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Creating Fire-Adapted Communities Through Recovery: Case Studies from the United States and Australia

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Wildfires can be devastating for social and ecological systems, but the recovery period after wildfire presents opportunities to reduce future risk through adaptation. We use a collective case study approach to systematically compare social and ecological recovery following four major fire events in Australia and the United States: the 1998 wildfires in northeastern

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Florida; the 2003 Cedar fire in southern California; the 2009 Black Saturday bushfires in Victoria, southeastern Australia; and the 2011 Bastrop fires in Texas. Fires spurred similar policy changes, with an emphasis on education, land use planning, suppression/emergency response, and vegetation management. However, there was little information available in peer-reviewed literature about social recovery, ecological recovery was mostly studied short term, and feedbacks between social and ecological outcomes went largely unconsidered. Strategic and holistic approaches to wildfire recovery that consider linkages within and between social–ecological systems will be increasingly critical to determine if recovery leads to adaptation or recreates vulnerability.

Keywords: Wildfire adaptation; disaster recovery; social–ecological systems; land management; fire suppression.

1. Introduction

Over the past decade, wildfire losses have soared across the globe: Australia, Canada, Chile, Portugal, Greece, Turkey, and the United States have all experienced record, loss-causing wildfires since 2010. A combination of human and ecological factors is responsible for this trend, including climate change (Westerling *et al.* 2006; Abatzoglou and Williams 2016; Abatzoglou *et al.* 2018), legacies of fire management (Miller *et al.* 2009; Brotons *et al.* 2013), increased human ignitions (Balch *et al.* 2017), and an expanding wildland–urban interface (WUI) where people live in proximity to wildland vegetation (Argañaraz *et al.* 2017; Oliveira *et al.* 2017; Radeloff *et al.* 2018; Tedim *et al.* 2018). Documenting wildfire impacts emerging from the confluence of climatic, social, and ecological factors is increasingly common (Eriksen and Simon 2017; Burke *et al.* 2021; Iglesias *et al.* 2022).

However, what comes after destructive wildfire is less well understood. There is increasing realization that examining long-term wildfire recovery is equally important as investigating causal factors, since recovery marks a critical turning point when we could better adapt ecological and social systems to future wildfire threats (Schumann III *et al.* 2020; Kramer *et al.* 2021). For example, heightened risk perceptions and political will following wildfire may combine with disaster-induced funding to enable reconstruction and retrofitting of physical infrastructure that is more fire-resistant. Reinvestment in social support structures and increased ecological restoration could also reduce vulnerability. Alternatively, recovery could be maladaptive. For example, residents and communities might pursue minimal change to the built environment in their push to quickly rebuild and "return to normal" (McGee *et al.* 2009; Mockrin *et al.* 2018). Additionally, vegetation recovery might increase wildfire risk, either through type conversions to shorter fire return interval systems or via homeowners' landscaping around homes, thereby missing the opportunity to enhance wildfire resilience through recovery (Turner *et al.* 2019; Syphard *et al.* 2022).

Given the complexity of wildfire governance and the long timeframe of recovery, understanding how wildfire risk increases or decreases through recovery will require systematically considering linked social–ecological changes in vulnerability over time. However, most existing studies tend to consider either social (i.e., human system) impacts (Rosenthal *et al.* 2021; Edgeley 2022) or ecological impacts after fire (Stevens-Rumann and Morgan 2019; Steiner *et al.* 2020); it is unclear how much integrated social–ecological knowledge on post-wildfire recovery exists in the literature. A better understanding of combined social–ecological recovery processes and outcomes is necessary if we are to understand how changes during post-wildfire recovery shape the vulnerability of human and ecological communities to the next wildfire event (Figure 1). Such efforts can specifically examine human–environment interaction after fire in two directions, considering the ways in which ecological impacts shape human actions to recover/adapt and the ways in which human actions shape the ability of ecosystems to recover/adapt.

