round spring flow monitoring; mapping and quantifying existing runoff storage ponds; and surface water peak- and base-flow estimates.

The second phase of work included identification of possible groundwater sources and siting and installation of production wells. This included sighting three drilling locations, obtaining County and State well drilling permits for a domestic water supply; coordination and oversight of driller; and directing final well construction. Upon completion of a well, Mr. Kamman directed a well pumping yield test and the collection and analysis of water quality samples (including Title 22) for small water supply system use. The final phase of work included assisting GGF with water treatment system options at the well head and integration of the groundwater supply into an existing ultra-violet light treatment system servicing spring water sources. Work was completed in 2000 with a budget of approximately $25,000, including all driller and laboratory subcontracting fees.

Stanford Groundwater Assessments, Santa Clara County, CA
Stanford University Real Estate Division, 2012-2016

Mr. Kamman provided technical hydrogeologic services to evaluate groundwater conditions and drainage requirements associated with the construction of several new facilities on or near Page Mill Road. The main objective of this study is to determine the seasonal depth to groundwater beneath the project site under existing and potential future conditions and provide an opinion on if the project is required to comply with the City of Palo Alto, Public Works Engineering Basement Exterior Drainage Policy (effective October 1, 2006). This work included obtaining and reviewing available technical reports, maps and literature pertaining to groundwater conditions in the project vicinity. Based on this review, we have prepared a letter report of findings and recommendations.

Bodega Bay Wetland Water Supply, Sonoma County, CA
Friends of Bodega Bay, 2007

Mr. Kamman Conducted an evaluation of the groundwater underflow feeding a large coastal wetland in Bodega Bay and recommended mitigation measures for potential losses in supply associated with proposed residential development in recharge areas. Work included: long-term monitoring of ground water quality and supply; monitoring surface water and spring flow and water quality; assessing and characterizing the interaction between surface and subsurface water sources during different seasons and water year-types; developing a detailed water budget for the site to assess impacts to recharge areas; and developing a number of physical solutions to mitigate for recharge losses.

SELECTED EXPERIENCE *(CONTINUED)*

L.A. Department of Water and Power, Groundwater Recharge Facility Operation Study, Los Angeles County, CA
ICF Consulting, 2006

Working as a subcontractor to ICF Consulting of Laguna Niguel, California, Mr. Kamman provided technical assistance in the hydraulic modeling of sediment accumulation in selected spreading ground facilities owned and operated by the Los Angeles Department of Public Works. The object of this work is to evaluate changes in infiltration and groundwater recharge rates over time within the spreading grounds in association with sediment accumulation from turbid waters.

Corde Valle Golf Club Surface-Groundwater Interaction Study, Santa Clara County, CA
LSA Associates, 2004

On behalf of LSA Associates of Pt. Richmond, CA, Mr. Kamman completed a 3rd party independent review of available reports and data sets (boring logs, well water levels, groundwater quality, aquifer pump-test, and surface water monitoring) to evaluate if pumping of the Corde Valle irrigation well is adversely impacting flow in West Llagas Creek. This investigation was implemented in response to a concern expressed by California Department of Fish and Game staff regarding the potential for differential drying of the West Branch of Llagas Creek along Highland Avenue. The analysis was also complicated by the likely effects of pumping from surrounding off-site wells.

Aquifer Testing for Tennessee Hollow Watershed Project, San Francisco County, CA
Presidio Trust, 2002

The Mr. Kamman assisted in the design and implementation of an aquifer test at the Presidio of San Francisco. We prepared an aquifer test work plan and conducted step-drawdown and constant-rate aquifer tests at the site using both manual and electronic data collection methods. This work included interpretation of the aquifer test results using software-based solution methods and prepared a written summary of methods and findings. In addition, Mr. Kamman located, coordinated and managed a drilling effort for the logging and installation of several groundwater monitoring wells in the project area to address identified data gaps.

San Joaquin River Riparian Corridor Restoration Project, San Joaquin Valley, CA
McBain-Trush, 2002

Mr. Kamman completed an assessment of historic and existing shallow groundwater conditions beneath and adjacent to the San Joaquin River between Friant Dam and the Merced River. This work focused on reviewing available reports and flow/groundwater- level data to characterize surface water and groundwater interaction and implications for riparian vegetation, water quality and fishery habitat restoration. Hydrologic analyses were performed to identify the location and seasonal evolution of losing and gaining reaches an implication on future restoration planning and design efforts. The main deliverable for this analysis was a report section focused on describing the historical changes in regional and local groundwater conditions in the San Joaquin Valley and evolution of anthropogenic activities (e.g., groundwater withdrawals, irrigation drainage systems and return flows, development of diversion structures, changes in land-use; and introduction of CVP/State Water Project deliveries) and associated impacts on deep/shallow groundwater levels, surface water flows, and surface and groundwater quality.

Tidal, Estuarine & Coastal Projects

Quartermaster Reach Wetland Restoration Project, San Francisco County, CA
Presidio Trust, 2006-present

Mr. Kamman was retained in 2006 as part of a multi-disciplinary team to develop restoration alternative designs for a 10-acre filled and paved site marking the historic confluence of Tennessee Hollow Creek and Crissy Marsh adjacent to San Francisco Bay. The Trust's planning documents define the main objectives for Tennessee Hollow restoration as: a) "Restoration [of Tennessee Hollow] will expand riparian habitat and allow for an integrated system of freshwater streams and freshwater, brackish, and tidal marsh, re-establishing a connection to Crissy Marsh" and b) "Restore and protect Tennessee Hollow as a vibrant ecological corridor". The project is located within the setting of a National Park and a National Historic Landmark District. Thus, another goal for the project is to protect the area's historic buildings and sensitive cultural and archeological resources to the extent possible, to enhance visitor experience to the area, and to integrate creek restoration with other urban land uses.

