Paradise Nature-Based Fire Resilience Project

Conservation Biology Institute
In partnership with TNC and Paradise Recreation & Parks District

Appendix A: Literature Review

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Purpose

As part of the project "Nature-Based Fire Resilience in Paradise, California," Conservation Biology Institute produced this review and summary of the most recent scientific research describing fire behavior in relation to land use patterns.

The overarching objective of the review is to summarize relevant literature to determine how structure loss or other metrics of human impacts are affected by community design, and especially how buffering communities with lower-flammability land uses (e.g., green spaces or agriculture) could potentially reduce structure loss and simultaneously protect natural areas from human impacts.

Specifically, we assemble information that could help determine:

- how greenbelts have the potential to mitigate wildfire impacts on California's communities, and inversely, community impacts on wildlands;
- relevant design elements or parameters such as buffer width, composition, or management that affect fire risks in differing ecological contexts;
- key uncertainties or data gaps for the efficacy of using natural, semi-natural, or human-created land uses to minimize wildfire risk to communities.

Background

California faces a daunting realization: its urban growth strategies over the past fifty or more years have allowed hundreds of thousands of people to live at direct risk from wildfires. Losses of human lives and structures have been rising globally in response to factors such as climate change, population growth, and expanding urban development, and California is no exception, experiencing record-setting human losses in recent years. (Keeley and Syphard, 2016; Schoennagel *et al.*, 2017).

Trends in urban planning and design since the 1970s have been driven more by real estate market considerations than by community health and safety. Current urban planning regulations, zoning schemes, and real estate marketing tend to support market trends favoring wildland-adjacent housing. Population growth combined with this market-driven economic development has resulted in significant urban sprawl into areas of wildlife habitat and watershed protection (Mockrin, Fishler, and Stewart, 2020). The result is an increase in the Wildland-Urban Interface (WUI), the frontline between human settlements and adjacent wildlands. The Wildland-Urban Interface has grown extensively in California in recent decades (Radeloff *et al.*, 2018).

The pattern of urban-wildland adjacency and intermixing in regions where wildfires are inevitable is resulting in people and property being exposed to wildfire hazards where the combination of fuels and terrain can feed rapidly spreading fires, especially during warm, dry, and windy conditions (Radeloff *et al.*, 2018). This type of urban growth also fragments wildland habitats and increases "edge effects" (Murcia, 1995) along this expanding WUI. The edge effect cuts both ways: Homes at the WUI experience increased exposure to wildfire, while the adjacent natural habitats are degraded by increased exposure to human influences, such as changes in runoff, night lighting, nitrogen deposition, impacts of pets and trampling, and weedy invasions (Bar-Massada, Radeloff, and Stewart, 2014).

Changes in land-use zoning and land acquisition may help reduce future risks to humans by siting new development in safer locations and arrangements (Godschalk, 2009; Syphard *et al.*, 2012; Syphard and Keeley, 2020b). Yet, California already has extensive development interspersed within flammable wildland vegetation. Therefore, fire risk management must also incorporate strategies that increase the resilience of these existing properties to wildfire (Keeley and Syphard, 2019). Given that wildfire is an important and natural component of most California ecosystems, an integrated and ecologically appropriate approach is also needed to balance fire risk reduction for human communities with conservation of the state's natural heritage, i.e., a co-existence of humans and wildfire (Moritz *et al.*, 2014). Such an approach could increase human community safety, reduce costs associated with fire suppression and property loss, and minimize ecological impacts.

The case of the town of Paradise, California, which was nearly entirely destroyed by the Camp Fire of November 8, 2019, presents a unique opportunity to enact such an integrated approach to fire risk mitigation. Using new ideas and concepts drawn from science combined with expert local knowledge, efforts are underway to guide the rebuilding of a community set in a fire-prone landscape.

As part of this effort to integrate fire risk reduction with ecologically appropriate planning, this literature review collates current information from the scientific literature, other literature such as community outreach materials, and even some anecdotal stories to provide support for this community's effort to rebuild in a smarter, safer manner. Given the complexity of wildfire issues and the uncertainties inherent in this era of rapid change, there are no definitive answers. However, there is sufficient information from multiple sources to support proactive action when combined with experience and common sense.

Community design effects on fire risk

How structure loss and other human impacts are affected by community design

In terms of understanding why homes are destroyed, there is an emerging literature of 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— for example, Penman *et al.* (2014) and Syphard *et al.* (2019). These are based on empirical data comparing characteristics of destroyed structures to surviving or unburned structures, in addition to simulation modeling approaches, to investigate drivers of structure loss in California and elsewhere.

Fire behavior, exposure, and sensitivity

Understanding fire behavior as a function of fuel types and distributions, terrain, and weather provides essential insights for risk-reduction strategies. Although every fire is simultaneously affected by fuel, topography, and weather conditions, it is useful to categorize fires as primarily fuel-driven or wind-driven to plan effective interventions. These two types of fires differ greatly in their fire behavior patterns and impacts, and therefore, appropriate management responses (Keeley and Syphard, 2019).

