International Journal of Disaster Risk Reduction 42 (2020) 101354

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: http://www.elsevier.com/locate/ijdrr

Wildfire recovery as a "hot moment" for creating fire-adapted communities

Ronald L. Schumann III[a,*], Miranda Mockrin[b], Alexandra D. Syphard[c], Joshua Whittaker[d], Owen Price[d], Cassandra Johnson Gaither[e], Christopher T. Emrich[f], Van Butsic[g]

[a] Department of Emergency Management and Disaster Science, University of North Texas, 1155 Union Circle #310637, Denton, TX 76203, USA
[b] Northern Research Station, USDA Forest Service, 5523 Research Park Dr Suite 350, Baltimore, MD 21228, USA
[c] Sage Insurance Holdings, 10423 Sierra Vista Ave., La Mesa, CA 91941, USA
[d] Centre for Environmental Risk Management of Bushfires, University of Wollongong, Northfields Avenue, Wollongong, NSW 2522, Australia
[e] Southern Research Station, USDA Forest Service, 320 Green St., Athens, GA 30602, USA
[f] School of Public Administration, University of Central Florida, HPA II – Suite 238, 4364 Scorpius St, Orlando, FL 32816, USA
[g] Department of Environmental Science, Policy, & Management, University of California Berkeley, 130 Mulford Hall #3114, Berkeley, CA 94270, USA

ARTICLE INFO

Keywords:
Wildfire adaptation
Community recovery
Vulnerability reduction
Coupled social-ecological models

ABSTRACT

Recent decades have witnessed an escalation in the social, economic, and ecological impacts of wildfires worldwide. Wildfire losses stem from the complex interplay of social and ecological forces at multiple scales, including global climate change, regional wildfire regimes altered by human activities, and locally managed wildland-urban interface (WUI) zones where homes increasingly encroach upon wildland vegetation. The coupled nature of the human-ecological system is precisely what makes reducing wildfire risks challenging. 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. Realizing such a vision will require widespread and decentralized action, but questions remain as to when and how such a transformation could take place. We suggest that the period following a destructive wildfire may provide a "hot moment" for community adaptation.

Drawing from literature on natural hazard vulnerability, disaster recovery, and wildfire ecology, this paper proposes a linked social-ecological model of community recovery and adaptation after disaster. The model contends that changes during post-wildfire recovery shape a community's vulnerability to the next wildfire event. While other studies have highlighted linked social-ecological dynamics that influence pre-fire vulnerability, few studies have explored social-ecological feedbacks in post-fire recovery. This model contributes to interdisciplinary social science research on wildfires and to scholarship on community recovery by integrating hazard vulnerability reduction with recovery in a cyclical framework. Furthermore, it is adaptable to a variety of hazards beyond wildfire. The model provides a basis for future empirical work examining the nature and effectiveness of recovery efforts aimed at long-term vulnerability reduction.

1. Introduction

Across the globe, wildfire impacts—social, economic, and ecological—have increased dramatically over the past thirty years [1–4]. Australia, Canada, Chile, Portugal, Greece, and the United States have all experienced record property destruction due to wildfires in the past decade [5–8]. These losses are occurring as a result of a complex interplay of social and ecological forces, including climate change [9–11], altered wildfire regimes due to human activities (e.g., fire suppression, increased ignitions) [12,13], and a growing global wildland-urban interface (WUI) where people live in close proximity to wildland vegetation [14,15]. As losses from wildfire have accelerated, an emerging research and management objective is to understand how to maintain ecologically functional levels of wildfire on the landscape while simultaneously reducing the risk of wildfire losses to human lives and property. Such an ability to live with wildfire, that is, to be fire-adapted, now forms the central tenet of wildfire policy globally [16–19].

* Corresponding author.
E-mail addresses: ronald.schumann@unt.edu (R.L. Schumann), mhmockrin@fs.fed.us (M. Mockrin), asyphard@sageunderwriters.com (A.D. Syphard), wjoshua@uow.edu.au (J. Whittaker), oprice@uow.edu.au (O. Price), cjohnson09@fs.fed.us (C.J. Gaither), Christopher.Emrich@ucf.edu (C.T. Emrich), vanbutsic@berkeley.edu (V. Butsic).

https://doi.org/10.1016/j.ijdrr.2019.101354
Received 18 March 2019; Received in revised form 27 September 2019; Accepted 3 October 2019
Available online 18 October 2019
2212-4209/© 2019 Elsevier Ltd. All rights reserved.

Despite recognition that wildfire impacts result from a coupled human-ecological system [1,19–22], this interconnectedness is also what makes reducing wildfire risks so challenging. The human system consists of mechanisms for wildfire governance at multiple scales, from individual homes to national governments. These mechanisms include development regulations, insurance, fire suppression activities, vegetation management programs, and others [22]. Fire ecology is equally complex given that fire regimes (i.e., regional patterns of fire size, frequency, type, and intensity) vary as a function of biophysical heterogeneity (e.g., vegetation characteristics, topographic variation, climatic patterns), and shifts in both climate and land use are differentially altering these natural fire regimes [23].

To understand these challenges and bring about change in this linked human-ecological system, most efforts have concentrated on experiences prior to, during, and immediately following wildfires [22]. While some have highlighted the linked social-ecological dynamics that give rise to pre-fire vulnerability (e.g. Ref. [1]), to our knowledge, no studies have focused explicitly on the post-wildfire recovery process in a linked social-ecological model (but see Ref. [4] for a schematic of social-ecological wildfire processes over time). Recovery represents a period of rebuilding physical infrastructure, realigning local institutions, and reevaluating policies that govern risk [24,25]. Merely replacing what was lost is no longer the standard for successful recovery in the broader natural hazards community. Instead, recovery efforts must foster resilience in a community's social, ecological, and built environments [26]. In terms of wildfire recovery, this means rebuilding structures that are more fire resistant, improving vegetation management practices, bolstering social support structures that reduce vulnerability, and preventing further encroachment of development into wildland vegetation. But are such resilience-minded changes occurring post-fire? Does wildfire recovery represent a critical or "hot" moment when creating a more fire-adapted community becomes possible?

As a first step toward answering these questions, this paper draws from literature on natural hazard vulnerability, disaster recovery, and wildfire ecology to propose a linked social-ecological model of community recovery and adaptation after disaster (Fig. 1). This model contends that changes during post-wildfire recovery shape a community's vulnerability to the next wildfire event. In the model, place vulnerability within the linked social-ecological system sets the stage for the wildfire event to occur (T_0). Impacts then result from the characteristics of the individual fire and the human responses to it. As the recovery process unfolds over the years following the wildfire event (T_1, T_3, T_{10}, … T_n), social and ecological outcomes are realized, and adaptation occurs. Changes in the exposure and sensitivity of social and ecological domains give rise to future vulnerability, thus completing the cycle. For reference, Table 1 provides definitions of major concepts contained in our model.

This model contributes not only to the growing body of interdisciplinary work on wildfires, but also to the disaster science literature on community recovery. As demonstrated below, post-disaster community recovery and adaptation, in general, are undertheorized. Furthermore, though scholars widely recognize that mitigation measures instituted during recovery are crucial for reducing future disaster losses [27–29], relatively few recovery frameworks explicitly engage with vulnerability reduction. Two primary strengths of the proposed model are: 1) its applicability to community recovery after any loss-causing hazard event—not only wildfires—and 2) its acknowledgment that place vulnerability results from linked social and ecological recovery outcomes. This cyclical, additive relationship between vulnerability and recovery illustrated by the model underscores a need for truly transformative human responses to stabilize or reverse current trends in disaster losses.

Below, we first examine linkages between wildfire losses, post-disaster recovery, and vulnerability reduction (section 2). We then proceed sequentially through the model, discussing how exposure and sensitivity combine to create pre-fire place vulnerability (section 3). Next, we consider how event characteristics interact with a range of human responses to produce unique wildfire impacts (section 4). During post-fire recovery, we describe how the emergent set of social, ecological, and linked outcomes gradually alters a community's vulnerability profile (section 5). We then problematize the concept of adaptation, considering how factors such as spatial scale and value judgments render changes in the post-wildfire landscape either adaptive or maladaptive to future wildfires (section 6). Finally, we discuss potential applications of the model to wildfire-related questions, outline data requirements, and consider limitations and transference to other hazards (section 7).

2. Wildfire recovery as a "hot moment?"

2.1. Wildfire's changing loss profile

Before recently, interdisciplinary hazards and disaster science rarely considered wildfires. Instead, earthquakes, floods, hurricanes, and other hydrometeorological hazards largely dominated studies on disaster risk and recovery (e.g., Refs. [25,30–32]). This is likely because total wildfire losses[1] during the last half-century were relatively low compared to other hazard types, notably hurricanes and floods (Fig. 2). Likewise, deaths and injuries from thunderstorms, tornadoes, and extreme temperatures have historically outpaced wildfire casualties (Fig. 2). For a variety of reasons, however, destructive wildfires in the US are becoming more frequent (Fig. 3) and wildfire property losses have risen in recent decades (Fig. 4). According to the US National Interagency Fire Center [33], wildfires destroyed on average 1,545 residences annually between 1999 and 2017; however, the last two wildfire seasons have far eclipsed this average, with over 8,000 residences destroyed in 2017 [33] and nearly 20,000 residences destroyed in 2018 [34]. Thus, historical data (Fig. 2) do not represent the current shifts in wildfire patterns that threaten greater numbers of human communities and may irreversibly transform or degrade ecological systems. Today's rapidly mounting wildfire losses, longer fire seasons, soaring suppression expenditures, and more frequent wildfires that reburn the same areas pose an ever-growing challenge for wildfire managers and residents who live in wildfire-prone environments.

2.2. Adaptation through recovery?

Despite the dominant federal role in wildfire suppression within the US, wildfire preparedness and recovery tasks largely fall to local governments, communities, and residents [22]. These diverse local stakeholders often hold competing interests, which may impede the success of adaptation to the mounting wildfire threat. For example, planning boards and local governments may adopt standards for fire-resistant construction or vegetation management, but homeowners and builders are responsible for ensuring that appropriate materials are used and for maintaining fire-safe landscaping. The need for such widespread and decentralized action in response to wildfire threats is daunting. How do residents and communities cooperatively confront growing losses and shifting environmental conditions in order to become "fire-adapted"? When could such a transformation take place?

The time after a wildfire event may spark such a reckoning—a "hot moment" for adaptation. In non-wildfire disasters, scientists have long identified the post-event recovery period as key to reducing future hazard losses [31,35,36]. Disasters can catalyze political and public will to harden infrastructure, revise land use regulations, and create new collaborative networks for risk reduction [37–40]. While studies after

[1] Loss numbers derived from the *Storm Data and Unusual Weather Phenomena* publication likely underestimate wildfire losses [164]; nevertheless they provide an adequate lower bound in estimating property losses from wildfires over time.