Accordingly, this paper serves as an initial investigation of the social and ecological effects of post-fire recovery and policy actions, for four separate wildfire events. Guided by a model of community-level adaptation after wildfire (Schumann III *et al.* 2020), we performed a systematic literature review to examine social and ecological recovery, as well as governmental policy responses, for fires

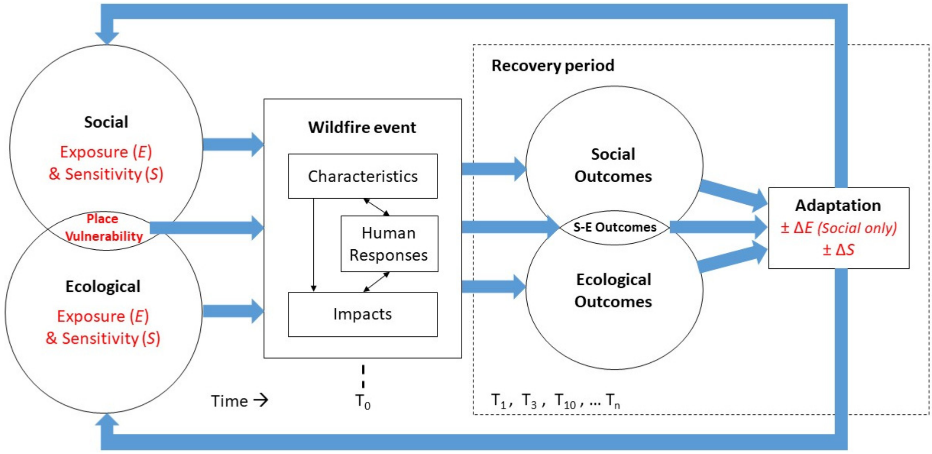

Fig. 1. Coupled Social–Ecological Model of Recovery and Adaptation to Wildfire

Source: Schumann III *et al.* (2020).

that occurred across a range of social and ecological settings: the 1998 Florida (US) fires; the 2003 Cedar fire in southern California (US); the 2009 Kilmore East fire in Victoria (Australia); and the 2011 Bastrop County Complex fire in central Texas (US). This review allowed us first to determine the prevalence of social, ecological, and coupled social–ecological research on wildfire recovery, and then to document responses and adaptations to wildfire during recovery. Drawing upon these findings, we consider potential changes in vulnerability that may prove adaptive or maladaptive for future wildfires. We conclude with a discussion of gaps in data availability on wildfire recovery and suggest directions for further research on post-wildfire adaptation.

2. Methods

2.1. *Case study selection*

We selected four study fires because they were nationally significant events that varied in social and ecological contexts. Each fire occurred during a period of pronounced drought in a known region of high wildfire risk, however, vegetation communities, fire regimes, and fire histories differed (Table 1). The fires also capture relative variation in scale: the Florida fires were a regional event comprising many small fires,[1] while the three other fires were the largest and/or most destructive events within regional wildfire outbreaks (Figure 2). At least one member of our author team also had embedded knowledge of each selected wildfire obtained either through research on wildfire dynamics or through participation in practitioner conversations about wildfire management. Furthermore, studying fires that occurred at least a decade ago enabled us to observe the recovery over time. Below, we briefly describe each fire incident and impacts (see also Table 1).

2.1.1. 1998 Florida fires

In early summer 1998, lightning from dry thunderstorms ignited more than 80 fires, with the largest fires along the Atlantic coast in Brevard, Flagler, and Volusia Counties (FEMA 1998). Fanned by strong winds, the fires moved eastward from wildland areas toward populated areas near the coast (Bruszek *et al.* 2010).

[1]Unlike the other three cases, individual fires in the 1998 Florida outbreak were not named. Instead, all found sources referenced these fires collectively. Therefore, we also consider these fires collectively as one event.

Table 1. Overview of Selected Case Studies

Fire	Date	Location	Vegetation Type	Fire Regime	Fire History	Study Fire Area (ha) and Losses	Study Fire Ecological Impacts
Florida Fires	Mid-May–24 July 1998	Florida, USA: State-wide	Dense pine and cypress forest with heavy undergrowth; grasses and native plants such as palmetto and palm.	Wildland fires are common, typically small surface fires. Prescribed fire is an important management tool.	Notable losses in 1985 (131 losses in Palm Coast). Recovery was rapid, with the population growing by 150% between 1985 and 1998 (Jakes 2003).	202,350 ha (approx.); 3 fatalities; 340 houses and 33 commercial buildings destroyed.	From 33% to 66% tree mortality in stands with medium and high-intensity fire, respectively. Fire-dependent plant species benefited.
Cedar Fire	25 October–16 November 2003	San Diego City and County, California, USA	Chaparral with some coastal sage scrub, grasslands, and woodlands in foothills, transitioning into montane conifer forest at higher elevations.	Mediterranean climate with periodic, large, stand-replacing crown fires in coastal shrublands. Short intervals between fires can lead to type conversion to invasive herbaceous vegetation, increasing flammability of the landscape.	An average 500 structures were lost per year from 1950–2000 in Southern California (Cal Fire 2000), and notable losses occurred within the County and City in the 1970s and 1980s. Starting as early as the 1960s, California adopted building codes and mandated defensible space.	110,580 ha; 15 fatalities; 2,232 houses and 22 commercial buildings destroyed.	Of the 18% of the fire that burned in forest, conifers experienced 95% mortality and oaks experienced 14% mortality. More than 30,000 ha was reburned in 2007. End result of both fires was increased invasive species, declines in chaparral-dependent fauna.