Structures are lost as a result of multiple, often interacting factors that variably influence the exposure (how likely the fire will reach the property) and sensitivity of a property to wildfire (how likely it is to burn). The increase in structure loss in recent years is mainly due to factors that govern exposure, including changes in wildfire behavior and activity, as well as the patterns of expanding development that place structures in the path of these wildfires (Syphard and Keeley, 2019).

The vast majority of structure losses occur during wind-driven fires (A.D. Syphard, unpublished data). These wind events are driven by synoptic weather conditions producing foehn winds — strong hot, dry, downslope winds developing in the lee of a mountain range — in the western part of California, from north of San Francisco to San Diego in the south; known in the northern part of the state as Diablo Winds or North Winds, as Santa Ana Winds in Southern California, and Jarbo Gap Winds in the Paradise area (Keeley and Syphard, 2019). Although these winds occur every autumn, the frequency of such wind events varies from year to year. It's worth noting that long-term records show no relationship between the frequency of such winds and large fire events (Keeley and Syphard, 2017). This is because humans are responsible for starting nearly all fires in this region and often these winds do not coincide with a human ignition (Keeley and A. D. Syphard, 2018).

In a high-speed wind event, new ignitions occur rapidly both at the flame front, which can be hundreds of feet high, and by "spotting" from burning embers that can be blown as far as two miles (Quarles *et al.*, 2010; Keeley and Syphard, 2019). Once ignited, these new fires can cover large areas very quickly, causing a leapfrog effect that is difficult and dangerous to fight. The California firestorms of 2017, ‘18, and ‘19 all began as wind-driven events, with most of the destruction and loss of life occurring in the first 8-12 hours, after which the winds abated and the fires became more fuel- and topography-driven. In the case of the 2018 Camp Fire, the communities of Paradise, Concow, and Magalia were largely destroyed in a single day (Almukhtar *et al.*, 2018).

Once structures ignite within communities, structure-to-structure spread can become very rapid depending upon the proximity of structures to one another and the building materials. Many structures are constructed out of wood and have high surface to volume ratios, often accompanied by gas lines, propane tanks, and other highly flammable fuel sources. In these cases, the structures represent almost perfect fire propagation entities—more so even than the forest-fire conditions that humans tend to focus on. Fire behavior models don't predict this kind of wind-driven spread and house-to-house spread accurately, because of its complex, rapidly-changing, and chaotic nature (Alex Syphard, pers. comm.).

In a wind-driven fire situation, structural characteristics related to ember penetration into the house are often what matter most, although landscape characteristics such as topography play a role in fire spotting and spread, and fuel characteristics at the source contribute to ember load. In a fuel-driven fire, the type, volume, moisture, and arrangement of fuels and structures are more important, along with topography and wind direction. In the absence of wind, fire will move uphill, progress more quickly through dry grasses and forbs, and form a higher, hotter flame front in tree-dominated vegetation. In the evergreen forests of the Sierra Nevada Mountains, extensive fuel loading due to a century of successful fire suppression and timber harvesting practices has been an important factor in driving fire behavior (Weatherspoon and Skinner, 1996; Van Wagtendonk *et al.*, 2019).

Wildfire and human communities: a coupled system

The scientific and resource management literature contains references to a coupled relationship between wildfire and human settlements, called a socio-ecological system or human-ecological system (McCaffrey, 2004; Paveglio, Abrams, and Ellison, 2016; Steelman, 2016; Tedim, Leone and Xanthopoulos, 2016). The human side of the system consists of mechanisms that operate at multiple scales, from individual homes to national governments. These mechanisms include development regulations, insurance, fire suppression activities, vegetation management programs, and others (Steelman, 2016). Fire ecology is equally complex given that fire regimes (long-term regional patterns of fire size, frequency, type, and intensity) vary as a function of biophysical heterogeneity (e.g., vegetation characteristics, topographic variation, and climatic patterns); and shifts in both climate and land use are differentially altering these natural fire regimes (Syphard *et al.*, 2019). For example, increased temperatures and aridity due to climate change are increasing wildfire activity in some regions, while legacies of fire management, vegetation shifts, and land use change are altering fire regimes differently in other regions. In many cases, interactions and feedback loops among all these drivers is exacerbating wildfire threats to people, homes, and infrastructure (Schoennagel *et al.*, 2017).

This coupled nature is one reason why reducing wildfire risks is so challenging to address. As losses from wildfire have accelerated, an emerging research and management objective has been to create fire-adapted communities where ecologically functional levels of wildfire are preserved but risks to human lives and property are minimized (Moritz *et al.*, 2014; Schoennagel *et al.*, 2017; Schumann *et al.*, 2019) suggest that the period following a destructive wildfire when awareness is heightened provides a "hot moment" for discussing new ideas for community adaptation, and focus on using a linked social-ecological model to promote an understanding of the post-wildfire recovery process.