Mr. Kamman provided H&H technical input and consultation to the design team to develop a restoration project consisting of a creek-brackish marsh-salt marsh interface and associated upland habitats. His work included evaluating surface water, groundwater and tidal sources. In addition, the development of a hydrodynamic model has informed and guided a preferred project design, including evaluation of storm surge, road crossing and Tsunami impacts to the project. A technical challenge addressed with the use of the model included predicting and quantifying salt/brackish marsh habitat zones within the restored wetland in response to periodically but prolonged closed-inlet conditions to Crissy Marsh - a water body that serves as the downstream connection to the proposed project.

Another unique challenge to this project includes integrating restoration planning and design efforts with the replacement and retrofit of Doyle Drive, the main on/off-ramp for the Golden Gate Bridge, being replaced along the entire northern boundary of the Presidio. Mr. Kamman is providing long-term technical review of this project to the Trust with respect to impacts to water resources and associated existing ecological habitats. The Quartermaster project also falls within the managerial jurisdiction of both the Presidio Trust and NPS-GGNRA, requiring work in close cooperation with both Presidio Trust and National Park Service (NPS) staff.

Salt River Ecosystem Restoration Project, Humboldt County, CA
Humboldt County RCD, 2005-2019

Mr. Kamman provided hydrology, engineering and environmental compliance services towards the planning and design of river and tidal wetland restoration on the Salt River (Eel River Delta plain) near Ferndale, California, in Humboldt County. The purpose of the Salt River Ecosystem Restoration Project (SRERP) is to restore historic processes and functions to the Salt River watershed. These processes and functions are necessary for re-establishing a functioning riverine, riparian, wetland and estuarine ecosystem as part of a land use, flood alleviation, and watershed management program. The Salt River Project has three components: 1) dredging the lower Salt River and lower Francis Creek from near the Wastewater Treatment Plant downstream for 2.5 miles; 2) restoring 247 acres of wetland estuary habitat in the lower Salt River within the 440-acre former

SELECTED EXPERIENCE *(CONTINUED)*

dairy; and 3) reducing sediment inputs from tributary watersheds. The Salt River Project was designed using an "ecosystem approach" to address hydrology, sedimentation, and fish and wildlife habitat.

As part of project feasibility assessment, Mr. Kamman completed a hydrologic and water quality monitoring program, and developed a MIKE11 hydrodynamic model of the lower Salt River and Eel River estuary in Humboldt County, for the Humboldt County RCD. The purpose of this work was to complete a hydrologic, geomorphic, and hydraulic modeling assessments of the character and dominant physical processes controlling flow of water and sediment through the lower Salt River. Land use changes in the area have caused significant aggradation and infilling of the Salt River, significantly reducing tidal exchange, fish passage, and exacerbating flooding in upland areas. A primary goal of this study is to evaluate the feasibility of proposed restoration elements intended to increase tidal prism and exchange and in-channel sediment scour and transport. The desired outcome is a sustained increase in river conveyance capacity to improve drainage of surrounding flood-prone lands and improve aquatic, wetland, and riparian habitat.

As part of project development and feasibility assessment, Mr. Kamman completed a hydrologic and water quality monitoring program and MIKE11 hydrodynamic model development of the lower Salt River and Eel River estuary in Humboldt County for the Humboldt County RCD. The purpose of this work is to complete a hydrologic, geomorphic, and hydraulic modeling assessments of the character and dominant physical processes controlling flow of water and sediment through the lower Salt River. Land use changes in the area have caused significant aggradation and infilling of the Salt River, significantly reducing tidal exchange, fish passage, and exacerbating flooding in upland areas. A primary goal of this study is to evaluate the feasibility of proposed restoration elements intended to increase tidal prism and exchange and in-channel sediment scour and transport. The desired outcome is a sustained increase in river conveyance capacity to improve drainage of surrounding flood-prone lands and improve aquatic, wetland and riparian habitat.

Western Stege Marsh Restoration Project, Contra Costa County, CA
Tetra Tech, 2008-2010

Mr. Kamman provided technical hydrology and wetland hydraulics support to post-project monitoring of the Western Stege Marsh Restoration Project. His involvement began by providing an independent technical review of previous year's hydrologic monitoring results to evaluate the proposed monitoring success criteria and the rationale used to develop these criteria. This work entailed reviewing historic monitoring data and available natural slough channel geometry data-sets for San Francisco Bay area marshes. Mr. Kamman's study approach was to independently develop desired and sustainable channel geometry relationships for natural, healthy San Francisco Bay salt-marshes and compare them to the published success criteria. Greg was also retained to implement the Year 4 post-project hydrologic monitoring, with modifications to aid in better linking hydrologic processes to ecological conditions and function within the restored marsh. This work consisted of completing more targeted water level monitoring and channel geometry surveys in reference marsh areas containing desired physical and ecological attributes. These data were used to develop geomorphic success criteria (target channel geometry) more tailored to the project marsh and augment the criteria provided in available literature. Working closely with the project team of scientists, Mr. Kamman compared these hydrologic monitoring results to available vegetation surveys to better assess the overall success and evolutionary trend of the marsh.