Table 1. (*Continued*)

Fire	Date	Location	Vegetation Type	Fire Regime	Fire History	Study Fire Area (ha) and Losses	Study Fire Ecological Impacts
Kilmore East Fire	7–16 February 2009	Central Victoria, Australia	Mostly dry forest (mixed eucalypt) with some wet forest (dominated by mountain ash).	Eucalypt forests have mean fire return interval of 20 years, typically moderate intensity, but approximately every 40 years they are catastrophic.	Long history of deadly and destructive wildfires in Victoria (1983 Ash Wednesday fires killed 47 people and destroyed 3,700 buildings). National bushfire standard for building in 1999.	125,400 ha; 119 fatalities; 1,242 houses destroyed.	Considerable tree mortality in dry and wet forest (up to 93% in dry forest). Biomass loss of 14% in high-severity fire burn areas in wet forest. Loss of $\sim 80\%$ of small mammals, birds, and nesting hollows.
Bastrop Fire	4 September–11 October 2011	Bastrop County, Texas, USA	Mixed pine–deciduous forest with loblolly pine canopy and dense understory of post and blackjack oak, cedar, and yaupon.	Fire regime during the last three centuries was driven primarily by human ignitions. In the past 100 years, fire had largely been excluded, leading to dense, flammable pine stands.	Notable fires in 1984 and 2009 (destroyed 52 structures combined). A CWPP was created in 2006; however, consistent with Texas' cultural values of home rule and individualism, mitigation actions remained voluntary, and county has no fire code.	13,100 ha; 2 fatalities; 1,660 houses and 36 commercial buildings destroyed.	High tree mortality during and immediately after fire (approx. 78%). Fire hindered loblolly pine regeneration, enabling oak resprouting; high mortality of endangered Houston toad.