Within-community design factors

There is a growing body of empirical research documenting that housing density and arrangement patterns are highly influential factors associated with structure loss during wildfires. Although the focus of this project is on the potential for green land use buffers around communities to reduce risk of ignitions coming from outside the community, we include a brief review here of recent literature addressing elements of community design that are important if a fire strikes within an urban area.

Examples of studies of recent fires with structure losses that provide valuable insights concerning those factors most contributing to structure losses or survival in California include: Maranghides and Mell (2011); Syphard *et al.*,(2012); Syphard, Brennan, and Keeley (2014); Alexandre *et al.* (2016); Radeloff *et al.*(2018); Syphard and Keeley, (2019); Miner (2014); Maranghides and Mell (2011); Syphard *et al.* (2012); Syphard, Brennan, and Keeley (2014); Alexandre *et al.* (2016); Radeloff *et al.* (2018); and Syphard and Keeley (2019). For similar studies in Australia, see Blanchi *et al.* (2010 and 2014); Gibbons *et al.* (2012 and 2018); Price and Bradstock (2013); and Penman *et al.* (2014). For other regions see Alexandre *et al.* (2016); and Kramer *et al.* (2019). Some patterns are emerging from this empirical research that, taken in context, may be helpful. These patterns need to be considered at the scale that they operate to inform decisions that planners face in their communities at the landscape level and for educating and encouraging action by homeowners at the property level.

These studies consistently support that, regardless of region, structure loss within a community is highest at relatively low housing density (Radeloff *et al.*, 2018; Syphard *et al.*, 2019) and at the WUI (Kramer *et al.*, 2019). Housing dispersion patterns—such as small, isolated clusters of development versus widely scattered houses or contiguous urban communities—also influence loss patterns, depending somewhat on region (Alexandre *et al.,* 2016). There appears to be a threshold at which the association with structure loss and low-density development reverses, such that high-density development may increase structure-to-structure fire spread once wildland fire ignites a home (Maranghides and Mell, 2009). The spread of fire is primarily house-to-house if the houses are within 50m of one another (Price and Bradstock, 2013).

Community design and risk factors at the wildland-urban edge

There is little question that land-use design plays an important role in mitigating the risk of wildfire damage in the rapidly growing WUI, and there is extensive literature examining the socio-economic facets of this topic. Bihari, Hamin, and Ryan (2012) provide information on how land-use planners can assist communities in learning to live with wildfire risk through planning, preparedness, and mitigation efforts in the wildland-urban interface, and explore solutions to achieving coordination between between land managers, federal agencies, neighbours, and local governments to make meaningful long-term change possible. Weir (2013) acknowledges this important link and cites similar disconnects between land-use planners and other sectors that create barriers to implementing fire-smart planning in Australia. Additional recommended reading on this topic: Blonski, Miller, and Rice (2010) and Buxton *et al.* (2011).

Butsic, Kelly, and Moritz (2015) point out that various land use planning measures are being enacted in the U.S. at the state, regional, and local scales with the goal of changing development patterns in fire prone areas by limiting areas where residential development can take place, the arrangement this development takes (for instance development densities), and recommending or even enforcing guidelines about vegetation near these developments.

Regarding physical factors that impact risk, housing density and the amount of edge where wildland vegetation abuts residential developments are key factors, as well as flammability of structures in the WUI. A modeling study by Spyratos et al. (2007) showed that fire size probability distributions can be strongly modified by the density and flammability of houses. Paveglio, Prato, and Hardy (2013) used a wildfire loss simulation model to evaluate how different land use policies are likely to influence wildfire risk in the WUI for Flathead County, Montana, finding that reducing the amount and footprint of future residential development in the WUI reduces fire risk. Canyons and hill slopes are important for urban design risk factors. Homes and outbuildings near the edges of developments, or in housing clusters on steep slopes, are more susceptible to fire than others (Syphard *et al.*, 2012). Historical fire frequency in an area is also an important predictor of risk, especially where wind corridors are associated with high fire frequency (Syphard *et al.*, 2012).

Building resilience in an existing wildland-urban interface community

Schoennagel et al. (2017) assert that current strategies aimed at resistance to wildfire through fire suppression and fuels management are inadequate to address a new era of western wildfires. They call for a shift in policy and management toward an "adaptive resilience approach" that accepts wildfire as inevitable and focuses on developing fire-adapted human communities. This approach is based on "(i) recognizing that fuels reduction cannot alter regional wildfire trends; (ii) targeting fuels reduction to increase adaptation by some ecosystems and residential communities to more frequent fire; (iii) actively managing more wild and prescribed fires with a range of severities (note that this recommendation does not apply to chaparral vegetation in Southern California, where the need is for less frequent fire (Keeley and A. Syphard, 2018); and (iv) incentivizing and planning residential development to withstand inevitable wildfire."