Giacomini Wetland Restoration Project, Marin County, CA
The National Park Service and Point Reyes National Seashore Association, 2003-2012

Mr. Kamman managed a multi-year project for the NPS in the design and feasibility analysis of a tidal wetland, riparian, and freshwater marsh complex, on the 500-acre Giacomini Dairy Ranch, at the south end of Tomales Bay. The project began in 2003 and included hydraulic, hydrologic, and geomorphic assessments to characterize existing physical conditions, developing restoration alternatives, and completing hydrologic feasibility analyses. Restoration alternatives evaluated creation of a mosaic of subtidal through upland wetland and riparian habitat zones, as well as improvements to salmonid passage, red-legged frog habitat, tidewater goby habitat, and clapper-rail habitat. Emphasis was placed on completing detailed studies to quantify project-induced changes in flood frequency, magnitude and duration, impacts on water quality to local groundwater supply wells, and changes in sediment and water quality conditions in Tomales Bay.

Beginning in 2006, Mr. Kamman managed and assisted design engineers, preparing plans, specification, and cost estimates for a three phased construction schedule, that was completed in the summer of 2008. This project illustrates Mr. Kamman's ability to complete a broad variety of hydrologic feasibility analyses, including flood frequency analyses for contributing watersheds, reproducing historic flood events through numerical modeling, flow duration analysis and evaluation of environmental flow regimes, development of a water budget for created freshwater marsh and frog breeding ponds, sediment yield estimates, completing field monitoring (flow, water level, groundwater level, sediment, and water quality monitoring) to characterize existing site hydrologic and geomorphic conditions (fluvial and tidal), wind-wave setup and run-up for levee stability determination and construction design, coordinating and performing topographic and hydrographic surveys, performing hydrodynamic and water quality modeling of existing and alternative conditions, developing detailed construction cost estimates preparation of technical reports and design drawings and specifications in support of NEPA/CEQA environmental compliance, and public meeting presentation and participation. In addition, Mr. Kamman managed staff in the generation of DEM and TIN models of the existing site and all action alternatives. All work was completed on budget and in a timely fashion, despite repeated expansions to the project boundary and last minute changes driven by endangered species issues.

Critical Dune Habitat Restoration to Protect Threatened and Endangered Species, Marin County, CA
The National Park Service, 2009-2010

Mr. Kamman provided and managed engineering, design, and implementation planning support for the restoration of 300 acres of critical dune habitat at Abbots Lagoon within the NPS Point Reyes National Seashore. He developed engineered drawings, technical specifications and engineer's cost estimates, and assisted NPS in defining a range of methodologies suitable to local conditions and sensitive flora and fauna. This area of the park supports the best remaining intact dune habitat, including some of the largest remaining expanses of two rare native plant communities: American dune grass (Leymus mollis) foredunes, and beach pea (Lathyrus littoralis). European beach grass and iceplant were removed from

SELECTED EXPERIENCE *(CONTINUED)*

the project site using mechanical removal and hand removal techniques. The project goal was to remove these invasive species from approximately 135 acres of prime dune habitat in the 300-acre project site, while not impacting sensitive species and habitats. The intended result was to remobilize this historic dune field and restore their natural form and migratory processes.

This project illustrates Mr. Kamman's ability to work closely with NPS staff to balance habitat protection and restoration across the landscape. As part of project design, he developed grading plans, and specified work flow, equipment movement and access routes which minimize impacts to special status species. Extensive fencing and exclusions zone planning was required to protect existing native habitats, and minimize tracking of plant stock to or through restored sties. In addition work elements had to be structured and prioritized to maximize ground work subject to budgetary constraints and work flow uncertainties. All work has been completed on budget and in a timely fashion, even with repeated expansions to the project boundary and affected area and last minute changes driven by endangered species issues.

Lower Gualala River and Estuary Assessment and Management Plan, Mendocino County, CA
California State Coastal Conservancy and Gualala River Watershed Council, and Sotoyome RCD, 2002-2005

Mr. Kamman worked with fisheries biologists to evaluate the hydrologic and water quality conditions in the lower Gualala River and estuary and identify and evaluate potential impacts to summer rearing habitat for salmonids and other aquatic organisms. This work included: assessing how the impacts of upstream land use (logging and water diversions) have altered water delivery and water quality to the Lower River and estuary over time; characterizing the physical coastal and riverine processes controlling opening and closure of the estuary inlet and lagoon morphology; monitoring and characterizing real-time and seasonal changes in lagoon water level and water quality; and evaluating the sediment transport capacity and geomorphic condition of the lower river and estuary. Mr. Kamman took the lead in developing and editing a management plan for the lagoon, prescribing actions to preserve, protect and enhance ecological habitats (with emphasis on salmonids) within the lagoon and lower Gualala River.

This project was completed on-time and on-budget and demonstrates Mr. Kamman's ability to integrate physical, water quality and biological data and information into a coherent and understandable description of the interrelated processes controlling the aquatic ecology of a lagoon system. A big challenge on this project was completing a high-quality and defensible field monitoring program on a "shoe-string" budget. The outcome of this study provides important understanding on how and why steelhead are surviving in a heavily logged (95% private ownership) watershed. The management plan prescribes recommendations to preserve and protect the lagoon as primary rearing habitat for steelhead.