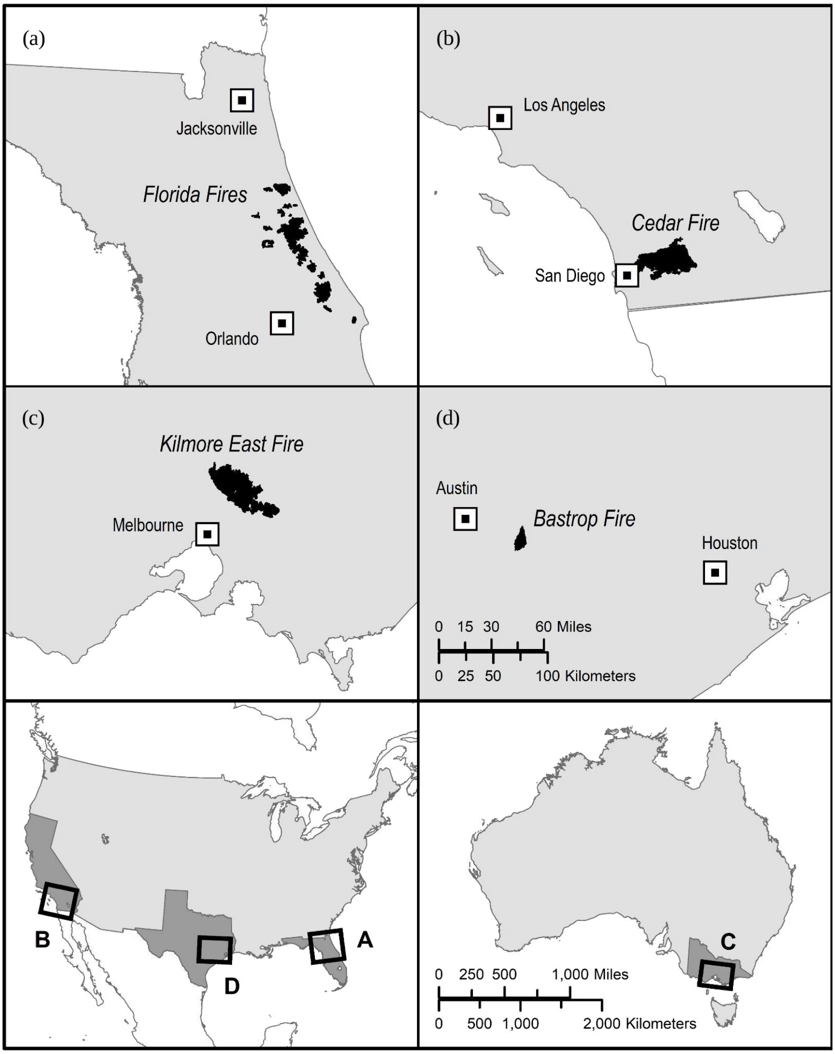

Fig. 2. Map Showing Size and Location of Four Cases: (a) Florida Fires, (b) Cedar Fire, (c) Kilmore East Fire, and (d) Bastrop Fire. Map Scale is Consistent for Panels (a)–(d). Similarly, Locator Maps Use the Same Scale

The fires triggered evacuation of over 125,000 people. Subdivisions affected by these fires were surrounded by natural vegetation, positioned between mesic pine flatwoods to the west and the Atlantic Ocean to the east (FEMA 1998). While subdivisions were platted at once, local regulations encouraged construction of one house at a time, so interspersed lots covered with highly flammable vegetation provided a ready fuel source (Jakes *et al.* 2007). Also, many residents were new to the area and unfamiliar with wildfire hazards (Brenner and Wade 2003). In total, nearly 350 houses were destroyed (Sorenson *et al.* 1999), and approximately 200,000 hectares ($\sim 494,000$ acres) of forest were burned, with significant impacts on tree mortality and northern Florida's timber inventory (net losses estimated at $400 million–$1.5 billion, 1999 USD) (Hanula *et al.* 2002) (Table 1). Wildfire intensity and resultant tree mortality were highest on sites with longer fire return intervals; those sites that experienced prescribed fire one to two years before wildfire had reduced mortality (Outcalt and Wade 2004).

2.1.2. Cedar fire

There was notable wildfire activity across southern California in October 2003, with the Cedar fire being the largest and most destructive (Cal Fire and USDA Forest Service 2004). At the time, it was the most destructive fire in San Diego County history, the second most destructive fire in the state, and the largest fire in state history (Franklin *et al.* 2006). The fire was started by a lost hunter to signal rescuers in the Cleveland National Forest, in an exurban area of the county. The fire spread rapidly due to the hot, dry Santa Ana winds and high temperatures (San Diego County 2004). The Cedar fire area included rural WUI neighborhoods and low-to-medium density residential neighborhoods in the suburban fringe, with considerable variation in housing quality and value (e.g., from mobile homes in rural areas to expensive single-family homes in affluent parts of the metropolitan area). Southern California has a long history of destructive wildfires, and despite decades of improvements to land use regulations and building codes (Table 1), post-fire analyses found that many of the buildings lost were built with fire-prone features (e.g., wooden decks, awnings) and lacked defensible space (City of San Diego 2004). During the Cedar fire, suppression and evacuation efforts were hindered by the lack of contingency planning and delayed warning communication, respectively (Hoyt and Gerhart 2004). Topography and ingress factored into home destruction, with many of the homes destroyed located atop steep slopes at the end of narrow roads and driveways (San Diego County 2004). In total, 15 people lost their lives and more than 2,000 structures were destroyed mostly outside of San Diego city boundaries (San Diego County 2004: Table 1). During the fire, wildfire smoke aggravated respiratory health for adults and children (Viswanathan *et al.* 2006; Kunzli *et al.* 20006; Delfino *et al.* 2009). In total, the fire covered 110,580 hectares, of which approximately 10% was coastal sage scrub, 50% chaparral, 10% oak woodland, and 7% conifer forest (Cal Fire and USDA Forest Service 2004: Table 1).