In their guidance document "Building to Coexist with Fire: Community Risk Reduction Measure for New Development in California", Moritz and Butsic (2020) offer principles for community planning and discuss key defensibility, ignition, and evacuation elements of community design when building or rebuilding in fire-prone areas. They recommend including fire professionals in the planning process and offer examples of risk-reduction measures and a discussion about challenges.

Also useful to consider are studies examining social and behavioral aspects involved in community resilience to fire, such as Maranghides and Mell (2011) which investigated the role of homeowner and fire-fighter defense of properties not only on the survival of those structures but also on the behavior of the fire, as well as factors that make that behavior likely or unlikely. Paveglio, Abrams, and Ellison (2016) conducted case-studies into fire-prone communities to illustrate how elements of local social context collectively influence wildfire perspectives and behaviors in a given locality, presenting the case for a more holistic view of local social context as a way to design tailored strategies for increasing resident responsibility for wildfire.

How green land uses mitigate wildfire impacts on communities

In addition to designing the placement of new development in ways that minimize exposure, another potential planning strategy - one that has captured attention but so far has not been well studied - is to locate irrigated greenspaces between structures and wildlands. In other words, placing parklands and greenbelts at the perimeter of a community instead of, or in addition to, locations within the community's boundaries could provide protection from wildland fire ignition sources while replacing other types of vegetation management efforts that are costly, potentially ecologically harmful, and possibly even counterproductive.

We found very little published empirical or modeling scientific studies focused specifically on how green land uses mitigate impacts to communities during fire events in California or elsewhere. Gonzalez-Mathiesen, March, and Others (2014) conducted research into land-use principles guiding the design of settlements at risk of bushfire impacts in Australia, making recommendations for design features at the site and subdivision level. They state: "The first planning principle observed across almost all of the cases studied is consideration of context and landscape impacts on exposure as a critical foundation to informing design responses to the nature of fire threats for each context." They recommend that features affecting possible fire behaviour for a given area to be assessed should include aspect, topography, fuel characteristics and proximity to forest/vegetation, water bodies, wind, fire weather, and likely direction and intensity of the fire front.

Gibbons et al. (2018) found empirical support that the "greenness", spatial arrangement, and proximity relative to the wind direction of trees and shrubs close to houses can be manipulated to reduce the risk of house losses during wildfires without necessarily clearing trees and shrubs. Xaud *et al.* (2009) evaluated the potential of pineapple crops as firebreak hedgerows in fire prone regions of Roraima State, Brazil, compared to plants from other groups of herbaceous species, and found pineapple cropland to have value for avoiding fire propagation due to its high moisture content. Curran *et al.* (2017) make the case for the use of greenbelts as biodiversity-friendly firebreaks based mainly on opinion, and calls for field experiments.

Anecdotal evidence suggests that "green land uses" (parkways and greenbelts, golf courses, ball fields, and agricultural areas such as orchards, community gardens, and vineyards) increase community resilience during fires by offering a buffer from oncoming fire. Embers landing on irrigated lands are more likely to die out than to ignite a destructive fire (common sense, and see also studies cited below). Because they are irrigated and managed for agricultural or parkland purposes, they are less likely to support dry, weedy fuel conditions than traditional fuel breaks. In the article "The Orchard at the End of Paradise" (Van der Leun, 2018), land owners describe the phenomenon of their apple orchard remaining unburned while the Camp Fire moved around it. The article "Golf Course on the Fire Line" (Gross, 2009) presents a compelling argument with recent examples of the buffering effect of large irrigated turf areas in stopping wildfire and protecting property, and also extolling the benefits of such features in a community for escaping and fighting fires.

Observations in Southern California also show that citrus and avocado orchards and vineyards serve as useful fire buffers where embers die out instead of igniting fires (Wayne Spencer, pers. comm.). A 2019 report by Zurich American Insurance Company promotes the concept of green land use buffers, saying that "planning and zoning can be used to develop in ways that decrease exposure and vulnerability. For example, using public lands, parks, and playing fields to create buffer zones can reduce community exposure." (Norton, R. *et al.*, 2019).

The current literature provides some useful information in the form of studies comparing flammability of different land cover types. Ganteaume *et al.* (2013) conducted an assessment of the flammability of ornamental vegetation (particularly hedges) planted around houses, corroborating the fire-fighting community's knowledge that species with thin leaves and a high leaf surface area-to-volume ratio were quickest to ignite. Ganteaume *et al.* (2009) investigated the relative flammability of different fuel beds, finding that an increase in bulk density and fuel moisture content results in an increase in the time to ignition, and a decrease in flammability.

The ability of firebrands to ignite fuel beds is highest when the firebrands drop in the flaming phase and with no air flow, compared to the glowing phase with air flow (Lautenberger and Fernandez-Pello, 2009).

Strategically-located open space can also serve as community gathering places and refuge areas in emergency events, and provide fire fighters with defensible space and staging areas for battling fire. During non-emergency times, these spaces can provide value for public health, recreation, and community beautification.