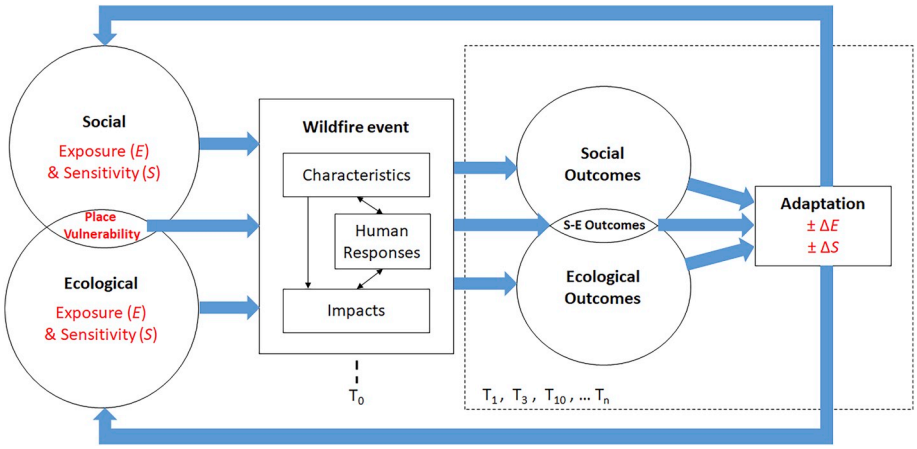

Fig. 1. Conceptual model of coupled social-ecological recovery from wildfire at the community level.

Table 1
Definitions of key concepts from the model of coupled social-ecological recovery from wildfire.

Model concept	Definition
Exposure	The extent to which people, assets, and natural features are at risk of loss from wildfire due to their location. Exposure is a prerequisite of vulnerability.
Sensitivity	The degree to which people, assets, and natural features are at risk of loss due to their intrinsic physical or social characteristics. If a feature is already vulnerable due to exposure, higher sensitivity can mean a higher propensity for loss and/or a higher degree of loss in a wildfire.
Place vulnerability	An area's susceptibility to harm or loss from wildfire; a combination of exposure and sensitivity, both ecological and social.
Wildfire characteristics	Attributes that describe the fire itself, including magnitude, intensity, timing, and spatial extent.
Human responses	Actions taken by individuals, organizations, and communities during an active wildfire based on the fire's characteristics and behavior.
Impacts	Losses caused by the fire, including direct and indirect losses to people, property, and ecosystems; secondary hazards and their resultant losses; and the spatial distribution of these losses.
Social outcomes	Changes to human systems during short-term (T_1), medium-term (T_3), and long-term (T_{10}) recovery after a wildfire.
Ecological outcomes	Changes to ecosystems during short-term (T_1), medium-term (T_3), and long-term (T_{10}) recovery after a wildfire.
Coupled social-ecological outcomes	Changes to the built and natural environment that show the effects of altered human actions on ecological conditions and/or the effects of altered ecological conditions on human actions.
Adaptation	The extent to which post-wildfire changes in the built and natural environments alter an area's exposure and/or sensitivity (i.e., place vulnerability) to future wildfires.

non-wildfire disasters have demonstrated the potential to enhance community mitigation and preparedness during the post-disaster policy window, by no means are adaptive practices guaranteed in all recoveries. Certain preconditions must exist for post-disaster policy windows to fundamentally reshape community development. These preconditions include policy-setting bodies that take a comprehensive view of hazards management (i.e., recognizing links between mitigation and economic development), institutional authority to enact and enforce such hazards management strategies, and the presence of hazards-policy entrepreneurs to identify solutions to problems [40,41]. We expect that these same preconditions generally hold after wildfires.

To date, however, limited cross-comparative research exists at a national scale or larger to draw conclusions about the adaptations realized through post-wildfire recovery. Localized case studies disagree[2] on whether the post-wildfire period is one of heightened risk perception and mitigation (e.g. Refs. [42–45]), or one of diminished concern that discourages mitigation (e.g., Refs. [46–49]). Beyond perceptions, both access to and use of recovery funding sources that support mitigation can affect the nature of post-fire adaptations. For instance, in the US, many wildfires do not generate enough losses to warrant a major disaster declaration, which authorizes funding[3] through the Federal Emergency Management Agency's Hazard Mitigation Grant Program (HMGP) [50]. Although individual wildfire events have motivated an array of local-level policy changes (e.g., stricter defensible space policies, more stringent building codes, vegetation thinning programs) aimed at curbing future destruction [51–53], efforts to foster response and preparedness capabilities continue to dominate efforts to lessen baseline wildfire risk itself. For example, Mockrin and colleagues [54] show that communities tend to focus on enhancing fire suppression and general planning documents after wildfire, but rarely enact comprehensive changes in land use.

2.3. Ignoring vulnerability reduction in recovery

Post-disaster interventions that remedy emergency preparedness and response deficiencies without addressing the root causes of risk are commonplace, not only following wildfires but all types of high-consequence, relatively low-frequency hazard events. These strategies often lead residents and communities to redevelop rapidly in the same unsafe ways as before (cf. [55–57]). Congruently, recovery policies that do not proactively adapt to shifting environmental risks end up restoring pre-disaster conditions that privilege pro-development forces [32], institutionalize forgetting of previous disaster events [58], and exacerbate the precarious position of the most vulnerable households [59]. Communities rebuilt along these lines possess larger ecological and physical footprints [60,61] and often contain fewer affordable housing options [62]. Within this unsustainable post-recovery environment, interactions between social and ecological systems magnify the potential for harm (i.e., vulnerability) and exacerbate future disaster losses [63].

Indeed, while recovery and vulnerability are intrinsically connected in communities facing the recurrent threat of destructive wildfire, most extant disaster recovery models lack an explicit connection to

[2] Disagreement may be due to inconsistencies in the measurement of such perceptions and resultant mitigation actions.

[3] The HMGP has provided resources to aid wildfire preparedness or mitigation after only 201 fire events—this represents 18% of wildfire declarations and 3.8% of all US major disaster declarations since 1953 [50].

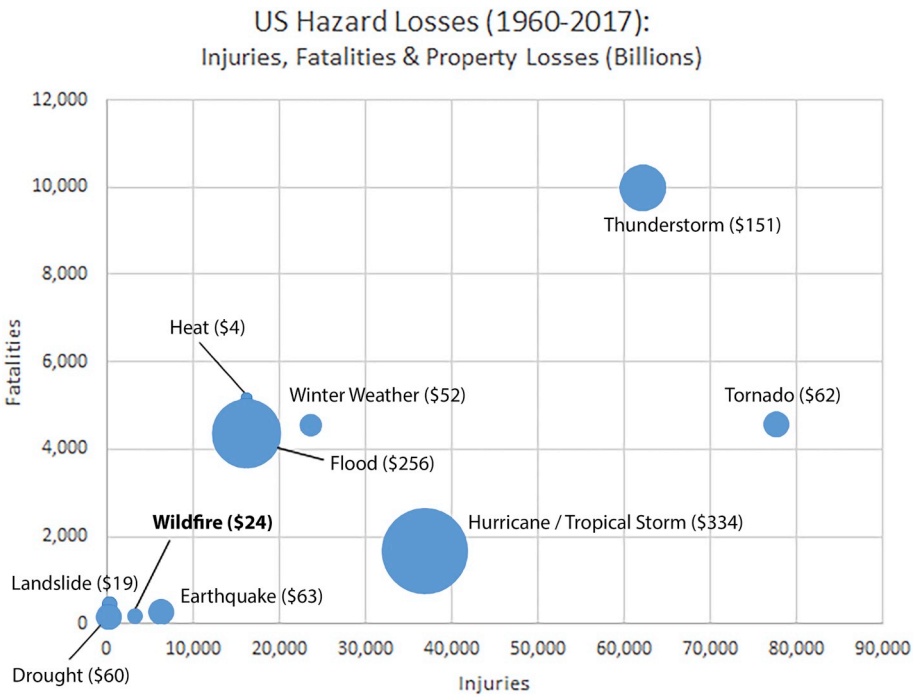

Fig. 2. Historical US hazard losses from top ten loss-causing hazards. The position of each hazard type represents cumulative injuries (x-axis) and fatalities (y-axis) over the period of record. Dot size is proportional to monetary losses (adjusted to 2017 US dollars) from each hazard type. Numbers in parentheses represent cumulative dollar losses (in billions) for each hazard type. Thunderstorm losses combine data for hail, thunderstorm wind, severe thunderstorm, and lightning hazards. Source: SHELDUS, Version 17.0. Loss estimates derive from National Centers for Environmental Information (formerly National Climatic Data Center) *Storm Data and Unusual Weather Phenomena*, published monthly.

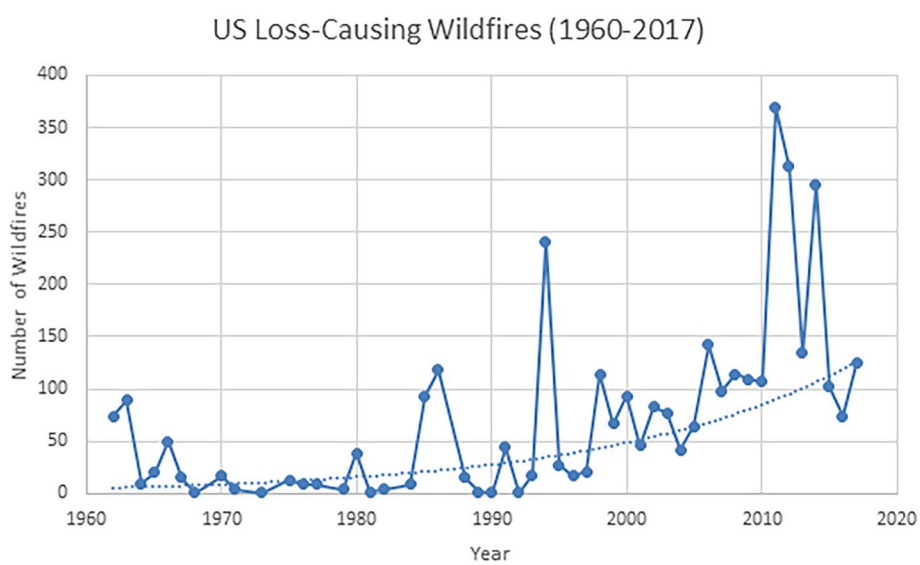

Fig. 3. Annual number of loss-causing US wildfires, 1960–2017. Loss-causing wildfires denote events with measurable property damages and/or human casualties. Note: No loss-causing wildfires were reported in 1960 and 1961. Source: SHELDUS, Version 17.0. Loss estimates derive from National Centers for Environmental Information (formerly National Climatic Data Center) *Storm Data and Unusual Weather Phenomena*, published monthly.

vulnerability reduction (for a notable exception in the form of a resilience model, see Ref. [35]). Furthermore, extant recovery models focus almost exclusively on human dimensions and pay little heed to post-event ecological conditions. They also ignore feedbacks between social and ecological variables shown to be critical in the wildfire context [2]. Table 2 contrasts several models for post-disaster recovery, highlighting shortcomings when addressing vulnerability and ecological feedbacks. The models differ in their spatial and temporal resolution and in their conceptualization of recovery itself (e.g., as an end state, a persistent trend, a process, or an outcome). Despite lacking consensus on the meaning of recovery [66], studies that utilize these models to measure post-disaster recovery abound. Frequently, these studies approximate actual community and household recovery levels with conditions in the built environment (e.g., Refs. [65,67,68]). At times, social vulnerability or other damage indicators (i.e., flood heights, wind speeds, etc.) serve as potential explanatory factors for observed differences in recovery across space [69–71]. These studies, however, seldom consider the ways in which rebuilding efforts may shape a region's future vulnerability to natural hazards. Therefore, the need to incorporate hazard characteristics, environmental impacts, ecological responses, and coupled social-ecological vulnerability in a cyclical model that does not conclude with recovery provides the impetus for our current model (Fig. 1). The next section discusses how linked social-ecological systems, altered through recovery, establish the vulnerability context in advance of future hazard events, particularly wildfires.