Suisun Bay Tidal Wetland Restoration Design, Contra Costa County, CA
East Bay Regional Park District and LSA Associates, 1999-2005

Mr. Kamman provided hydrologic design services to the restoration of a 55-acre tidal wetland on Suisun Bay. The design will maximize habitat for special status fish species, and (to the extent possible) habitat for other special status animal and plant species. Working with a multi-disciplinary design team, Mr. Kamman assisted in developing a design based on analysis of habitat needs, tidal hydrodynamic and geomorphic processes, sedimentation rates and soil characteristics. Project tasks included: a site analysis defining existing ecological and hydrologic conditions; a hydrologic and biological restoration opportunities and constraints analysis to define restoration and management objectives; and hydrodynamic and sedimentation modeling to evaluate design alternatives. The final restoration and management plan included a grading plan, landscape revegetation plan and monitoring and maintenance plans. This work again illustrates his capabilities in the characterization of physical site conditions, development and feasibility analysis of project alternatives, and preparation of preliminary designs of sufficient detail to allow for environmental compliance through the CEQA/NEPA process.

Santa Clara River Estuary and Lower River Assessment, Ventura County, CA
Nautilus Environmental on behalf of the City of Ventura, Public Works Department, 2003-2004

Mr. Kamman directed a hydrologic and geomorphic assessment of the lower Santa Clara River and estuary. This work was completed for prime contractor in an effort to assist with re-permitting of treated effluent discharges to the estuary. The proposed study entailed characterizing existing and historic hydrologic and physiographic conditions and an assessment of historic changes in inflow to the estuary. This task included a comprehensive review and evaluation of available hydrologic reports and flow data within the watershed to characterize changes in flow associated with development of numerous water projects within the Santa Clara River basin. The main deliverable from this analysis was the development of a historic unimpaired flow record to the estuary based on regional regression analyses and water operations modeling. Within the estuary, Mr. Kamman designed and conducted a multi-year monitoring program of water levels, water quality (temperature, dissolved oxygen, salinity, and pH), and sand-spit morphology in order to evaluate inlet opening/closure frequency and associated changes in aquatic habitat (esp. tidewater goby) and other ecologic communities. A considerable portion of this subtask included detailed coastal process analysis (including wave power analyses and littoral sand transport), which, considered with the inflow analysis, provides a basis to evaluate the seasonal cycle of barrier beach buildup and destruction.

This project illustrates Mr. Kamman's ability to complete a broad variety of hydrologic and coastal process analyses under strict regulatory oversight. A premier study completed on this project was the development of a detailed water and salinity budget model for the estuary to evaluate the impacts of a wide variety of proposed and modified estuary inflow regimes to determine potential future water level and salinity conditions in the lagoon and impact on frequency of inlet breaching. In addition to coordinating and implementing a variety field monitoring and surveys, Mr. Kamman also provided real-time information and input to informational and negotiation meetings with state resource and regulatory agencies.

Eden Landing Ecological Reserve Restoration, Alameda County, CA
East Bay Regional Park District, 2000-2003

Mr. Kamman developed and completed hydraulic and hydrodynamic modeling assessments for the design of an approximately 1000-acre tidal marsh restoration in former Cargil salt manufacturing ponds, located a mile inland of San Francisco Bay. The restoration goals required balancing the desires to restore tidal marsh conditions to the site, while maintaining and enhancing the open water and salt

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panne habitats preferred by resident and migratory shorebirds. The restoration plan also needed to incorporate restoration objectives with remediation of high soil salinities resulting from past salt production, subsided ground elevations, dredging of new channels to the bay, existing infrastructure constraints, public access for the San Francisco Bay Trail, and preservation of several important cultural and historical sites. Hydraulic design objectives include maximizing both interior circulation and tidal exchange between the restoration parcel and the bay. A series of one-dimensional unsteady hydrodynamic models (MIKE11) were used to design the channel network, identify high velocity areas requiring erosion protection, and characterize expected habitat conditions. An important component of this design and feasibility assessment was to translate desired ecological habitat conditions identified in the EIR into specific hydrologic design criteria, considering channel velocities, scour, sediment transport, tidal water inundation frequencies and seasonality of ponding. Mr. Kamman worked closely with EBRPD civil engineers, assisting with the translation of hydraulic design criteria into final engineered drawings and specifications.

Wetland & Pond Projects

Design of California Red-Legged Frog Breeding Ponds, San Francisco Bay Area (various), CA
The National Park Service and Golden Gate National Parks Conservancy, 1997-present

Mr. Kamman has lead or provided hydrologic and engineering design assistance to the sighting and design of nearly two dozen breeding ponds for California red-legged frog throughout the San Francisco Bay Area. Work has been completed in Marin, Sonoma, Solano, Contra Costa, Alameda, and Santa Clara Counties under the auspices of numerous federal, state, and local county/city agencies. A common study approach consists of an initial site reconnaissance of watershed conditions and identification of potential sites. The reconnaissance is followed by a surface water hydrologic sufficiency analysis using available meteorologic and stream flow information. An important variable sought during pond sighting is the presence of migration corridors between known breeding areas and/or perennial water sources. Based on in-depth research and post-project monitoring, Mr. Kamman has refined or developed site-specific evapotranspiration estimates, which commonly do not match standard applied values. Accurate evapotranspiration rates are necessary if ponds are intended to periodically dry-down as a means to preclude undesired species such as bullfrog or mosquito fish. In many instances, a seasonal groundwater-monitoring program is implemented in order to better investigate and quantify potential and seasonal groundwater contributions. Other design challenges we commonly experience include: design of impermeable liners for ponds located in upland areas or highly permeable soils; hydraulic analyses and design of outfalls/spillways; sedimentation management/maintenance approaches; and requirements of inoculum and water used to line and fill the pond, respectively.