How green land uses mitigate community impacts on wildlands

Wildfire patterns in California are changing in response to global climate change and human land-use changes (Safford and Van de Water, 2014). Many of California's ecosystems are naturally prone to and adapted to frequent fire (Syphard and Keeley, 2020a). Major shifts in fire regime, such as changes in fire frequency, size, and severity, can threaten the ecosystem components and functions that evolved within specific ranges of variability reducing ecological integrity and ecosystem services.

The inter-relationships and feedbacks among fire-regime drivers and vegetation characteristics are complex, and impacts to the natural system may result from a range of interactions among humans and the biophysical environment (Moritz *et al.*, 2014). We are experiencing greater losses in both human and natural communities and the ecosystem services they provide (Syphard and Keeley, 2020b). In some cases, management strategies intended to reduce wildfire impacts on humans degrade native ecosystems, especially where vegetation management strategies are not conducted in alignment with a region's natural fire regime (Noss *et al.*, 2006).

Simulation modeling experiments suggest that land-use decision-making, either in the form of zoning decisions or private land acquisition, can not only reduce fire risks but may also benefit biodiversity conservation (Syphard *et al.*, 2012, 2013). Given what we know about how structure loss has occurred historically, we can develop land-use planning strategies to reduce wildfire risks, preserve habitat values, and provide multiple other benefits to humans and wildlife.

Altering natural fire regimes negatively impacts ecosystems

In the dry, mixed conifer forests in northern California, as well as some isolated mountains in Southern California, a long history of fire suppression has altered natural fuel conditions and fire regimes (frequency, intensity, and seasonality), leading to a negative effect on the health of California's forest ecosystems (Covington and Moore, 1994; Sherriff and Veblen, 2006) and chaparral communities (Keeley and A. Syphard, 2018). Climate change in these northern forests is also contributing greatly: What was once a fairly clear "fire season" in California (late summer-autumn) has given way to almost year-round fire risk in some regions (Westerling *et al.*, 2006). In these dry, mixed-conifer forests with a fire history of frequent, low-intensity fire, effective suppression and fire exclusion contributed to increased abundance of shade-tolerant, fire-intolerant species that may now burn with uncharacteristically high severity (J. E. Keeley *et al.*, 2009), thereby potentially creating large, homogenous burn patches that are difficult to re-inhabit by some fauna species. The potential for higher severity fire in these forests may also lead to mortality of high-ecological-value old trees that not only serve as critical habitat for many animals, but also sequester substantial amounts of carbon.

In Southern California and coastal shrubland communities, the opposite issue has occurred. Here, fire frequency greatly exceeds the historical range of variability in many areas (Safford and Van de Water 2014), in large part due to increased human-caused ignitions; and this in turn is resulting in vegetation type conversion—from native woody shrublands to weedy, flammable, alien herbaceous vegetation (Syphard et al. 2019ab). While much type conversion is driven by repeated burning, drought is also strongly correlated with these vegetation shifts, suggesting that a climate with more drought in Southern California could lead to widespread conversion of the landscape (Syphard, Brennan, and Keeley, 2018) to simple communities with much lower biodiversity and ecosystem services (Underwood *et al.*, 2018), and that are also much more flammable (Park *et al.*, 2018) altering native vegetation towards more weedy and flammable vegetation types via overly frequent burning. Invasive species thrive on mechanical disturbance of soil such as that involved in the creation of firebreaks (Hobbs and Huenneke, 1992), (Marvier, Kareiva, and Neubert, 2004). Such weedy vegetation communities, dominated by invasive, non-native plant species, do not support native biological diversity as well as the native plant communities that they replaced.

Holling and Meffe (1996) write that this 'command and control' approach that has been used in fire management with the goals of protecting human lives, property, and timber, causes a "pathology of natural resource management," defined as a loss of system resilience when the range of natural variation in the system is reduced. This reactive approach is not only unsustainable as more and more settled area requires the need for ever more fire suppression, it results in unforeseen consequences for both natural ecosystems and human welfare by ignoring the fundamental role that fire regimes have in sustaining biodiversity and key ecosystem services (Noss *et al.*, 2006; Driscoll *et al.*, 2010).

Moritz et al. (2014) expand on this concept, stating that unless humans can view and plan for fire as an inevitable and natural process, it will continue to have serious consequences for both social and ecological systems.

Traditional fire management techniques are damaging to some ecosystems

Prescribed fire and bulldozed firebreaks have been a mainstay of wildland fire management in California and other Mediterranean regions. However, there are often conflicts between traditional fire management approaches and biodiversity conservation (Driscoll *et al.*, 2010, 2016). There is an increasing sense that these methods are not ideal in some landscapes, and potentially counterproductive, with multiple risks and drawbacks (Wayne Spencer, pers. comm.), including:

- increased flammability and weediness;
- often regarded publicly as significant eyesores, especially in hilly terrain;
- may represent problematic fragmentation for species along the WUI, preventing climate adaptation;
- may cause habitat and soil erosion in sensitive habitats (DFES undated);
- may not necessarily even improve access for firefighting equipment, especially in rocky or montane habitats.