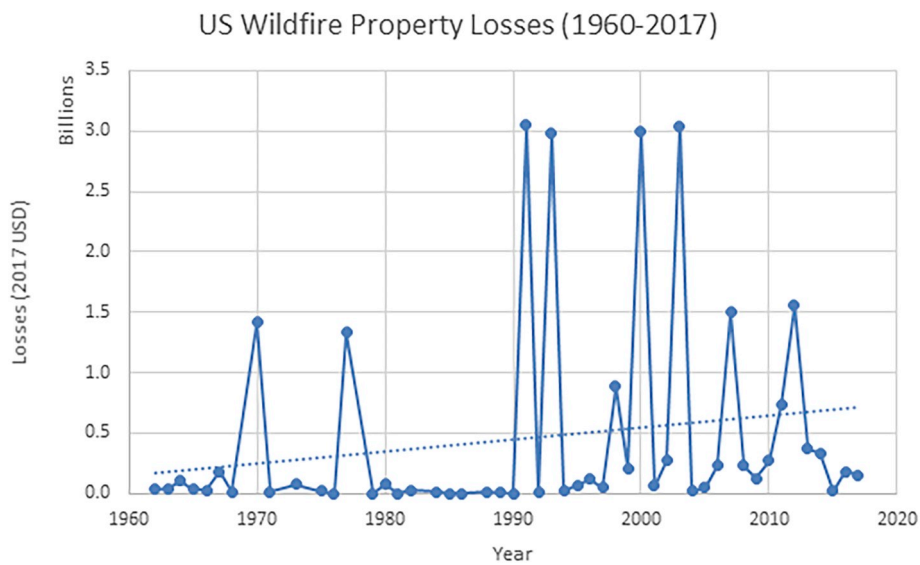

Fig. 4. US wildfire property losses, 1960–2017. Amounts in 2017 dollars, adjusted for inflation. Note: No loss-causing wildfires were reported in 1960 and 1961. Source: SHELDUS, Version 17.0. Loss estimates derive from National Centers for Environmental Information (formerly National Climatic Data Center) *Storm Data and Unusual Weather Phenomena*, published monthly.

Table 2
Comparison of extant post-disaster recovery conceptual models, listed chronologically.

Source	Hazard agent(s)	Model scale	Recovery concept	Treatment of vulnerability	Treatment of ecology
[31]	Earthquake, hurricane	Community	Sequential model of recovery where the final (fourth) wave of activity also includes development beyond pre-disaster levels, suggesting a recovery criterion based on restoration of stock variables (e.g., number of people, housing units).	Considers vulnerability reduction indirectly through betterment or improvement. Betterment is never explicitly defined, but it may include adapting infrastructure to withstand future environmental extremes. Betterment is not a prerequisite of full recovery.	None.
[25]	Multiple hazards: hurricane, blizzard, riverine flood, flash flood, dam failure, landslide, debris flow, tornado, earthquake	Community	Discusses organizational characteristics of local decision making during long-term recovery, focusing on inter-governmental relations.	Integrates mitigation as one domain of recovery activity, which competes with residential, business, and utility repair/reconstruction. Acknowledges differences in successful implementation of mitigation at the local level.	Does not address ecology directly, but does recognize environmental impacts of structural (e.g., levees, breakwaters) and non-structural (e.g., land use regulation) mitigation activities.
[64]	All hazards	Household	Describes four possible temporal stages of sheltering and housing prior to household recovery in a permanent residential dwelling.	Acknowledges vulnerable groups (e.g., low income, minorities, renters, etc.) will likely progress neither quickly nor linearly through the four stages. Future vulnerability of the dwelling is not addressed.	None.
[32]	Hurricane	Community	Characterizes post-disaster rebuilding as a politically powerful and spatially diffuse "growth machine" that fuels rapid expansion of the built environment and increases social inequality in the recovering community.	Most explicit of the models in connecting post-event rebuilding to future hazard vulnerability. Describes how the recovery process differently affects residential elites, non-elites, and newcomers, destabilizing communities and heightening uneven exposure to hazards.	Does not explicitly address ecology but does recognize the high potential for social and environmental imprudence in recovery decisions fueled by "growth machine" dynamics.
[30]	Earthquake	Community	Conceptualizes disasters as perturbations capable of altering trends in the human and built environment. Recovery is the end state when post-disaster trends (e.g., housing, employment) have stabilized to a new normal, regardless of pre-disaster levels.	None.	Does not explicitly address ecology, however by extension, disasters could alter trends in local environmental conditions. Method for determining trend stabilization could be applied to ecological variables.
[65]	Hurricane	Household & Housing Unit	Sequential, dual pathway model of residential building recovery, with the end state comprising a rebuilt house and a rehoused family.	Does allude to potential for alterations in rebuilt structures, but it is unclear how structures may differ (e.g., safer, sturdier, more energy efficient, or better adapted to endemic hazards like wildfire).	None.

3. Vulnerability as a pre-condition

Vulnerability, or the susceptibility to harm or loss, is widely used in the hazards, disasters, and human dimensions of global change literature to describe the potential for differential impacts of environmental threats on people and the places where they live and work [72–78]. Social and ecological (biophysical) vulnerability each result from a combination of hazard exposure and sensitivity (see Table 1), such that vulnerability precipitates loss only when sensitive attributes of places are exposed to hazard events [75,79]. Human exposure to wildfire hazards increases as more buildings are constructed within wildland vegetation; accordingly, were no human systems located in fire-prone areas, the human exposure to wildfire hazards would be negligible [80]. Ecologically, certain landscapes are more likely to be exposed to wildfire occurrence than others, due to factors such as vegetation continuity, ignition frequency (from lightning or human negligence), or location within topographically induced wind corridors. Additionally, regions where burning is an accepted cultural practice face an elevated likelihood of wildfire exposure.

Sensitivity is the degree to which a system will respond either adversely or beneficially to a change in climatic/hazard conditions; it provides greater insight into specific interactions between place characteristics (ecological or social) and circumstances acting to mitigate or exacerbate impacts [81]. For example, human sensitivity to wildfire increases when it is difficult for firefighters to access homes that are located far from roadways or within unsafe, dense vegetation. Structures comprised of flammable building materials or with adjacent flammable vegetation, such as trees overhanging roofs, are also more sensitive to impacts than structures that are built and maintained to reduce fire risk. At the community level, a social system with high employment in primary sector economic activities such as farming or forestry may be more sensitive to changes in natural conditions (e.g., drought, wildfire) than a community with a different macroeconomic makeup (cf. [82]). Similarly, rural communities with high proportions of elderly residents may be ill-equipped to prepare for wildfires [83]. Human sensitivity can also vary temporally. For instance, large-scale economic recessions or simultaneous wildfires occurring in a region may reduce available financial resources to combat additional wildfires. On the ecological front, a natural system's sensitivity to the wildfire hazard depends on factors such as the frequency and intensity of wildfire relative to the capacities of plant and animal species to resist or recover from an event. Some species possess traits or mechanisms to better resist or regenerate after a fire, which are adaptations to long-term fire regimes [84]. Alternatively, drought conditions during regeneration can increase the flammability of vegetation, and ultimately, its mortality [85]. Ecological sensitivity can also arise from short-term meteorological conditions, such as a windstorm during a drought, which can increase vegetation flammability, and in turn, the likelihood and intensity of a wildfire, were an ignition to occur. Likewise, biological agents such as insect infestations can interact with pathogens and fire to compound ecological sensitivity via tree mortality [86]. In addition to increasing landscape flammability, interactions—or feedbacks—between invasive species and fire can increase the sensitivity of ecological systems to wholescale vegetation type changes [87] and subsequently alter regional biodiversity [88].

As wildfires are recurrent events, the long-term recovery period is the time in which endpoint vulnerability transforms into starting point vulnerability for the next event. Kelly and Adger's [89] "wounded soldier" analogy illustrates this well: a soldier's existing injuries from previous battles limit or condition the soldier's ability to bear future assaults. Accordingly, our model (Fig. 1) accounts for place vulnerability as both a pre-condition and post-condition of destructive wildfire. Two caveats regarding vulnerability must be acknowledged. First, combinations of characteristics that enhance vulnerability in one setting may reduce vulnerability in another. For example, high fire severity in one region may result in ecologically damaging mortality of fire-sensitive species, but in another region where high fire severity is part of the natural fire regime, it may promote successful post-fire regeneration of plant species. Thus, regionally specific adaptations of species to historical fire regimes contribute to ecological vulnerability. The second vulnerability caveat is that within a human or ecological community (i.e., a local jurisdiction or an ecosystem) the sensitivity of populations can vary greatly. For instance, human vulnerability may fluctuate widely between neighborhoods in places where social stratification is high [90,91]. Likewise, in mountainous regions the diversity of microclimates and species composition at differing altitudes and aspects can produce substantial variation in ecological vulnerability across short distances [92,93]. Thus, attention to local geographic contexts and cause-effect relationships at multiple scales is necessary to appropriately represent vulnerability.

4. Event characteristics

Although exposure and sensitivity parameters give rise to latent place vulnerability, each discrete wildfire event also brings unique impacts to human and ecological systems. The specifics of when, where, and how a fire begins, and under what conditions, influence its eventual pattern of impact. In this section, we apply to wildfire events several general characteristics used to compare the magnitude, temporal dimensions, and spatial patterns of hazards [80,94]. Then, we describe how these wildfire characteristics guide response-focused human activities and engender a range of impacts.

Wildfire magnitude describes an event's cumulative degree of impact. It is typically expressed in terms of fire size (i.e., total area burned) and burn severity, which is a measure of change in above- and below-ground organic matter (i.e., vegetation). Alternatively, the total energy released by a wildfire may denote magnitude, irrespective of the burn severity. As Burton et al. [80] note, defining an event's magnitude serves to categorize some events as "extreme"; however, this effort often requires versatility in leveraging available data.[4] Distinct from magnitude, wildfire intensity refers to the amount of heat generated along the flaming front at a given point in space and time. With regard to timing, both a wildfire's speed of onset (i.e., time from ignition to arrival of the initial fire line) and its duration (i.e., length of time for the fire to consume fuel and pass through an area) are relevant temporal characteristics that affect human and ecological responses. Over the longer term, the temporal spacing (i.e., return period in years) between subsequent fires, which is decreasing in some regions due to climatic forcing [9–11], may also irreversibly alter both fuel composition and ecosystem functioning. Finally, relevant spatial parameters for wildfire include the fire perimeter itself (i.e., outline of burned extent) and variation in burn severity within the perimeter. Although these characteristics may be measured statically, feedbacks occur among them during an active wildfire event. For example, burn severity is affected by both the intensity of the fire and the duration of burning [95,96]. Temporal aspects are a function of the rate of fire spread [97], which in turn, are influenced by factors including the location and source of ignition (e.g., lightning, arson, control burn, electrical line failure); the type, condition, and age of fuels present; topographic characteristics; suppression attempts (human response); and local meteorological conditions (temperature, humidity, and winds) prior to and during the wildfire event. These aspects collectively determine the overall spatial pattern of impact for each wildfire.

Aspects of the human response also interact with aspects of the fire itself to influence the fire's magnitude and degree of impacts. For instance, wildfire speed of onset (i.e., rate of spread) and expected

[4] Recently Tedim et al. [4] proposed that "extreme wildfire events" be distinguished by their fire line intensity, rate of spread, spotting distance, and erratic behavior; this characterization of magnitude combines intensity with temporal and spatial dimensions.

duration may influence residents' decisions to stay and defend their property or to evacuate, thus affecting the number of casualties [98]. Similarly, large-scale fire suppression tactics can limit fire size or intensity and can route active fire lines away from communities, thereby lessening the impact on human systems.