Hydrologic Feasibility Assessment for Mana Plain Wetland Restoration Project, Kauai, HI
State of Hawaii Department of Land and Natural Resources, 2010-2019

Working on behalf of the Mana Plain Wetland Restoration Partnership, Mr. Kamman completed a hydrologic feasibility assessment for the Mana Plain Wetland Restoration Project proposed by the State of Hawaii Department of Land and Natural Resources (DLNR), Division of Forestry and Wildlife (DOFAW) on the island of Kauai. The Mana Plain Wetland Restoration Project site is approximately 105 acres of low-lying abandoned sugarcane fields immediately north of the Kawaiele Waterbird Sanctuary and east of the Pacific Missile Range Facility. The purpose of the Mana Plain Wetland Restoration Project is to maximize the area of constructed wetlands within the restoration site. Palustrine emergent wetlands within the project will create habitat for four species of endangered Hawaiian waterbirds and other sensitive species, including: Hawaiian stilts; Hawaiian ducks; Hawaiian coots; Hawaiian moorhen; migratory waterfowl; and migratory shorebirds. The Mana Plain is of vital importance for the recovery of endangered waterbirds species. This restoration project will be designed to provide important breeding and feeding wetland habitats on an island where; 1) wetlands have been severely degraded, and 2) mongoose, an introduced predator, have not been established.

Mr. Kamman's work on this project included technical assessments and development of proposed restoration alternatives. Analyses completed included: a synthesis of the physical site setting (topography, geology, hydrogeology and soil); reviewing available data to characterize site meteorology, surface water drainage, water quality, and groundwater conditions; preparing a detailed water budget to describe the characteristics and processes of surface water and groundwater movement into and through the project area; evaluating project feasibility, water supply alternatives and costs; and completing a flood hazard impact assessment to evaluate potential project benefits and impacts to local area flooding. Working with the project partners, Mr. Kamman developed a preferred project alternative and supported in preparation of the project Environmental Assessment document. Mr. Kamman's firm was also retained by the State of Hawaii to develop engineering designs of the project.

MacArthur Meadow Wetland Restoration, San Francisco County, CA
Presidio Trust, 2013-2016

Mr. Kamman has been working on over a dozen independent wetland and creek restoration planning and design efforts within the Presidio of San Francisco since 2001. Most recently (2016), he developed a wetland restoration grading plan for the MacArthur Meadow Wetland Restoration Project in the central portion of the Tennessee Hollow watershed. As part of the site assessment, Greg characterized and modeled surface and groundwater interactions and identified a unique opportunity to restore 4 acres of mixed meadow, natural wetlands and creek/riparian corridor. This was possible due to the discovery of shallow groundwater conditions beneath this historically disturbed landscape. Various design components were integrated into the grading plan in order to enhance groundwater recharge and storage in the Meadow, while retarding runoff and drainage out of the wetland, including: daylighting storm drain runoff into the Meadow; reconfiguring internal channel alignments to enhance channel habitat and groundwater recharge; creation of wetland depressions to retain and recharge surface water; and removal of fill material to decrease the depth to the water table. Notable challenges of this work include restoring heavily disturbed natural resources in an urban setting while integrating designs with archeology/cultural resources, education and remediation programs.

Dragonfly Creek Restoration Project, San Francisco County, CA
Presidio Trust, 2007-2011

Mr. Kamman designed and managed hydrologic monitoring and analysis studies in support of planning and design for riparian and wetland habitat restoration along approximately 500-linear feet of the Dragonfly Creek corridor near Fort Scott of the Presidio of San Francisco. Work has included completing subsurface

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investigations including the installation of shallow wells and a sharp-crested weir with recorder to gauge creek flows. Mr. Kamman assisted in the development and selection of a preferred project alternative, considering on-site cultural resource protection, education and resource management issues (including flood control). Mr. Kamman prepared permit applications. Major components of the project included removal of significant fill and building foundations and installation of a new creek road crossing that will maintain the historical alignment, function and architectural character of a culturally significant roadway. Mr. Kamman oversaw development of PS&E for this project, which will create mitigation wetlands for a highway earthquake retrofit project that passes through the Park.

This project illustrates Mr. Kamman's ability to complete a broad variety of hydrologic analyses, including: surface water and groundwater hydrologic monitoring to characterize and quantify existing hydrologic conditions; rainfall-runoff modeling; hydraulic modeling of flood and scour conditions (including road crossing); preservation of existing wetland habitat and vegetation communities; integration with other Presidio Trust programs; and contracting flexibility to assist in conceptual planning and environmental compliance without increasing project design costs.