Merrian, Keeley, and Beyers (2006) provide data that suggest that fuel breaks provide establishment sites for nonnative plants, and that surrounding areas may be susceptible to invasion, particularly after disturbances such as fire.

It is also being argued that traditional fuel treatments and prescribed fire are often not very effective during the wind-driven fires that destroy most structures (Syphard *et al.*, 2011). Although fuel breaks and other attempts to mitigate fire risk do play an important role in fire-safe planning, it is critical that community planners understand fire behavior during the severe weather conditions that cause the greatest losses, and avoid a sense of false security that fire breaks can provide (Alexandra Syphard, pers. comm.).

Gaining conservation co-benefits

In simulated research in Southern California (Syphard et al., 2016), the twin objectives of biodiversity conservation and fire risk reduction appear to be highly compatible when the management strategy is private land acquisition for conservation and the priority is to purchase lands in high species-richness or high fire-hazard areas. Strategic land acquisition can simultaneously fulfill multiple objectives of fire risk reduction and conservation (Butsic et al., 2017). The authors suggest that these results can be generalized to any similar fire-prone region because of the common overlap between species richness, development potential, and fire hazard. However, fuels reduction to reduce fire hazard often reduces conservation co-benefits in shrubland and other non-forested ecosystems because of the direct conversion of native woody plant cover to weedy grasslands, providing corridors for invasion of non-native species, or altering hydrological regimes (Jon E. Keeley et al., 2009). On the other hand, fuels reduction in tree-dominated dry forests could have a favorable impact on conservation. However, it may be important to consider different decision-support methods (e.g., (Driscoll et al., 2016)) to identify the most appropriate timing and location of fuels management to provide the largest benefit with the smallest ecological impact.

Greenbelts and urban growth boundaries can buffer adjacent wildlands from human edge effects, such as trampling, increased fire ignitions, roadkill, chemical drift, noise, and light pollution. Urban growth boundaries prevent sprawl and encourage infill. If increased fire risk drives the clustering of housing development, research suggests that clustered, high-density development patterns substantially reduce the overall impact of development on wildlife habitat (Odell, Theobald, and Knight, 2003). In the simulated study by Syphard et al. (2016), the clustered, infill-type development resulted in less edge and fragmentation, both of which have long been associated with biodiversity decline (Turner, 1989). Replacing non-native trees, shrubs, and invasive grasses with native species as part of fire mitigation in wildland-urban interfaces would increase habitat for native insects, birds, and animals (Curran et al., 2017). Egbert (2010) recommends using native trees such as coast live oak as better protection against fire than highly flammable non-natives such as eucalyptus, which are "full of volatile oils, dropping quantities of leaves, bark strips, and litter that is slow to decompose, they can create a bonfire pile ready to burn."

Community buffer design elements

As discussed above, it is necessary to consider fire behavior and associated risks and to plan land use to reduce each type of risk at the scales at which they operate: wind-driven fire versus fuel-driven fire situations, and risk of ignition (exposure) versus risk of burning and fire spread (sensitivity). Reducing the risk to a community from fire can thus be thought of as a two-fold process: 1) reducing exposure, especially in the early usually wind-driven stage of a wildland fire, and 2) reducing sensitivity when ignition sources have arrived on the property or neighborhood. A range of factors at each of these scales should therefore be included in strategies designed to effectively increase community resilience (Alexandra Syphard, pers. comm.).

Planning of green land use buffers is primarily focused on reducing ignitions from wildfires coming from outside the urban area, and specifically on those wind-driven events such as that which characterized the first 12-24 hours of the Camp Fire and California's other catastrophic fires of 2017, '18, and '19.

Although the vast majority of structures are lost at low density (Syphard *et al.*, 2019), if a fire strikes within an urban area, the spread of fire is primarily house-to-house if the houses are within 50m of one another (Price and Bradstock, 2013). In these situations, home hardening takes precedence in reducing vulnerability and fire spread. The community also needs strategies to facilitate emergency evacuation and refuge, and for staging and conducting the fire fight. Advance planning of open space and land use can serve these purposes to save lives and property, protect the safety of fire-fighters, and increase community overall well-being.

While there is published information about community design and its effect on reducing the exposure of structures to fire (see previous sections above), we did not find published scientific studies specifically about how to design green land uses buffers. Below are resources that we think are informative for planning the design of community buffers.

Minimizing edge, avoiding high-risk locations

The American Planning Association promotes "safe growth" by guiding growth away from high-risk locations. They state that the starting point for a safe growth analysis is mapping existing hazard areas where development should be discouraged or allowed only with special protections from building codes or other regulations (Godschalk, 2009).