Wildfire impacts result from the interaction of event characteristics and human responses and can be measured in direct losses (e.g., deaths, injuries, property loss, habitat loss, decreased water quality), indirect losses (e.g., subsequent health effects, decreases in ecosystem function), and the spatial distribution of the impact. Additionally, wildfires often trigger secondary events that compound direct losses. For example, flooding, debris flows, and landslides can cause additional property damage [99], while increased smoke exposure can aggravate underlying respiratory conditions like chronic obstructive pulmonary disease (COPD) or asthma [100,101]. These indirect losses delay and complicate recovery for residents of impacted and adjacent communities.

Importantly, even wildfire events that minimally affect human system functioning may greatly impact the ecological system in adverse or beneficial ways. The proportion of plants that are killed by fire varies with burn severity, fire interval, and species' specific traits [102]. Likewise, animals may be killed, flee the fire, or survive in situ, with the immediate impact varying based on burn severity or fire size [2,103]. In some ecosystems, the loss of vegetation following a fire allows for the invasion of nonnative plants (primarily grasses), which can outcompete native species or eventually result in vegetation type shifts [104]. These nonnative plants may decrease the biodiversity of the area, reduce carbon storage, or limit available forage for surviving native fauna. On the other hand, low-intensity surface fires in some forested systems may enhance ecological resilience by reducing ground or ladder fuels that could lead to crown fires in ecologically important old trees [105]. In sum, individual wildfire exposure patterns, coupled with the place vulnerability characteristics of both social and ecological systems, shape the degree of wildfire impacts and set the course for post-wildfire recovery.

5. Social and ecological outcomes

After a wildfire, both social and ecological features respond and begin to recover, in independent and linked ways. Post-fire social outcomes, including residents' long-term health outcomes (e.g., mental health, trauma), population and economic changes (e.g., outmigration, loss of tax revenue), and changes to the built environment (homes, infrastructure, roads), can be measured over time through quantitative surveys, qualitative interviews, photography, and time series analyses [30,68,106,107]. Meanwhile, vegetation response is the most frequently considered post-fire ecological outcome since it is the most dramatically altered and visible ecological impact of a wildfire. The degree of vegetation recovery is influenced by the severity of the fire, which typically varies across the burned area [108]. Vegetation also strongly influences other ecological indicators, such as soil properties (e.g. Ref. [109]), hydrological response (e.g. Ref. [110]), carbon storage (e.g. Ref. [111]), and faunal biodiversity (e.g., Ref. [103]). Social and ecological outcomes are also linked and influence each other directly and indirectly. For example, landscape-level vegetation recovery unfolds as a result of both natural influences (e.g., post-fire response traits of plant species) and human influences (e.g., rehabilitation programs, fuel treatments, vegetation management around homes, land use change, and altered human ignition patterns) [102,112,113]. Vegetation recovery, in turn, influences emotional well-being [114], thus aiding psychological recovery in human communities.

5.1. Immediate post-fire outcomes (T_1)

Initial recovery during the first year after wildfire typically focuses on immediate social needs and prevention of further ecological damage. In the affected human communities, mass care, temporary housing, and infrastructure repair consume the attention of local emergency managers during the earliest weeks and months post-emergency [115]. Although the risk of subsequent wildfire in the burned area is low at this time, secondary hazards like flooding, erosion, and debris flows can occur. In the US, state and federal agencies coordinate vegetation stabilization to mitigate potential flooding and erosion issues [116–118]. They also provide financial aid to offset ranching and agricultural losses [117,118]. Meanwhile in ecological communities, plant species, depending upon their life history traits, begin to recover during the first post-fire year. This can occur through resprouting, seeding in from unburned areas, or establishing as new seedlings in the case of fire-cued germination [119]. The success of early-stage ecological recovery depends largely upon the environmental context, which includes precipitation patterns, the size and severity of the fire, and in some cases, the time since the previous fire, as certain reseeding plant species can only withstand longer intervals between fires [120,121].

5.2. Short-term recovery (T_3)

As recovery of the human system continues, the next several years often see a focus on rebuilding homes. This process happens more slowly in rural or exurban settings where housing construction is expensive and logistically challenging, while faster rebuilding (i.e., one to two years) is more common in urban or suburban settings [49]. During the first several years following a wildfire, communities also formally re-examine their wildfire management and mitigation practices. Suppression capacity and large-scale fuel treatments are a typical focus of these post-event examinations [54,122–124]. At the household scale, property owners may reduce fuels around houses, remove dangerous or damaged trees, or replant less flammable species in gardens, thus altering the local ecology; such actions can also be carried out collectively by property owners' associations [21]. Social networks expand and new organizations form to support recovery, post-disaster learning, and adaptation [122,123,125]. In some cases, communities also devise new wildfire mitigation programs, building regulations, and planning efforts [51,52,54,126]. As suggested earlier, a recent fire may briefly amplify residents' risk perception during this short-term recovery period and galvanize receptivity to new policies and educational programs aimed at reducing wildfire risk [37,40,54]. Alternatively, however, communities and residents intent on a quick return to normal may opt not to take such adaptive actions [41]. As documented after non-wildfire disasters, the presence of a disaster subculture (cf. [127,128]) where residents are accustomed to recurrent hazard impacts may breed fatalism rather than heightened awareness and action [44,45]. Risk perception may also diminish over time before any change to policy or practice takes root [21,129].

In the ecological system, vegetation composition during this period may still reflect the establishment of short-lived species that tend to germinate after a fire (e.g., Ref. [130]). Severe droughts occurring at this time may also differentially affect seedling and resprout survival (e.g. Ref. [85]) as well as the colonization or expansion of exotic species at the burn site (e.g., Ref. [131]). Thus, by the third-year post-fire, vegetation composition may reflect these changes in local climatic conditions. In addition to vegetation regrowth, the short-term ecological recovery may reflect immediate human decision-making. For example, depending on the treatment method and ecological context, soil stabilization efforts taken earlier in recovery could now show positive or negative ecological impacts (e.g., Ref. [132]). Ongoing fuel treatment of the recovering vegetation, adoption and maintenance of defensible space, and/or replanting behaviors among property owners may have also changed based on the perceived impact of the fire, thus further shaping ecological conditions. By this time, many animal species may also be returning to the burned area (e.g., Ref. [133]). Importantly, it is at this stage of recovery that wildfire risk once again becomes significant, both as a function of increasing exposure (e.g., more structures being rebuilt in formerly burned areas) and sensitivity (e.g., regrowth of grasses and

shrubs on soil formerly cleared by the fire).

5.3. Long-term recovery (T_{10})

Ultimately, wildfire impacts and resultant policy changes regarding homes, the built environment, and open space will play out over years and even decades. These long-term, coupled post-wildfire changes to housing and vegetation in residential settings are not yet well understood. There are relatively few studies of long-term recovery and built environment change after wildfire. Evidence from both US and Australian wildfires suggests that residents can take several years even to decide whether or not to rebuild [49,134]. Rapid reconstruction can return housing stocks to pre-fire levels, as observed after wildfires (2010–2012) on the Colorado Front Range [52]. Alexandre et al. [135] suggest regional and national housing market conditions may greatly influence post-fire housing patterns; in their nationwide study of fires between 2000 and 2005, new development eclipsed house rebuilding within wildfire perimeters. Whether new housing or rebuilt, a net increase in housing units during the post-fire recovery period appears typical [135,136]. After the 1991 Oakland Hills fire in northern California, homes were also rebuilt larger, which increased overall exposure to wildfire as well as the risk of house-to-house fire spread [137]. Similar patterns have been found in Australia, where some areas burnt in the 2009 Black Saturday fire experienced an increase in population between 2006 and 2016 [138].

Though difficult to determine to what extent these rebuilding patterns result from post-wildfire policy decisions or from prevailing regional development trends, the ways in which communities build—both in terms of voluntary mitigation actions and in response to local mandates—influence future vulnerability to wildfire. For example, after the Cedar Fire of 2003, San Diego County responded by changing building codes, improving firefighting technology, and increasing the required amount of defensible space from 65 ft to 100 ft (20 m–30 m) [139]. Although the long-term change in defensible space has not been quantified county-wide, field inspections and aerial photos reveal there has been substantial vegetation reduction over time [140]. However, people may also decline to rebuild with wildfire mitigation strategies in mind [45]. More broadly, social recovery outcomes such as social division, community cohesion, and mental and economic well-being are rarely monitored long-term after wildfire, although these events do have lasting impacts [43] and such social recovery outcomes are directly relevant for both household-level and community-level wildfire mitigation.

Given that most ecological systems evolve over long time periods (i.e., it can take decades for vegetation succession to occur or for animal species to recolonize), assessment of ecological impacts and recovery outcomes necessarily requires longer time spans. The timing of post-fire ecological recovery will vary substantially depending upon the geographical and ecological context of the setting. This is because different plant communities go through vegetation succession at widely different rates, depending on environmental conditions and species composition [102,141]. In some forests, full succession and canopy recovery may take decades to centuries, whereas plant communities in many non-forested ecosystems may return to pre-fire conditions in only a few years. The rate of biomass accumulation (i.e., fuel volume) and flammability also vary widely depending on native or exotic species' composition and environmental conditions [102,141]. Though some vegetation communities may still be in a state of transition a decade post-fire, in many cases, the plant and animal species reestablished by that time will signify the area's long-term ecological trajectory. From this point onward, external factors primarily influence ecological recovery and the landscape's future vulnerability to wildfires. These factors include localized human decisions on types of rebuilding, landscaping, or vegetation management strategies; the timing of the next fire; and the wildcard of global climate change, which may directly and indirectly alter regional fire regimes (cf. [142]).

6. Fire-adapted communities: changing the vulnerability landscape

Given the potential for heightened public buy-in and increased financial resources for wildfire risk reduction (via private insurance payouts and publicly-supported recovery programs), the post-fire recovery period seems a logical time for instituting changes to make communities more fire-adapted [35,41]. However, the processes that might facilitate or stifle linked social-ecological adaptation, particularly during long-term recovery, remain poorly understood [49,143]. Although we know little about how place vulnerability changes during recovery, drawing from the broader hazards literature we posit that three interrelated factors are critical in shaping the effectiveness of post-wildfire adaptations in reducing vulnerability. These factors include the degree of coordination among institutions, the implications of human values and attitudes, and the inherent tradeoffs in outcomes that occur across spatial and temporal scales [144,145]. We describe these interrelated factors below, acknowledging that success in achieving the ideal of fire-adaptedness demands multi-scalar policies that use bottom-up approaches to reconcile the varying interests and capacities of diverse stakeholders.

First, adaptation can be challenging at the community scale because it requires coordination among individuals and across formal and informal institutions, all of which may have competing interests and values [16,49]. For example, individual homeowners associations may require residents to rebuild in accordance with aesthetic standards, but may not re-examine wildfire risk in the process [21,52]. At the community level, fire department staff may be concerned about the enhanced wildfire risk that accompanies residential development, while local building department and land use staff emphasize the economic incentives generated by rebuilding and expanded development [54]. Interactions between scales are also critical when it comes to coordination, as individual homeowners' decisions about rebuilding–situated within a local policy context–compound to determine community-level risk. For example, after losing homes to wildfire, individuals with resources often rebuild larger homes [52,146]. As with other natural hazards[5] [32,147], these larger, higher-valued homes lead to greater hazard exposure due to their sheer presence. With wildfire, however, if these larger homes are in closer proximity to one other, they may also increase wildfire risk via house-to-house wildfire spread [148]. Sensitivity of the built environment to wildfire is further heightened if the homes are not built of fire-resistant materials.