Mori Point Sensitive Species Habitat Enhancement Project, San Mateo County, CA
Golden Gate National Recreation Area and Golden Gate National Parks Conservancy, 2005-2011

Mr. Kamman provided hydrologic analyses, sighting and engineering design (PS&E) for three California red-legged frog breading ponds within the 105-acre Mori Point area. These efforts were completed in association and collaboration with a larger Coastal Trail improvement and ecosystem restoration effort. Quarrying and off-road vehicle use have left this site heavily scarred. The focus of restoration work was to protect the endangered San Francisco garter snake and the threatened red-legged frog. Most of this work will be focused on invasive species removal and enhancing endangered species habitat. As part of species habitat improvement, Mr. Kamman worked with project ecologists to design the ponds to optimize breeding habitat for California red-legged frog.

Work started with an initial site reconnaissance and study of watershed conditions and identification of potential sites. The reconnaissance was followed by a surface water hydrologic sufficiency analysis using available meteorological and stream flow information and installation and monitoring of shallow piezometers to quantify the proximity and seasonal variability in depth to water table. An important variable sought during pond sighting was the presence of migration corridors between known breeding areas and/or perennial water sources. Based on in-depth research and post-project monitoring for other ponds they created in the San Francisco Bay area, Mr. Kamman refined site-specific evapotranspiration estimates. Accurate evapotranspiration rates are necessary if ponds are intended to periodically dry-down as a means to preclude undesired species such as bullfrog or mosquito fish.

Other design challenges experienced included: design of impermeable liners for ponds located in upland areas or highly permeable soils; hydraulic analysis and design of outfalls/spillways; sedimentation management/maintenance approaches; and requirements of inoculum and water used to line and fill the pond, respectively. Mr. Kamman has designed numerous ponds for the NPS and affiliates within the Bay Area, including Mori Point (constructed 2007), Banducci (constructed 2007) and Giacomini (Phase I and Phase II constructed in 2007 and 2008) project sites.

Hydrologic Assessment and Restoration Feasibility Study for Shadow Cliffs Regional Recreation Area, Alameda County, CA
East Bay Regional Park District, 2009-2010

Mr. Kamman developed and implemented an assessment to identify groundwater levels and supplemental water supplies that will sustain seasonal wetland restoration areas and riparian habitats under an altered future hydrologic regime. This work will inform a forthcoming Land Use Plan Amendment for park occupying a series of former gravel quarry pits. Work included: obtaining and synthesizing available surface water and groundwater data to characterize existing hydrologic and water supply conditions and seasonal variability; quantifying the likely changes in groundwater conditions and quarry pit lake levels in association with changes in regional water transmission and groundwater recharge operations; and identifying, developing and evaluating a suite of ecosystem restoration alternatives. Other important project objectives include: improving habitat for waterfowl and wildlife; broadening recreational use; enhancing visitor education and wildlife interpretation; improve park aesthetics. Mr. Kamman evaluated a preferred park and ecosystem enhancement alternative that involves diverting high winter flows from an adjacent arroyo. This project demonstrates Greg's ability to characterize hydrologic conditions and quantify the relationship between groundwater, surface water and wetland habitat conditions, both under existing conditions and in predicting future hydrologic and ecologic conditions under an altered hydrologic regime (i.e., lower groundwater table).

Laguna Salada Marsh and Horse Stable Pond Restoration Project, San Mateo County, CA
Tetra Tech, 2007-2009

Mr. Kamman provided technical hydrology and hydraulics support to the planning and conceptual restoration design of Laguna Salada marsh and Horse Stable Pond, located adjacent to Sharp Park Golf Course in the town of Pacifica, California. The primary objectives of the project are: to reduce flood impacts within the project vicinity; improve sustainable ecological habitat for the endangered San Francisco garter snake and the threatened California red-legged frog; better understand and characterize the hydrologic and water quality conditions/processes affecting flood and ecological habitat conditions within the project vicinity; provide an effective pumping operation plan to meet ecological objectives; and develop appropriate hydrologic analytical approaches and models to assist Tetra Tech and the San Francisco Recreation and Park Department in the planning and design for marsh, pond, and creek restoration. The project is also a unique opportunity to connect this resource with the California Coastal Trail, the Bay Area Ridge Trail, and the surrounding GGNRA lands.

Mr. Kamman's work included completing a comprehensive review of available hydrologic and site information and implementing selected field investigations to develop and calibrate an integrated hydrology-flood routing-pond water operations model that will quantify the volume and depth of water moving through the project system. The investigation will also further characterize shallow groundwater conditions and water quality with respect to effects on Laguna Salada and Horse Stable Pond. Analytical and numerical modeling tools are being used to better characterize existing hydrologic and water quality conditions and to assist in identifying project opportunities and constraints as well as evaluate potential restoration design components - all necessary to inform a sustainable

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and successful restoration design.

Tolay Lake Restoration Feasibility Assessment, Sonoma County, CA
Sonoma County Agricultural Preservation and Open Space District, 2003

Mr. Kamman completed a detailed hydrologic feasibility analysis to evaluate a suite of potential freshwater lake and wetland restoration alternatives. Sites were evaluated under existing watershed land-use practices and under existing and forecasted water demands (in the form of existing water rights/applications). Analysis consisted of developing a detailed water budget model to simulate alternative restored lake inundation areas and depths under median and dry year conditions, as well as a 50-year historic period (1947-1997) displaying highly variable rainfall and runoff supplies. Three lake restoration alternatives were evaluated based on existing topography and likely historic lake configurations. The restoration alternatives include lakes with storage volumes equivalent to 136-, 1100-, and 2550-acre feet.