While different housing patterns and other variables are more or less important in influencing fire risk depending on regional variation, a general rule of thumb is that fire risk could be substantially minimized by placing new development in less fire-prone areas, filling in existing development, or expanding from existing development, to minimize the edge between housing and wildland vegetation. Overall, more compact, clustered development reduces exposure far more than isolated and dispersed development (Syphard *et al.*, 2012, 2013). However, it may be important when planning for compact development patterns to avoid placing homes too close together to reduce the potential for structure-to-structure ignition, at least if these structures are relatively close to the wildland. The farther the development is from flammable wildland, the lower the chance that an ember could reach the structure during a wind event.

Each community will have its own unique situation and set of opportunities and constraints, which may include planning entirely new urban development, rebuilding in the aftermath of catastrophes, and retrofitting existing developed areas. The book Sprawl Repair Manual (Tachieva, 2010) presents urban design, regulatory, and implementation techniques for addressing growing housing demand through the intensification of mid- and late-twentieth century sprawl developments, offering ways to reduce edge and correct housing density, egress and refuge, and vulnerability from wildland fire in already-developed areas.

Separation from the fire source

In the report "Nine design features for bushfire risk reduction via urban planning", Gonzalez-Mathiesen, March, *et al.* (2014) present nine planning principles for guiding community design based on themes they say converge across different international contexts. In the category of reducing vulnerability, they recommend creating adequate separation from heat and flame sources (given topography, vegetation, likely weather and any other relevant factors), and managing vegetation— including the strategic placement of greenbelts— as part of a mult-faceted set of place-based strategies for increasing community fire safety and resilience.

There is useful information in guidance pamphlets and reports from land management agencies and local governments. A Forest Service technical report, "Living More Safely in the Chaparral-Urban Interface" (Radtke, 1983) has extensive and useful recommendations mostly for the property owner and contains a section on greenbelts, saying that "more gentle terrain with deep soils is often well suited for the establishment of a wider greenbelt buffer zone that may include recreational facilities and commercial agriculture such as orange or avocado groves. This requires strong community support and long-range planning but may be the most effective way of separating wildland fuels from flammable structures." Although published decades ago, a book called Green Belts for Brush Fire Protection and Soil Erosion Control in Hillside Residential Areas (Montgomery, 1973) is a potentially relevant resource, although we did not review it.

Learning from studies on defensible space

We did not find published empirical or modeled scientific studies of how green land uses serve as ember-catchers during fire events. However, community buffers are a form of defensible space operating at the whole-neighborhood scale rather than the single property scale. It follows that some of what we know about defensible space can be applied to the design of a community greenbelt buffer.

Defensible space plays an important role at the urban-wildland interface, and the issue becomes one of how to use defensible space as a buffer between the fire front and the structures and to reduce the ember-rain from upwind fire. 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. Cohen (2000) empirically tested the relative benefits of defensible space, demonstrating that up to 30 m (100 ft) of vegetation reduction around a structure can significantly increase the chance of structure survival. However, in this and other case studies — for example see Miner (2014) — the most effective distance of defensible space was much less than regulations require, 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 (Syphard, Brennan, and Keeley, 2014).

There are risk-reduction tradeoffs that must be considered. Open, unobstructed space around structures is useful for fire responders during a fire-fighting situation, and reduction of ladder fuels near a house is part of a good management plan along with home hardening techniques to decrease the likelihood of new ignitions from wind-born embers. However, clearing all the vegetation around a structure has negative impacts on fire risk, too, such as providing a corridor for ember-laden wind and even allowing for increased wind speed (Rubin, 2010).

Maranghides and Mell (2009) provides research showing that two out of every three homes destroyed during the 2007 Witch Creek fire in San Diego County were ignited either directly or indirectly by wind-dispersed burning or glowing embers and not from the actual flames of the fire. When considering the role of defensible space in this light, designing to address the threat from ember assault shifts the emphasis away from wholesale clearing of vegetation. Land cleared of established woody vegetation is susceptible to invasion by annual grasses and fast-growing invasive forbs, defeating the fuel-reduction goal and creating a maintenance problem. Grasses and forbs dry early and extend the fire season, are easily ignited, and propagate fire very rapidly. The adage that native plants are a fire hazard is currently being debunked, and more recent guidance documents are advocating for combinations of thinning and irrigating rather than clearing vegetation around homes (Egbert, 2010; Rubin, 2010; Santa Monica Mountains Fire Safe Alliance, 2010).

Vegetation management efforts intended to reduce and break up heavy and continuous fuel distributions, such as fire breaks, can have little effect on fire spread during the most intense fire weather, such as the strong downslope wind event that drove the Camp Fire through the town of Paradise on November 8, 2018 (Syphard, Keeley, and Brennan, 2011a, 2011b). For example, the 2003 Cedar Fire in San Diego County — at that time the largest and most destructive fire in California history — blew across a wide system of fire breaks and even interstate highways (over 1,000 feet of complete fire break in some locations) to destroy whole neighborhoods that were generally considered safe. This was also the case in the 2017 Sonoma County Tubbs Fire, which easily crossed the four lanes of Highway 101.