A second challenge is that during post-fire recovery, a community's social-ecological setting and underlying wildfire risk parameters may change so drastically that residents' attitudes toward their surroundings are upended. Subsequent decisions to stay or relocate, shaped by these new attitudes, may then spell different consequences for the community and its future vulnerability to wildfires. For example, substantial clearing of vegetation around residential developments to reduce wildfire risk may alter public environmental values toward native vegetation and biodiversity [21,149]. In turn, some residents may opt to relocate, deciding that the benefits of living in the WUI (e.g., aesthetic, amenity) have been compromised by wildfire risk reduction measures. Alternatively, upon experiencing the fire and subsequent wildfire risk reduction measures, residents may also choose to relocate reasoning that the unacceptably high risk burden of living in the WUI outweighs its quality-of-life benefits. Either way, these decisions to relocate may reduce wildfire risk for those who leave but produce unexpected changes to place vulnerability for those who remain. The 2009 Black Saturday wildfires in Victoria (Australia) may illustrate this counterpoint. After these fires, most residents opted to remain in areas deemed by

[5] A so-called "jacuzzi effect" was observed after Hurricane Hugo when insurance windfalls enabled residents to rebuild larger, stronger homes with improved amenities.

authorities to possess 'unacceptably high' wildfire risk, while a small number participated in a formal buyout scheme [150]. This 'retreat' strategy of land acquisition and resident relocation [151] aims to lessen the exposure of people and property to wildfire; however, the strategy may have the adverse effect of increasing vulnerability for the sizeable remaining population. Outmigration, whether triggered by post-wildfire buyouts or by large-scale demographic processes, raises questions about responsibility for managing fuel on these acquired and abandoned properties. Left unattended, these vacant parcels could make for more sensitive vegetation stands (e.g., greater biomass, higher flammability, more exotic species), and therefore increase the risk of socially and ecologically disastrous fires. Studies suggest such a trend is already underway in Europe [19,152].

Finally, the temporal dimension cannot be ignored, since the effectiveness of adaptations in reducing wildfire vulnerability is not static. As time from an event progresses, subsequent failure to maintain standards of vegetation management, fire resistance of houses (e.g., through poor maintenance or modifications), and emergency management capability (e.g., complacency, budget cuts) may ultimately lead to increased vulnerability to wildfire. Moreover, adaptations such as fire-resistant housing materials and enhanced emergency management capability that reduce wildfire risk in the short-term by decreasing sensitivity, could encourage further residential development and population growth in high wildfire risk environments, thus increasing future exposure over the longer-term. Regardless of local decision-making, expected increases in the frequency and severity of wildfires in some areas [9,153] may eventually render certain adaptations ineffective in the future [154]. Ultimately, these tradeoffs between exposure and sensitivity to wildfire demonstrate the dynamic nature of place vulnerability and the complexity of achieving a cohesive, fire-adapted community vision. Any hope of realizing fire-adaptedness requires envisioning long-term recovery of the linked social-ecological system as part of a larger, ongoing risk governance process [155,156] rather than a temporary, self-contained process with a discrete endpoint.

7. Discussion

Amid escalating wildfire losses worldwide, this paper introduces a theoretical model for community recovery that integrates principles of vulnerability reduction. As with natural hazards generally, much of the emphasis on wildfire recovery (in both research and practice) is focused on short-term restoration of housing and other basic human needs in response to previous conditions (i.e., a "return to normal"). Where we do see a broader consideration of adaptation and change, communities and residents typically focus on bolstering suppression and emergency response capabilities [54,123,154]. Transformative strategies that tailor human systems to fit their regional fire regimes remain elusive [2,17,19,22]. Furthermore, given the complex and coupled ways in which ecological and social systems recover and change over time, it is not immediately obvious how residents, fire managers, and local policy professionals can best work to reduce future wildfire vulnerability through recovery. Yet, the proposed model provides a basis for guiding future systematic, comparative research to that end.

7.1. Future inquiry

To determine whether wildfire recovery is truly a "hot moment" for adaptation, numerous big-picture questions about community-level wildfire adaptation efforts must be examined. Though not exhaustive, the list below illustrates the breadth of potential inquiry utilizing the current model that links social and ecological recoveries through time:

- To what extent are post-fire changes in land use and fuel management taking place on a national level in countries facing increased wildfire losses?
- How does post-fire vegetation differ from pre-fire vegetation in terms of its sensitivity to burning in the next fire, and what new risks might it pose to human assets?
- To what extent do macroeconomic influences and new approaches to growth management in the WUI affect trajectories of community recovery from wildfire?
- What unique risks to future wildfires are posed by rural land abandonment versus development in the WUI?
- How do cultural practices of fire usage contribute to place vulnerability? How might these practices and other traditional knowledge on wildfire be incorporated into strategies for wildfire risk reduction?
- How do residents' notions of place attachment, perceptions of risk, and environmental values influence their willingness to adapt or relocate after a fire?
- To what extent do property owners retrofit existing housing stock and add wildfire mitigation features to rebuilt housing?
- How does the wildfire recovery process affect community-level social cohesion and coping capacity for future fires?
- Are some regional vulnerability reduction strategies locally maladaptive (or vice versa)? If so, what is the nature of these vulnerability and adaptation trade-offs?

7.2. Data requirements

While we do not present a case study here, we do suggest clear requirements necessary to apply our model. First, the model requires both ecological and social data with a high degree of spatial resolution. Ecologically, we suggest that fine scale maps of vegetation (which are often future fuel for wildfire) coupled with other physical features that drive fire frequency and severity (e.g., slope and aspect), along with climatic variables, provide the minimum datasets needed. On the social side, data on the built environment (e.g., home placement and construction) should be married with proxies for vulnerability (e.g., income, age, race, housing tenure, etc.) tailored to the geographic context. Importantly, these data must be examined with an understanding of how social and environmental systems interact through fuels management, fire suppression, land use policy, and local cultural practices involving fire usage. Additionally, geospatial data on previous wildfire ignition locations and fire perimeters coupled with attribute information on fire causality would be beneficial in characterizing such human-environmental interaction. Second, our model requires sustained temporal resolution. Successful application of the model will require data from before fires, shortly after fires, and then at sustained intervals in order to understand changing vulnerability in the coupled system through time. Ancillary data culled from after-action reports, community wildfire protection plans, or local hazard mitigation plans may also be helpful in monitoring social, ecological, and coupled outcomes over time. Third, for some applications of the model, research will require either multiple study communities or a control community (i.e., a community that did not burn) in order to understand how fire changed the community. Without multiple sites, or a control site, it may be hard to differentiate changes in community vulnerability caused by wildfire recovery from changes unrelated to wildfire (e.g., changes driven by macroeconomic conditions).

All three of these requirements may be challenging to meet, though not insurmountable. For example, gathering, analyzing, and understanding both ecological and social data is rarely proficiently done by a single researcher. Therefore, our approach may require interdisciplinary expertise. Likewise, long-term longitudinal datasets that provide ecological and social data at resolutions that are useful may be difficult to find or costly to create. Even in the most data-rich environments, key information (e.g., parcel boundaries, census variables) from as little as 20 years ago can be scarce. Using multiple sites may increase the complexity of analysis, while choosing an appropriate control is part art and part science.

7.3. Limitations and contributions

Limitations of the present model itself must also be acknowledged. Instead of engaging explicitly with the concept of resilience, it remains implicit in our model. The rationale for this approach lies in the conceptual slipperiness of the resilience concept and its varying overlap with vulnerability in subfields of hazard and disaster science scholarship [35,157,158]. Secondly, the model does not depict the compounding of many household-level responses to wildfire that will collectively comprise community-level adaptation. Yet, we stress that the model does not assume uniformity of responses either. Embedded within the place vulnerability concept is the notion that human adaptation will vary within a fire-affected community to the extent that there are variations along wealth and income lines. Additionally, although the model may be applied in a variety of cultural contexts in both developing and developed regions of the world, our articulation of the model has focused more deeply on the latter. Future research on the cultural drivers of disaster risk and integration of traditional knowledge into risk reduction efforts (cf. [159,160]) are likely to reveal even tighter coupling of ecological and social systems before and after wildfires than described in our current US and Australian-based examples.

Difficulties may also arise when applying the model to other hazard agents, as several aspects distinguish wildfires. First is the sinusoidal nature of the wildfire threat. Fuels must exist for a wildfire to occur, yet once the wildfire has consumed these fuels, the risk of a repeat wildfire in the short-term drops precipitously. This differs from floods, whose probability of occurrence in any given year remains constant. Second, a case could be made that, with wildfire, ecological outcomes are more tightly linked to human responses than with other hazards. Fuel treatments and vegetation management are primary solutions used to prevent wildfires, and by extension, their losses. Moreover, ecological recovery left unchecked could lead to more destructive future fires. Given the ecological and cultural value of fires, devising best practices for wildfire risk reduction should account for dynamic environmental conditions, local cultural realities, and their resulting feedbacks. Third and finally, the management of wildfire ignition, exposure, and propagation (the latter vis-à-vis sensitivity) are three distinct issues demanding separate but inter-reliant techniques for prevention and loss mitigation. For example, effective maintenance of defensible space around residences may require a combination of land use or development regulations, building codes that harden structures, vegetation management programs, and community education campaigns. These elements, which work in tandem, represent substantively different types of mitigation practices: prevention, property protection, source control, and public information, respectively [161,162]. To further illustrate interdependence of these techniques, take California's "One Less Spark" public education campaign to promote safety in lawn equipment use, debris and campfire burning, and other activities known to spark wildfires [163]. Were this investment in ignition management education to be made without concomitant investments in defensible space and/or vegetation management, fires that did ignite may arguably cause greater losses.

While wildfire may be unique, these aspects do not preclude the application of the model to non-wildfire hazards; rather, it is incumbent upon the researcher to select appropriate proxies for each model component (see Table 1) based on the hazard of study and geographic context. In terms of event characteristics, every hazard has a return period, and the temporal spacing of other hazards like hurricanes (influenced by prevailing upper air patterns) or earthquakes (with accompanying foreshocks and aftershocks) also occurs sinusoidally, though on different time scales. Coupled social-ecological outcomes are apparent with some non-wildfire hazards, but not others. For instance, remediation techniques after an oil spill affect species recovery, and with floods, further development increases lateral floodplain growth and urban stream flashiness. Conversely, tornado frequency does not correlate with proliferation of mobile homes, nor do earthquakes result from increased construction along fault lines. Finally, parallels to other hazards exist with regard to risk reduction strategies. Although the precise timing and location of a wildfire ignition acts as an additional source of chance in the risk equation, it is not unlike a sudden, point-source, airborne chemical release from a fixed facility. In both cases, strategies for hazard containment (preventing wildfire sparks or chemical releases) versus loss reduction (reducing exposure and sensitivity in the area) should be distinct yet complimentary. As with other hazards, best practices to reduce wildfire vulnerability should be devised cooperatively with local populations. Limiting the use of fire (e.g., who can burn, when, where, how much, for what reasons) rather than eliminating its use from the landscape entirely would seem the most prudent solution.

Ultimately, through empirical research we hope to better illuminate potential trajectories for long-term human and ecological community recovery after wildfire. To do so, we believe a cyclical framework is an essential cornerstone. Furthermore, including vulnerability as a dynamic variable both arising from and formative of disaster impacts allows us to more fully describe wildfire recovery (social and ecological). As articulated here, this model does make several notable theoretical contributions. Distinct from current theory, we consider longer time frames after hazard events, while also recognizing that recovery does not have an end point. Our model is also unique in emphasizing the links between social and ecological systems, both in recovery and future vulnerability—something lacking in extant recovery models. Finally, our current model is applicable to community recovery after any disaster—not only wildfire. We anticipate such cross-hazard and multidisciplinary frameworks will be increasingly valuable as extreme events and their impacts soar as a result of climate change.