Haypress Pond Decommissioning and Riparian and Channel Restoration, Marin County, CA
Golden Gate National Recreation Area (GGNRA), 2001-2002

This project restored 170 meters of historic creek and riparian habitat through removal of Haypress Pond dam in Tennessee Valley within GGNRA. The goals of the project were to alleviate long-term maintenance needs and eliminate non-native bullfrog habitat threatening native California red-legged frog habitat in adjacent watersheds.

Working with the Park biologist, Mr. Kamman developed designs to decommission the dam and restore natural riparian and meadow habitat. This work included: characterization of existing topographic conditions; design of a channel profile through the proposed restoration project reach; preparation of a grading plan for the restoration project; and hydrologic and hydraulic analyses to evaluate the performance of the creek channel and flood plain below the former dam during a variety of flows. Challenges of this work included integrating sediment reuse into plans and construction phasing.

Damon Slough Site Seasonal Wetland Design, Alameda County, CA
Port of Oakland, 1999-2001

Working on behalf of the Port of Oakland, Mr. Kamman completed extensive surface and groundwater monitoring and data analyses to develop a detailed water budget to assist in the evaluation and design of a 7.5 acre seasonal freshwater wetland. Primary project objectives included a design that would provide shorebird/waterfowl roosting habitat, minimize impacts to existing seasonal wetland areas, and lengthen the duration of ponding through the end of April to promote use by migratory birds. In addition to developing hydrologic design criteria, responsibilities included development of grading plans to accommodate a local extension of the Bay Trail and wetland outlet works.

Water Quality Projects

Chicken Ranch Beach Soil and Groundwater Quality Investigation and Restoration Planning, Marin County, CA
Tomales Bay Watershed Council, 2007-present

Mr. Kamman is leading scientific and engineering efforts for a wetland and riparian corridor restoration project on Third Valley Creek and Chicken Ranch Beach in Inverness, California. The main project goals are to create a self-sustaining riparian and wetland system (requiring minimal operation and maintenance) and eliminate public exposure to high levels of bacteria that exist in a site drainage ditch discharging to the beach. The design will likely include establishing a blend of habitats, including: riparian stream corridor, seasonal/perennial freshwater marsh, and tidal/saltwater marsh.

Current efforts have included the development and implementation of a soil and groundwater quality investigation to delineate the source of elevated bacteria levels. This work includes: the collection and testing of depth-discrete soil samples; groundwater well installation, sampling and testing; and surface water sampling and testing; analysis of laboratory results; and reporting, including recommendations for further/expanded investigations. Mr. Kamman coordinated this time-sensitive sampling and analysis (six hour hold times) with Brulje and Race Laboratories in Santa Rosa.

Lower Miller Creek Channel Maintenance and Material Reuse Sampling Analysis Plan, Marin County, CA
Las Gallinas Valley Sanitary District, 2015

Mr. Kamman was commissioned to formulate and implement a plan for sediment removal and improved flood flow conveyance in the Lower Miller Creek channel. Accumulation of course sediment in the project reach had reduced discharge efficiencies at District outfalls. Miller Creek supports a population of federally listed Steelhead and adjacent wetland/marsh areas potentially support other state and federally listed special status species. Working with District Staff, Greg developed a suite of potential project alternatives and identified a preferred approach. Mr. Kamman completed all CEQA compliance (IS/MND), permitting and oversaw development of engineered plans and specifications.

In order to evaluate if reuse of excavated material from 2,655 feet of creek corridor in upland areas was feasible, Mr. Kamman developed and implemented a Sampling Analysis Plan (SAP) pursuant to U.S. Army Corps Guidance for Dredging Projects within the San Francisco District. Sample collection, sample handling, and analysis were performed in accordance with the SAP. Results for analytes were compared to a variety of screening criteria to determine the material's suitability for reuse in aquatic environments. A full suite of chemical and physical analyses were performed on soil samples collected from 16 locations, including: metals, PAHs, PCBs, pesticides, TOC, specific conductance, pH, sulfides, percent moisture and grain-size. Mr. Kamman managed all aspects of this effort including reporting and presentations/negotiations at multi-agency meetings through the Corps Dredge Materials Management Office (DMMO).

Lower Pitkin Marsh Hydrologic and Water Quality Monitoring, Sonoma County, CA
Sonoma Land Trust, 2008-2010

Mr. Kamman was retained to develop and implement a hydrologic and water quality monitoring program at Lower Pitkin Marsh outside of Forestville, California. The Pitkin Marsh area is one of the most valuable complexes of mixed riparian woodland and thicket, freshwater marsh, wet meadow, oak woodland and grassland in Sonoma County. The complex interaction of surface water, ground water, and scattered seeps and springs on the site creates unusual hydrologic conditions that promote a rare assemblage of plant species which includes several endemics. The primary objective of the hydrologic monitoring program was to understand the annual and season sources of both surface and ground water supplying wetlands. Hydrologic and water quality monitoring was

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initiated during the winter wet season of 2008/09 and will be conducted for a 12-month period through the ensuing summer dry-down and into the following wet season. Understanding how groundwater levels, spring flow and creek flow rates recede from winter wet to summer dry conditions will provide an important understanding and quantification of the seasonal variability in water supplies feeding selected wetland types. General water quality parameters (temperature, pH, specific conductance, and ORP) are measured at all monitoring locations during each visit. Nutrients (N and P) are measured in selected surface water and groundwater samples collected during at least three monitoring events, including a winter high flow, spring high base flow and summer low baseflow.