2.1.3. Kilmore East fire

The Kilmore East fire in Australia's Victoria state, ignited by failed electrical infrastructure, was part of a series of over 400 fires that occurred under severe weather conditions on "Black Saturday" (Karoly 2009). It was the deadliest and most destructive event to occur on Black Saturday and, to date, in Australia. The two local government areas (similar to a US county) most affected by the fire — Nillumbik and Murrindindi — were considered moderately advantaged, but both contained pockets of relative socio-economic disadvantage (Australian Bureau of Statistics 2006). The vast majority (80%) of insured people were underinsured, and 13% of those who lost homes were uninsured (Munich Re 2015). Subsequent analysis of building destruction found that only 8% were built in accordance with 1999 wildfire standards (Teague *et al.* 2010). A survey of people affected by the Black Saturday fires found many had taken simple actions to mitigate risk, such as clearing fuels around homes, but fewer had taken more costly and complex building materials retrofits (Whittaker *et al.* 2013). The fire caused 119 fatalities and the loss of 1,242 houses (Teague *et al.* 2010), burning over 125,000 hectares (over a quarter of the total area burned by the Black Saturday fires). People with disabilities, the aged, and the very young were disproportionately represented among those who perished in the fires, reflecting the greater pre-fire vulnerability of these populations (Handmer *et al.* 2010). Tree mortality was high in dry forests (Bennett *et al.* 2016) and mountain ash mortality in wet forests was also significant (Keith *et al.* 2014) (Table 1).

2.1.4. Bastrop fires

On September 4, 2011, winds toppled active power lines, igniting the Bastrop County Complex in central Texas (TAMU Forest Service 2012). Intense spotting was reported with wind carrying embers up to 3 miles ahead of the active fire front (Risseil and Ridenour 2013). The fire remains the most destructive fire in state history, and the 2011 fire season the most active wildfire year on record in Texas (TAMU Forest Service 2012; Horney *et al.* 2018). The affected neighborhoods in Bastrop County were largely outside city limits and varied widely in lot size and housing density, yet all contained a checkerboard of undeveloped and unmanaged lots with high fuel loads located amid developed, managed lots (Risseil and Ridenour 2013). According to the U.S. Census Bureau (2011), mobile homes in burned areas[2] represented a higher proportion of housing stock (approximately 23%), compared to US and Texas averages (7% and 8%, respectively). Median

[2]Housing characteristics were aggregated for tracts intersecting the burned area.

house values in the burned area were average for the state of Texas, with 79% of homes owned, versus 65% state-wide (U.S. Census Bureau 2011). Post-fire assessments found both exposure and sensitivity of buildings to wildfire were influenced by building materials and lack of defensible space (TAMU Forest Service 2012). In total, the fire covered more than 13,000 hectares, caused two fatalities, and destroyed 1,660 homes (TAMU Forest Service 2012; Risseil and Ridenour 2013). Nearly 40% of the Lost Pines ecoregion burned at high severity [6,555 hectares (16,200 acres) of pine and mixed pine–oak woodland forests]. Nearly 1.5 million trees were killed (Texas Forest Service 2011), resulting in tree cover loss of 78% in the burned area (Lost Pines Recovery Team 2011 cited in Brown *et al.* 2014b).

2.2. *Conceptual model*

A conceptual model of coupled social–ecological recovery from wildfire informs our collective case study approach. Our model (Figure 1) is a modified version of Schumann III *et al.* (2020) recursive community-level model that considers the extent to which post-wildfire adaptation alters the conditions (i.e., exposure, sensitivity) making a location vulnerable to future wildfire impacts. Consistent with the IPCC (2022), exposure is defined spatially as the co-location of people, assets, and natural features with the wildfire hazard, and sensitivity is an intrinsic property of each system resulting from biological, physical, and/or social characteristics. Departing from the IPCC (2022), however, is that exposure remains an explicit term contributing to wildfire vulnerability, specifically at the community scale, because so many wildfires are caused by direct human ignition (Balch *et al.* 2017). Place vulnerability, including ecological conditions, infrastructure, and populations at risk shape both wildfire event characteristics (e.g., magnitude, duration, areal extent) and human responses (e.g., resources for suppression and evacuation). In turn, these influence the impacts and outcomes we document post-fire (Figure 1). For each case presented, we intend to examine *actual* outcomes and adaptations occurring in social and ecological domains in the short- (T_1), medium- (T_3), and long-term (T_{10}) recovery, therefore, we do not explicitly treat adaptive *capacity* as its own term. Instead, we view it as implicit in the observed changes to exposure and sensitivity that set the stage for the next wildfire. Finally, in conceptualizing adaptation, we acknowledge that actively changing exposure conditions is most likely to occur as a result of human rather than ecosystem system components (adaptation goals focus on reducing ignition or exposure of vulnerable people though social actions, not removing forested vegetation or eliminating wildfire as an ecological process, see Sharma and Ravindranath (2019)). We note as well that wildfire in certain ecosystems is a valuable ecological process; current adaptation goals may therefore include restoring wildfire regimes and living with the ecological and social benefits that wildfire can provide (Tedim *et al.* 2020). For further explanation of model terms, see Schumann III *et al.* (2020).