Declaration of competing interest

None.

Acknowledgments

This work was supported by the National Socio-Environmental Synthesis Center (SESYNC) under funding from the National Science Foundation DBI-1639145. The authors also thank Teresa Brennan-Kane for her contributions to the paper.

References

[1] M.A. Moritz, E. Batllori, R.A. Bradstock, A.M. Gill, J. Handmer, P.F. Hessburg, J. Leonard, S. McCaffrey, D.C. Odion, T. Schoennagel, A.D. Syphard, Learning to coexist with wildfire, Nature 515 (2014) 58–66.
[2] A.P. Fischer, T.A. Spies, T.A. Steelman, C. Moseley, B.R. Johnson, J.D. Bailey, A. A. Ager, P. Bourgeron, S. Charnley, B.M. Collins, Wildfire risk as a socioecological pathology, Front. Ecol. Environ. 14 (2016) 276–284.
[3] D.M. Bowman, G.J. Williamson, J.T. Abatzoglou, C.A. Kolden, M.A. Cochrane, A. M. Smith, Human exposure and sensitivity to globally extreme wildfire events, Nat. Ecol. Evol. 1 (2017), 0058.
[4] F. Tedim, V. Leone, M. Amraoui, C. Bouillon, M. Coughlan, G. Delogu, P. M. Fernandes, C. Ferreira, S. McCaffrey, T.K. McGee, J. Parente, D. Paton, M. G. Pereira, L.M. Ribiero, D.M. Viegas, G. Xanthopoulos, Defining extreme wildfire events: difficulties, challenges, and impacts, Fire 1 (1) (2018) 9.
[5] M. Cruz, A. Sullivan, J. Gould, N. Sims, A. Bannister, J. Hollis, R. Hurley, Anatomy of a catastrophic wildfire: the Black Saturday kilmore east fire in Victoria, Australia, For. Ecol. Manag. 284 (2012) 269–285.
[6] S. Gómez-González, F. Ojeda, P.M. Fernandes, Portugal and Chile: longing for sustainable forestry while rising from the ashes, Environ. Sci. Policy 81 (2017) 104–107.
[7] B.M. Wotton, M.D. Flannigan, G.A. Marshall, Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada, Environ. Res. Lett. 12 (9) (2017), 095003.
[8] D.M.J.S. Bowman, A. Moreira-Muñoz, C.A. Kolden, R.O. Chávez, A.A. Muñoz, F. Salinas, Á. González-Reyes, R. Rocco, F. de la Barrera, G.J. Williamson, N. Borchers, L.A. Cifuentes, J.T. Abatzoglou, F.H. Johnston, Human-environmental drivers and impacts of the globally extreme 2017 Chilean fires, AMBIO A J. Hum. Environ. (August) (2018) 1–13.
[9] J.T. Abatzoglou, A.P. Williams, Impact of anthropogenic climate change on wildfire across western US forests, Proc. Natl. Acad. Sci. 113 (42) (2016) 11770–11775.

[10] J.T. Abatzoglou, A.P. Williams, L. Boschetti, M. Zubkova, C.A. Kolden, Global patterns of interannual climate-fire relationships, Glob. Chang. Biol. 24 (11) (2018) 5164–5175.
[11] A.L. Westerling, H.G. Hidalgo, D.R. Cayan, T.W. Swetnam, Warming and earlier spring increase western U.S. Forest wildfire activity, Science 313 (5789) (2006) 940–943.
[12] J.K. Balch, B.A. Bradley, J.T. Abatzoglou, R.C. Nagy, E.J. Fusco, A.L. Mahood, Human-started wildfires expand the fire niche across the United States, Proc. Natl. Acad. Sci. 114 (11) (2017) 2946–2951.
[13] A.D. Syphard, J.E. Keeley, A.H. Pfaff, K. Ferschweiler, Human presence diminishes the importance of climate in driving fire activity across the United States, Proc. Natl. Acad. Sci. 114 (52) (2017) 3314–3319.
[14] J.P. Argañaraz, V.C. Radeloff, A. Bar-Massada, G.I. Gavier-Pizarro, C. M. Scavuzzo, L.M. Bellis, Assessing wildfire exposure in the wildland-urban interface area of the mountains of central Argentina, J. Emerg. Manag. 196 (2017) 499–510.
[15] S. Oliveira, J.L. Zêzere, M. Queirós, J.M. Pereira, Assessing the social context of wildfire-affected areas. The case of mainland Portugal, Appl. Geogr. 88 (2017) 104–117.
[16] H. Brenkert-Smith, J.R. Meldrum, P.A. Champ, C.M. Barth, Where you stand depends on where you sit: qualitative inquiry into the notions of fire adaptation, Ecol. Soc. 22 (3) (2017) 7.
[17] S.J. O'Neill, J. Handmer, Responding to bushfire risk: the need for transformative adaptation, Environ. Res. Lett. 7 (1) (2012), 014018.
[18] T. Schoennagel, J.K. Balch, H. Brenkert-Smith, P.E. Dennison, B.J. Harvey, M. A. Krawchuk, N. Mietkiewicz, P. Morgan, M.A. Moritz, R. Rasker, M.G. Turner, Adapt to more wildfire in western North American forests as climate changes, Proc. Natl. Acad. Sci. 114 (18) (2017) 4582–4590.
[19] F. Tedim, V. Leone, G. Xanthopoulos, A wildfire risk management concept based on a social-ecological approach in the European Union: fire Smart Territory, Int. J. Disaster Risk Reduc. 18 (2016) 138–153.
[20] S. McCaffrey, Thinking of wilfire as a natural hazard, Soc. Nat. Resour. 17 (2004) 509–516.
[21] T.B. Paveglio, J. Abrams, A. Ellison, Developing fire adapted communities: the importance of interactions among elements of the local context, Soc. Nat. Resour. 29 (10) (2016) 1246–1261.
[22] T.A. Steelman, U.S. wildfire governance as social-ecological problem, Ecol. Soc. 21 (4) (2016) 3.
[23] A.D. Syphard, H. Rustigian-Romsos, M. Mann, E. Conlisk, M.A. Moritz, D. Ackerly, The relative influence of climate and housing development on current and projected future fire patterns and structure loss across three California landscapes, Glob. Environ. Chang. 56 (2019) 41–55.
[24] B.D. Phillips, Disaster Recovery, second ed., CRC Press, Boca Raton, FL, 2013.
[25] C.B. Rubin, Community Recovery from A Major Natural Disaster, University of Colorado Institute of Behavioral Science, Boulder, CO, 1985.
[26] Federal Emergency Management Agency, National Disaster Recovery Framework: Strengthening Disaster Recovery for the Nation, Federal Emergency Management Agency, Washington, D.C., 2011.
[27] D.R. Godschalk, D.J. Brower, T. Beatley, Catastrophic Coastal Storms: Hazard Mitigation and Development Management, Duke University Press, Durham, NC, 1989.
[28] R.B. Olshansky, L.D. Hopkins, L.A. Johnson, Disaster and recovery: processes compressed in time, Nat. Hazards Rev. 13 (3) (2012) 173–178.
[29] G. Smith, Planning for Post-Disaster Recovery: A Review of the United States Disaster Assistance Framework, Public Entity Risk Institute, Fairfax, VA, 2011.
[30] S.E. Chang, Urban disaster recovery: a measurement framework and its application to the 1995 Kobe earthquake, Disasters 34 (2) (2010) 303–327.
[31] J.E. Haas, R.W. Kates, M.J. Bowden, Reconstruction Following Disaster, MIT Press, Cambridge, MA, 1977.
[32] J.F. Pais, J.R. Elliott, Places as recovery machines: vulnerability and neighborhood change after major hurricanes, Soc. Forces 86 (4) (2008) 1415–1453.
[33] National Interagency Fire Center, National Interagency Coordination Center Wildland Fire Summary and Statistics Annual Report, 2017. Available at: https://www.predictiveservices.nifc.gov/intelligence/2017_statssumm/annual_report_2017.pdf. Accessed: 2 Jan.
[34] Insurance Information Institute, Facts + Statistics: Wildfires, 2018. Available at: https://www.iii.org/fact-statistic/facts-statistics-wildfires. (Accessed 18 January 2019).
[35] S.L. Cutter, L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, J. Webb, A place-based model for understanding community resilience to natural disasters, Glob. Environ. Chang. 18 (4) (2008) 598–606.
[36] NRC, Facing Hazards and Disasters: Understanding Human Dimensions, The National Academies Press, Washington, D.C., 2006.
[37] T.A. Birkland, After Disaster: Agenda Setting, Public Policy, and Focusing Events, Georgetown University Press, Washington, D.C., 1997.
[38] J.W. Kingdon, Agendas, Alternatives, and Public Policies, Little, Brown, Boston, MA, 1984.
[39] C. Rosenzweig, W.D. Solecki, Hurricane Sandy and adaptation pathways in New York: lessons from a first-responder city, Glob. Environ. Chang. 28 (2014) 395–408.
[40] W.D. Solecki, S. Michaels, Looking through the postdisaster policy window, Environ. Manag. 18 (4) (1994) 587–595.
[41] G.P. Smith, D. Wenger, Sustainable disaster recovery: operationalizing an existing agenda, in: H. Rodriguez, E.L. Quarantelli, R.R. Dynes (Eds.), Handbook of Disaster Research, Springer, New York, 2007, pp. 234–257.
[42] H. Brenkert-Smith, K.L. Dickinson, P.A. Champ, N. Flores, Social amplification of wildfire risk: the role of social interactions and information sources, Risk Anal. 33 (5) (2013) 800–817.
[43] M.S. Carroll, T. Paveglio, P.J. Jakes, L.L. Higgins, Nontribal community recovery from wildfire fiver years later: the case of the rodeo-chediski fire, Soc. Nat. Resour. 24 (2011) 672–687.
[44] W.E. Martin, I.M. Martin, B. Kent, The role of risk perceptions in the risk mitigation process: the case of wildfire in high risk communities, J. Environ. Manag. 91 (2) (2009) 489–498.
[45] T.K. McGee, B.L. McFarlane, J. Varghese, An examination of the influence of hazard experience on wildfire risk perceptions and adoption of mitigation measures, Soc. Nat. Resour. 22 (2009) 308–323.
[46] S. Schulte, K.A. Miller, Wildfire risk and climate change: the influence on homeowner mitigation behavior in the wildland–urban interface, Soc. Nat. Resour. 23 (5) (2010) 417–435.
[47] G. Winter, J.S. Fried, Homeowner perspectives on fire hazard, responsibility, and management strategies at the wildland–urban interface, Soc. Nat. Resour. 13 (2000) 33–49.
[48] P.A. Fischer, Reducing hazardous fuels on nonindustrial private forests: factors influencing landowner decisions, J. For. (July/August) (2011) 260–266.
[49] M.H. Mockrin, S.I. Stewart, V.C. Radeloff, R.B. Hammer, Adapting to wildfire: rebuilding after home loss, Soc. Nat. Resour. 28 (8) (2015) 839–856.
[50] Federal Emergency Management Agency, OpenFEMA Dataset: Disaster Declarations Summaries - V1, 2018. (Accessed 17 December 2018).
[51] L.M. Labossière, T.K. McGee, Innovative wildfire mitigation by municipal governments: two case studies in Western Canada, Int. J. Disaster Risk Reduc. 22 (2017) 204–210.
[52] M.H. Mockrin, S.I. Stewart, V.C. Radeloff, R.B. Hammer, Recovery and adaptation after wildfire on the Colorado front range (2010-2012), Int. J. Wildland Fire 25 (2016) 1144–1155.
[53] S.R. Plevel, Fire policy at the wildland-urban interface: a local responsibility, J. For. 95 (10) (1997) 12–17.
[54] M.H. Mockrin, H.K. Fishler, S.I. Stewart, Does wildfire open a policy window? Local government and community adaptation after fire in the United States, Environ. Manag. (2018) 1–19.
[55] R.C. Francaviglia, Xenia rebuilds: effects of predisaster conditioning on postdisaster redevelopment, J. Am. Plan. Assoc. 44 (1) (1978) 13–24.
[56] E.L. Quarantelli, Disaster Recovery Process: what We Know and Do Not Know from Research, University of Delaware Disaster Research Center, 1999. Preliminary Paper #286.
[57] L.J. Vale, T.J. Campanella, The cities rise again, in: L.J. Vale, T.J. Campanella (Eds.), The Resilient City, Oxford University Press USA, New York, 2005, pp. 3–26 (Introduction).
[58] C.E. Colten, A. Giancarlo, Losing resilience on the Gulf Coast: Hurricanes and social memory, Environment 53 (4) (2011) 6–19.
[59] W.G. Peacock, B.H. Morrow, H. Gladwin (Eds.), Hurricane Andrew: Ethicity, Gender and the Sociology of Disasters, Routledge, London, 1997.
[60] R.R. Hagelman III, M.H. Connolly, E.M. Zavar, K.R. Dahal, Disaster reconstruction and business geography following the 2007 Greensburg, Kansas Tornado, Environ. Hazards 11 (4) (2012) 283–302.
[61] W.E. Rees, Ecological footprints and appropriated carrying capacity: what urban economics leaves out, Environ. Urbanization 4 (2) (1992) 121–130.
[62] M. Comerio, Disaster Hits Home: New Policy for Urban Housing Recovery, University of California Press, Berkeley, CA, 1998.
[63] P. O'Keefe, K. Westgate, B. Wisner, Taking the naturalness out of natural disasters, Nature 260 (1976) 566–567.
[64] E.L. Quarantelli, Patterns of sheltering and housing in US disasters, Disaster Prev. Manag. 4 (3) (1995) 43–53.
[65] D. Rathfon, R. Davidson, J. Bevington, A. Vicini, A. Hill, Quantitative assessment of post-disaster housing recovery: a case study of Punta Gorda, Florifa, after Hurricane Charley, Disasters 37 (2) (2013) 333–355.
[66] R.L. Schumann III, Ground truthing spatial disaster recovery metrics with participatory mapping in post-Katrina Mississippi, Appl. Geogr. 99 (2018) 63–76.
[67] J.W. Mills, A. Curtis, S. Barrett Kennedy, S. Wright Kennedy, J.D. Edwards, Geospatial video for field data collection, Appl. Geogr. 30 (2010) 533–547.
[68] C. Burton, J.T. Mitchell, S.L. Cutter, Evaluating post-Katrina recovery in Mississippi using repeat photography, Disasters 35 (3) (2011) 488–509.
[69] S.L. Cutter, R.L. Schumann III, C.T. Emrich, Exposure, social vulnerability and recovery disparities in New Jersey after hurricane sandy, J. Extrem. Events 1 (1) (2014).
[70] C. Finch, C.T. Emrich, S.L. Cutter, Disaster disparities and differential recovery in New Orleans, Popul. Environ. 31 (4) (2010) 179–202.
[71] Y. Xiao, S. Van Zandt, Building community resiliency: spatial links between household and business post-disaster return, Urban Stud. 49 (11) (2012) 2523–2542.
[72] W.N. Adger, Vulnerability, Glob. Environ. Chang. 16 (2006) 268–281.
[73] J. Birkmann (Ed.), Measuring Vulnerability to Natural Hazards: towards Disaster Resilient Societies, United Nations University Press, Tokyo, 2006.
[74] H. Eakin, A.L. Luers, Assessing the vulnerability of social-environmental systems, Annu. Rev. Environ. Resour. 31 (2006) 365–394.
[75] H.-M. Fussell, Vulnerability: a generally applicable conceptual framework for climate change research, Glob. Environ. Chang. 17 (2) (2007) 155–167.
[76] M. Pelling, The Vulnerability of Cities: Natural Disasters and Social Resilience, Earthscan, London, 2003.