Pescadero Lagoon Restoration and Enhancement, San Mateo County, CA
California State Coastal Conservancy, 2005-2006

Mr. Kamman was retained to support restoration and water quality enhancement planning efforts in Pescadero Lagoon. In 2005-2006, he completed a synthesis of available hydrologic and water quality information in responding to requests for development of a hydrodynamic and water quality model of the lagoon. This model was considered as a means to identify causes for repeated fish-kills in the lagoon that occurred during initial breaching of the inlet. Mr. Kamman assisted in preparing a synthesis and model development feasibility report from this effort.

Water Temperature Simulations for Trinity River Fish and Wildlife Restoration Project, Trinity County, CA
Trinity County Planning Department, 1994-2004

For over a decade, Mr. Kamman completed a number of hydrology and water quality investigations in support of alternative feasibility studies on the Trinity River Fish and Wildlife Restoration Project in direct support of the Trinity River Restoration EIR/EIS. Studies involve assessing the effects of proposed flow alternatives on water temperature within and downstream of Lewiston Reservoir. Mr. Kamman was responsible for data collection, processing, and flow/temperature modeling of Lewiston Reservoir as part of a coordinated evaluation including other Trinity River system models. Another study included evaluating how project operations could be implemented or modified to optimize Lewiston Lake release temperatures to meet downstream temperature criteria and compensate for increased warming of the river associated with side channel and feather edge restoration activities. Mr. Kamman continues to evaluate how more recent water projects (raising Shasta Dam, Sites Reservoir, and the Waterfix tunnels) consider and integrate with the Trinity Restoration Project.

Upper Eel River Unimpaired Flow and Water Temperature Assessments, Humboldt County, CA
CalTrout, 1997-1999

Mr. Kamman evaluated changes in the natural flow regime of the upper Eel River, and developed an Upper Eel River proposed release schedule to enhance downstream Chinook and Steelhead spawning and rearing habitat. This work was triggered by proposals set forth by PG&E as part of their Potter Valley Project FERC relicensing process. Work consisted of two main investigations. The first included reviewing results of a ten year PG&E study and development of multivariate regression and stream reach (SSTEMP) temperature models to assess the effects proposed flow alternatives would have on downstream temperatures. The second investigation consisted of characterizing unimpaired flow conditions and developing a daily unimpaired flow record for use in project operation models.

Selected Litigation Support Projects

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Kamman, G.R., 2018, Review of Amendments to the Sonoma County Cannabis Ordinance, California. Prepared for: Shute, Mihaly & Weinberger LLP, August 3, 10p.

Kamman, G.R., 2018, Written Testimony of Greg Kamman for Part 2 of the California Waterfix Change of Diversion Hearing before the State Water Resources Control Board, November 28, 10p.

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Kamman, G.R., 2017, Review Comments: PAD and SD1, FERC Relicensing of Potter Valley Project (PVP). Professional declaration prepared for: Friends of Eel River, July 31, 8p.

Kamman, G.R., 2017, Review Comments, Draft Environmental Impact Report, Fish Habitat Flow and Water Rights Project. Professional declaration prepared for: Friends of Eel River, March 8, 18p.

Kamman, G.R., 2016, Review of Draft General Waste Discharge Requirements for Vineyard Dischargers in the Napa River and Sonoma Creek Watersheds. Prepared for: Law Offices of Thomas N. Lippe APC, December 12, 4p.

Kamman, G.R., 2016, Review of Middle Green Valley Specific Plan Project, Second Revised Recirculated Draft Environmental Impact Report, Solano County, CA, Sch# 2009062048. Professional Declaration Prepared for: Law Offices of Amber Kemble, October 25, 3p.

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Kamman, G.R., 2014, Review of Middle Green Valley Specific Plan Project, Revised Recirculated Draft Environmental Impact Report, Solano County, CA, Sch# 2009062048. Professional Declaration Prepared for: Law Offices of Amber Kemble, August 11, 11p.

Kamman, G.R., 2012, Deposition of Gregory Richard Kamman, R.G., C.H.G., Schaefer vs. City of Larkspur, CA, Superior Court of the State on California, County of Marin. August 23, 2012.

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Kamman, G.R., 2011, Supplemental Declaration of Greg Kamman regarding Laguna Salada, Wild Equity Institute v. City and County of San Francisco, et al., Case No.: 3:11-CV-00958 SI, United States District Court, Northern District of California, San Francisco Division. Prepared for Wild Equity Institute, November 4, 50p.

Kamman, G.R., 2011, Declaration of Greg Kamman regarding Laguna Salada, Wild Equity Institute v. City and County of San Francisco, et al., Case No.: 3:11-CV-00958 SI, United States District Court, Northern District of California, San Francisco Division. Prepared for Wild Equity Institute, September 23, 7p.

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Kamman, G.R., 2012, The role of physical sciences in restoring ecosystems. November 7, Marin Science Seminar, San Rafael, CA.

King, N. and Kamman, G.R., 2012, Preferred Alternative for the Chicken Ranch Beach/Third Valley Creek Restoration Project. State of the Bay Conference 2012, Building Local Collaboration & Stewardship of the Tomales Bay Watershed. October 26, Presented by: Tomales Bay Watershed Council, Inverness Yacht Club, Inverness, CA.

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