California's fire-stricken communities are working to develop and disseminate information to property owners about what they should do to reduce risk to their homes and property. An example of these is "Santa Monica Mountains Fire Safe Alliance: How to Create Defensible Space in the Santa Monica Mountains" (Santa Monica Mountains Fire Safe Alliance, 2010), which prescribes vegetation management plans that are specific to zones based on distance from the home, slope and topography, and vegetation type, down to details such as the species of trees and balancing erosion control and fuel loads. Another is "Living with Fire in Sonoma County, a Guide for the Homeowner" (Fire Safe Sonoma, 2005).

Shared local experience is an important source of useful information. For example, Pepperwood Preserve in Sonoma County, most of which has burned in two major firestorms within two years, is conducting research on land management practices and fire resilience. Preserve Ecologist Michelle Halbur has presented her observations at various local fire workshops as part of the ongoing conversation about living with fire in the Sonoma County region. An example is that areas with slash piles left from fuel-reduction treatments burned more intensely than surrounding vegetation, killing nearby trees. On this 3,000 acre preserve, land management is a dynamic, never-ending task. Fuels-reduction is a temporary fix, even when fire has recently moved through, as illustrated by the invasive plants such as Italian thistle that grew up rapidly and densely after the 2017 Tubbs fire and dried out to form highly flammable fuels (M. Halbur pers. comm.)

Regional differences

It is important to recognize that each fire and each community is different, and caution must be used to avoid wholesale extrapolation of conclusions from one situation to others. Syphard and Keeley (2020b) state that "misunderstandings and disagreements" have arisen over the cause and direction of trends in wildfire activity (Doerr and Santín, 2016), fire risk and structure loss (Mccaffrey, Duffner and Decker, 2019), and the most effective approach for prioritizing management decisions (Moritz *et al.*, 2014). Thus, management techniques appropriate for one region can be applied inappropriately to a different region (Noss *et al.*, 2006).

That said, there is plenty to learn from studies and efforts in other regions. Despite the fact that vegetation communities, settlement patterns, and social structures are very different, the wealth of information from other places, particularly Southern California and Australia, can be successfully adapted if one is heedful of the ways these differences affect risks and their mitigation. A good place to start to build confidence in this area is the report "Nine design features for bushfire risk reduction via urban planning" (Gonzalez-Mathiesen, March, *et al.*, 2014). This useful report provides a compilation of strategies that, planned in the specific context of the community and applied in concert would increase a community's ability to survive and reduce losses in the face of increased frequency and severity of wildland fire regardless of the geographic and ecological setting.

Key uncertainties and data gaps

There are several fronts at which there is more information needed that would help communities, land use planners, and wildland managers understand the options available to them and provide a scientific basis for implementation.

One area needing attention is that there has been little empirical testing of green firebreaks, particularly with field experiments that would provide for comparison across ecological and fire risk settings. Additional case study documentation is also needed for illuminating the usefulness and limitations of greenbelts, especially with an eye toward avoiding a false sense of security. There is a need for pre- and post-fire empirical data to document and validate what happens under actual wildfire conditions, as well as more discussion about how greenbelts work in strategic combination with other risk-reduction techniques such as "slow-it-spread-it-sink-it" surface water runoff management, habitat restoration, agricultural lands, timberland management, and property-scale vegetation management.

Mell et al. (2010) calls for a well-characterized, systematic testing of fuel treatment approaches across a range of community and structure types and fire conditions. Laboratory experiments, field measurements and fire behaviour models can be used to better determine the exposure conditions faced by communities and structures. This work would assist the development of recommendations for designing fire risk buffers that are context-specific and that address the confusing trade-offs involved in reducing the force of wind and wind-blown embers while simultaneously providing enough distance and open space. Land management agencies and the fire-fighting community also need more convincing evidence about the role of native vegetation in fire risk reduction to begin to try techniques that contradict the highly-entrenched practices that are often destructive to ecosystems.

Buxton *et al.* (2011) states that the location of population growth and associated regulatory failure are contributing factors associated with life and property losses that are under-researched. More real-world examples of multi-agency cooperation and stories of communities where past incentive-versus-consequence disconnects are addressed are needed.

An examination is needed of the impacts of recent land-use regulations on reducing fire risk. Butsic, et al. (2015) state that "The goal of many of these regulations is to change development patterns in fire prone areas—especially in the wildland urban interface (WUI). Thus far, however, there is little empirical evidence that these land use regulations actually reduce fire risk. While a few studies demonstrate how different housing arrangements may impact fire risk, more comprehensive analysis of such policies is an area of great research need."

There is an urgent need for more information about sustainable approaches to fire management for biodiversity conservation. Driscoll et al. (2010) examine the limitations of empirical and model-based research to address the need for knowledge about how species respond to fire regimes, and defines a research agenda. Evidence is needed for the argument that a more sustainable coexistence with wildfire is not only possible, but that it can protect ecosystems and does not come at a cost associated with protecting human communities.

As the scientific community works to gain this knowledge, there is also a need for access to this information as well as outreach and education of communities and planners to adopt and incorporate it.

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