[77] C. Polsky, R. Neff, B. Yarnal, Building comparable global change vulnerability assessments: the vulnerability scoping diagram, Glob. Environ. Chang. 17 (3–4) (2007) 472–485.
[78] B. Wisner, P. Blaikie, T. Cannon, I. Davis, At Risk: Natural Hazards, People's Vulnerability and Disasters, second ed., Routledge, London, 2004.
[79] S.L. Cutter, Vulnerability to environmental hazards, Prog. Hum. Geogr. 20 (4) (1996) 529–539.
[80] I. Burton, R.W. Kates, G.F. White, The Environment as Hazard, second ed., Guilford Press, New York, 1993.
[81] R.T. Watson, M.C. Zinyowera, R.H. Moss (Eds.), Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses, Cambridge, Cambridge, U.K., 1996.
[82] J. Whittaker, J. Handmer, D. Mercer, Vulnerability to bushfires in rural Australia: a case study from East Gippsland, Victoria, J. Rural Stud. 28 (2) (2012) 161–173.
[83] T.K. McGee, S. Russell, "It's just a natural way of life…" an investigation of wildfire preparedness in rural Australia, Environ. Hazards 5 (1) (2003) 1–12.
[84] J.E. Keeley, J.G. Pausas, P.W. Rundel, W.J. Bond, R.A. Bradstock, Fire as an evolutionary pressure shaping plant traits, Trends Plant Sci. 16 (8) (2011) 406–411.
[85] R.B. Pratt, A.L. Jacobsen, A.R. Ramirez, A.M. Helms, C.A. Traugh, M.F. Tobin, M. S. Heffner, S.D. Davis, Mortality of resprouting chaparral shrubs after a fire and during a record drought: physiological mechanisms and demographic consequences, Glob. Chang. Biol. 20 (3) (2014) 893–907.
[86] T.J. Parker, K.M. Clancy, R.L. Mathiasen, Interactions among fire, insects and pathogens in coniferous forests of the interior western United States and Canada, Agric. For. Entomol. 8 (3) (2006) 167–189.
[87] M. Vilà, F. Lloret, E. Ogheri, J. Terradas, Positive fire-grass feedback in Mediterranean Basin woodlands, For. Ecol. Manag. 147 (1) (2001) 3–14.
[88] E. Conlisk, A.D. Syphard, J. Franklin, H.M. Regan, Predicting the impact of fire on a vulnerable multi-species community using a dynamic vegetation model, Ecol. Model. 301 (2015) 27–39.
[89] P.M. Kelly, W.N. Adger, Theory and practice in assessing vulnerability to climate change and facilitating adaptation, Clim. Change 47 (2000) 325–352.
[90] S.L. Cutter, J.T. Mitchell, M.S. Scott, Revealing the vulnerability of people and places: a case study of Georgetown, South Carolina, Ann. Assoc. Am. Geogr. 90 (4) (2000) 713–737.
[91] R. Ojerio, K. Lynn, A. Evans, M. DeBonis, W. Gerlitz, Engaging Socially Vulnerable Populations in Community Wildfire Protection Plans, 2008. Available at: https://scholarsbank.uoregon.edu/xmlui/handle/1794/10711. (Accessed 2 January 2019).
[92] W.C. Fischer, A.F. Bradley, Fire Ecology of Western Montana Forest Habitat Types (General Technical Report INT-223). (Ogden, UT), 1987.
[93] W.F. Laurence, B. Dell, S.M. Turton, M.J. Lawes, L.B. Hutley, H. McCallum, P. Dale, M. Bird, G. Hardy, G. Prideaux, B. Gawne, C.R. McMahon, R. Yu, J. Hero, L. Schwarzkopf, A. Krockenberger, M. Douglas, E. Silvester, M. Mahony, K. Vella, U. Saikia, C. Wahren, Z. Xu, B. Smith, C. Cocklin, The 10 Australian ecosystems most vulnerable to tipping points, Biol. Conserv. 144 (2011) 1472–1480.
[94] G.A. Tobin, B.E. Montz, Natural Hazards: Explanation and Integration, The Guilford Press, New York, 1997.
[95] W.P. Sousa, The role of disturbance in natural communities, Ann. Rev. Ecol. Syst. 15 (1984) 353–391.
[96] J.E. Keeley, Fire intensity, fire severity and burn severity: a brief review and suggested usage, Int. J. Wildland Fire 18 (2009) 116–126.
[97] S.J. Pyne, Fire in America: a Cultural History of Wildland and Rural Fire, University of Washington Press, Seattle, WA, 2017.
[98] R. Blanchi, J. Leonard, K. Haynes, K. Opie, M. James, F.D. de Oliveira, Environmental circumstances surrounding bushfire fatalities in Australia 1901-2011, Environ. Sci. Policy 37 (2014) 192–203.
[99] J.V. De Graff, Improvement in quantifying debris flow risk for post-wildfire emergency response, Geoenvironm. Disasters 1 (1) (2014) 5.
[100] A. Rappold, J. Reyes, G. Pouliot, W.E. Cascio, D. Diaz-Sanchez, Community vulnerability to health impacts of wildland fire smoke exposure, Environ. Sci. Technol. 51 (2017) 6674–6682.
[101] L. Thie, K.T. Tart, On the front lines of climate health effects in North Carolina, N. C. Med. J. 79 (5) (2018) 318–323.
[102] W.J. Bond, B.W. Van Wilgen, Fire and Plants' *Population and Community Biology*, vol. 14, Chapman & Hall, London, 1996.
[103] E.F. van Mantgem, J.E. Keeley, M. Witter, Faunal responses to fire in chaparral and sage scrub in California, USA, Fire Ecol. 11 (3) (2015) 128–148.
[104] J.E. Keeley, M. Baer-Keeley, C.J. Fotheringham, Alien plant dynamics following fire in Mediterranean-climate California shrublands, Ecol. Appl. 15 (2005) 2109–2125.
[105] R.E. Keane, E. Karau, Evaluating the ecological benefits of wildfire by integrating fire and ecosystem simulation models, Ecol. Model. 221 (8) (2010) 1162–1172.
[106] F.H. Norris, M.J. Friedman, P.J. Watson, 60,000 disaster victims speak: Part I. An empirical review of the literature, 1981-2001, Psychiatry 65 (3) (2002) 207–239.
[107] L. Annang, S. Wilson, C. Tinago, L.W. Sanders, T. Bevington, B. Carlos, E. Cornelius, E. Svendsen, Photovoice: assessing the long-term impact of a disaster on a community's quality of life, Qual. Health Res. 26 (2) (2016) 241–251.
[108] C.E. Gordon, O.F. Price, E. Tasker, Mapping and exploring variation in post-fire vegetation recovery in the Warrumbungle National Park using airborne LiDAR, Ecol. Appl. 27 (2017) 1618–1632.
[109] T.N. Williamson, R.C. Graham, P.J. Shouse, Effects of a chaparral-to-grass conversion on soil physical and hydrologic properties after four decades, Geoderma 123 (1–2) (2004) 99–114.
[110] R.A. Shakesby, S.H. Doerr, Wildfire as a hydrological and geomorphological agent, Earth Sci. Rev. 74 (3–4) (2006) 269–307.
[111] M.D. Petrie, S.L. Collins, A.M. Swann, P.L. Ford, M.E. Litvak, Grassland to shrubland state transitions enhance carbon sequestration in the northern Chihuahuan Desert, Glob. Chang. Biol. 21 (3) (2015) 1226–1235.
[112] M.S. Carroll, P.J. Cohn, D.N. Sessholtz, L.L. Higgins, Fire as a galvanizing and fragmenting influence on communities: the case of the Rodeo-Chediski fire, Soc. Nat. Resour. 18 (4) (2005) 301–320.
[113] A.D. Syphard, K.C. Clarke, J. Franklin, Simulating fire frequency and urban growth in southern California coastal shrublands, USA, Landsc. Ecol. 22 (3) (2007) 431–445.
[114] C. Kooistra, T.E. Hall, T. Paveglio, M. Pickering, Understanding the factors that influence perceptions of post-wildfire landscape recovery across 25 wildfires in the Northwestern United States, Environ. Manag. 61 (1) (2018) 85–102.
[115] R.W. Kates, C.E. Colten, S. Laska, S.P. Leatherman, Reconstruction of new orleans after hurricane katrina: a research perspective, Proc. Natl. Acad. Sci. 103 (40) (2006) 14653–14660.
[116] United States Department of Agriculture, Burned Area Emergency Response, 2018. Available at: https://www.fs.fed.us/naturalresources/watershed/burnedareas-background.shtml. (Accessed 11 January 2019).
[117] United States Department of Agriculture, Disaster Assistance Programs, 2018. Available at: https://www.fsa.usda.gov/programs-and-services/disaster-assistance-program/index. (Accessed 21 January 2019).
[118] United States Department of Agriculture, Emergency Watershed Protection Program, 2018. Available at: https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/landscape/ewpp/. (Accessed 11 January 2019).
[119] S. Paula, M. Arianoutsou, D. Kazanis, C. Tavsanoglu, F. Lloret, C. Buhk, F. Ojeda, B. Luna, J.M. Moreno, A. Rodrigo, J.M. Espelta, Fire-related traits for plant species of the Mediterranean Basin, Ecology 90 (5) (2009), 1420-1420.
[120] J.G. Pausas, E. Carbo, R.N. Caturla, J.M. Gil, R. Vallejo, Post-fire regeneration patterns in the eastern Iberian peninsula, Acta Oecol. 20 (5) (1999) 499–508.
[121] J.E. Keeley, C.J. Fotheringham, M. Baer-Keeley, Factors affecting plant diversity during post-fire recovery and succession of Mediterranean-climate shurblands in California, USA, Divers. Distrib. 11 (6) (2005) 525–537.
[122] B.E. Goldstein, Skunkworks in the embers of the Cedar fire: enhancing resilience in the aftermath of disaster, Hum. Ecol. 36 (2008) 15–28.
[123] P.J. Jakes, V. Sturtevant, Trial by fire: community wildfire protection plans put to the test, Int. J. Wildland Fire 22 (8) (2013) 1134–1143.
[124] T.B. Paveglio, M.S. Carroll, T.E. Hall, H. Brenkert-Smith, Put the wet stuff on the hot stuff': the legacy and drivers of conflict surrounding wildfire suppression, J. Rural Stud. 41 (2015) 72–81.
[125] K. Reid, R. Beilin, J. McLennan, Shaping and sharing responsibility: social memory and social learning in the Australian rural bushfire landscape, Soc. Nat. Resour. 31 (4) (2018) 442–456.
[126] T.D. Penman, C. Eriksen, B. Horsey, A. Green, D. Lemcke, P. Cooper, R. A. Bradstock, Retrofitting for wildfire resilience: what is the cost? Int. J. Disaster Risk Reduc. 21 (2017) 1–10.
[127] W.A. Anderson, Some Observations on a Disaster Subculture: the Organizational Response of Cincinnati, Ohio to the 1964 Flood, 1965. Columbus, OH.
[128] R. Burnside, D.S. Miller, J.D. Rivera, The impact of information and risk perception on the hurricane evacuation decision-making of greater new orleans residents, Sociol. Spectr. 27 (6) (2007) 727–740.
[129] S. McCaffrey, E. Toman, M. Stidham, B. Shindler, Social science research related to wildfire management: an overview of recent findings and future research needs, Int. J. Wildland Fire 22 (2013) 15.
[130] S.C. Keeley, J.E. Keeley, S.M. Hutchinson, A.W. Johnson, Postfire succession of the herbaceous flora in southern California chaparral, Ecology 62 (6) (1981) 1608–1621.
[131] M.E. Hunter, P.N. Omi, E.J. Martinson, G.W. Chong, Establishment of non-native plant species after wildfires: effects of fuel treatments, abiotic and biotic factors, and post-fire grass seeding treatments, Int. J. Wildland Fire 15 (2006) 271–281.
[132] J.A. Vega, C. Fernández, T. Fonturbel, Comparing the effectiveness of seeding and mulching+ seeding in reducing soil erosion after a high severity fire in Galicia (NW Spain), Ecol. Eng. 74 (2015) 206–212.
[133] J. Diffendorfer, G.M. Fleming, S. Tremor, W. Spencer, J.L. Beyers, The role of fire severity, distance from fire perimeter and vegetation on post-fire recovery of small-mammal communities in chaparral, Int. J. Wildland Fire 21 (4) (2012) 436–448.
[134] G. Ireton, I. Ahmed, E. Charlesworth, Reflections on residential rebuilding after the victoriam Black Saturday bushfires, Open House Int. 39 (3) (2014).
[135] P.M. Alexandre, M.H. Mockrin, S.I. Stewart, R.B. Hammer, V.C. Radeloff, Rebuilding and new housing development after wildfire, Int. J. Wildland Fire 24 (2015) 138–149.
[136] J. Burchfield, Community impacts of large wildfire events: consequences of actions after the fire, in: T. Daniel, M.S. Carroll, C. Moseley, C. Raish (Eds.), People, Fire and Forests: A Synthesis of Wildfire Social Science, Oregon State University Press, Corvallis, OR, 2007, pp. 124–140.
[137] G.L. Simon, Vulnerability-in-Production: a spatial history of nature, affluence, and fire in Oakland, California, Ann. Assoc. Am. Geogr. 104 (6) (2014) 1199–1221.
[138] Australian Bureau of Statistics, Census 2016, 2018. Available at: http://www.abs.gov.au/. (Accessed 18 September 2018).
[139] J. Mainar, Fighting a Wildfire - 10 Years after the Cedar Fire, 2013. Available at: https://www.sandiego.gov/sites/default/files/cedartenth.pdf. (Accessed 16 January 2019).
[140] J.E. Keeley, A.D. Syphard, C.J. Fotheringham, The 2003 and 2007 wildfires in southern California, in: S. Boulter, J. Palutikof, D.J. Karoly, D. Guitart (Eds.),

Natural Disasters and Adaptation to Climate Change, Cambridge University Press, Cambridge, UK, 2013, pp. 42–52.
[141] D.C. West, H.H. Shugart, D.F. Botkin (Eds.), Forest Succession: Concepts and Application, Springer Science & Business Media, 2012.
[142] J.E. Keeley, A.D. Syphard, Climate change and future fire regimes: examples from California, Geosciences 6 (3) (2016) 37.
[143] S.M. Newman, M.S. Carroll, P.J. Jakes, T.B. Paveglio, Land development patterns and adaptive capacity for wildfire: three examples from Florida, J. For. 111 (3) (2013) 167–174.
[144] W.N. Adger, N.W. Arnell, E.L. Tompkins, Successful adaptation to climate change across scales, Glob. Environ. Chang. 15 (2) (2005) 77–86.
[145] W.N. Adger, S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D.R. Nelson, L. O. Naess, J. Wolf, A. Wrefold, Are there limits to adaptation to climate change? Clim. Change 93 (2009) 335–354.
[146] C. Eriksen, G. Simon, The Affluence-Vulnerability Interface: intersecting scales of risk, privilege and disaster, Environ. Plan. Econ. Space 49 (2) (2017) 293–313.
[147] E. Mullener, A Sister City Flourishes - after Hurricane Hugo, The Times-Picayune, 2005, p. 01, 14 Dec 2005.
[148] W.E. Mell, S.L. Manzello, A. Maranghides, D. Butry, R.G. Rehm, The wildland-urban interface fire problem – current approaches and research needs, Int. J. Wildland Fire 19 (2) (2010) 238–251.
[149] A.C. Foerster, A. Macintosh, J. McDonald, Transferable lessons for climate change adaptation planning? Managing bushfire and coastal climate hazards in Australia, Environ. Plan. Law J. 30 (6) (2013) 469–490.
[150] P. Akerman, Land Sales Close Book on Black Saturday Bushfires Tragedy, The Australian, 2017.
[151] M. Hino, C.B. Field, K.J. Mach, Managed retreat as a response to natural hazard risk, Nat. Clim. Chang. 7 (5) (2017) 364–370.
[152] F. Moreira, O. Viedma, M. Arianoutsou, T. Curt, N. Koutsias, E. Rigolot, A. Barbati, P. Corona, P. Vaz, G. Xanthopoulos, F. Mouillot, E. Bilgili, Landscape-wildfire interactions in southern Europe: implications for landscape management, J. Environ. Manag. 92 (2011) 2389–2402.
[153] A.L. Westerling, Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring, Philos. Trans. R. Soc. London, Ser. A B 371 (1696) (2016) e178.
[154] P.M. Fernandes, Fire-smart management of forest landscapes in the Mediterranean basin under global change, Landsc. Urban Plan. 110 (2013) 175–182.
[155] J.B. Abrams, M. Knapp, T.B. Paveglio, A. Ellison, C. Moseley, M. Nielsen-Pincus, M.C. Carroll, Re-envisioning community-wildfire relations in the U.S. West as adaptive governance, Ecol. Soc. 20 (3) (2015) 34.
[156] K. Tierney, The Social Roots of Risk: Producing Disasters, Promoting Resilience, Stanford University Press, Stanford, CA, 2014.
[157] W.N. Adger, Social and ecological resilience: are they related? Prog. Hum. Geogr. 24 (3) (2000) 347–364.
[158] D.E. Alexander, Resilience and disaster risk reduction: an etymological journey, Nat. Hazards Earth Syst. Sci. 13 (2013) 2707–2716.
[159] Federal Emergency Management Agency, Building Cultures of Preparedness: Report for the Emergency Management Higher Education Community, 2019. Available at: https://training.fema.gov/hiedu/docs/latest/2019_cultures_of_preparedness_report_10.22.18%20final.pdf. Accessed 11 Sep.
[160] United Nations, Sendai Framework for Disaster Risk Reduction 2015-2030, 2015. Available at: https://www.unisdr.org/we/inform/publications/43291. (Accessed 11 September 2019).
[161] M.K. Lindell, C.S. Prater, R.W. Perry, W.C. Nicholson, Hazard Mitigation' Fundamentals of Emergency Management. Emmitsburg, MD: Federal Emergency Management Agency Higher Education Program, 2006. Available at: https://training.fema.gov/hiedu/aermc/booksdownload/fem/.
[162] A.K. Schwab, K. Eschelbach, D.J. Brower, Hazard Mitigation and Preparedness, second ed., CRC Press, Boca Raton, FL, 2017.
[163] Cal Fire, One Less Spark, 2017. Available at: http://www.readyforwildfire.org/One-Less-Spark-Campaign/.
[164] D.S. Mileti. Disasters by Design: A Reassessment of Natural Hazards in the United States, Joseph Henry Press, Washington, D.C., 1999.