2.3. *Data sources and analysis*

Our collective case study approach (Cresswell 2007) relies on published documents to compare recoveries from the four fires. We used a systematic, iterative approach to locate and compile these data (Figure 3). First, we searched academic literature in Scopus (www.scopus.com) using each fire name, state, and year. We then reviewed each publication, winnowing our data to papers that were relevant to our study fires, peer-reviewed, and available. To supplement the peer-reviewed literature, we then searched for gray literature and news articles using Google. Gray literature included white papers, FEMA declarations, and state- and county-level reports, including "after action" reports, damage assessments, community wildfire protection plans (CWPPs), local hazard mitigation plans, and best practice guidelines. We systematically noted information on post-fire recovery of human and ecological systems using a deductive coding scheme, which we describe below. After compiling information, we then performed additional Google and Google Scholar searches with keywords for missing information (e.g., suppression, evacuation) for each fire. Some additional peer-reviewed publications were added through these Google Scholar searches, or from authors' knowledge of the literature from their focal areas. We concluded data collection when we reached

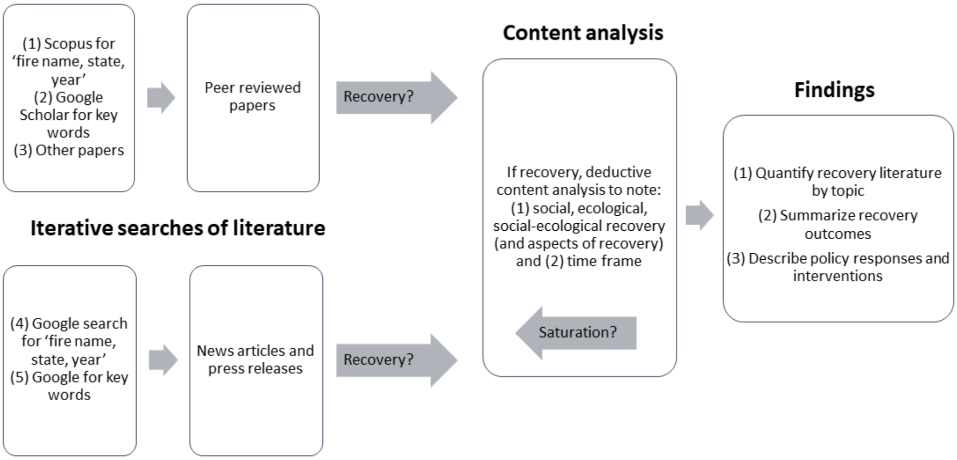

Fig. 3. Flowchart of Literature Review, Including Multistage Data Collection to Saturation, Content Analysis, and the Three Main Findings we Created

thematic saturation (i.e., when additional sources did not contain any new information). This multistage data collection and analysis approach was necessary to first identify the most reliable information on each fire's cause and immediate impacts, and then to reconstruct details related to pre-fire vulnerability and post-fire recovery outcomes (Figure 3).

Next, we used social and ecological aspects of recovery (Figure 1) to structure a deductive content analysis of the found materials (Mayring 2000). Drawing from a model on wildfire recovery and adaptation presented by Schumann III *et al.* (2020), we defined recovery as "post-fire changes to human or ecological environments that reshape vulnerability for the next wildfire event". Defining recovery in this way included changes that were consequences of the fires and changes that merely occurred during the post-fire period. If a paper documented recovery, we noted which aspects of recovery were studied: social (i.e., human system), ecological, both social and ecological, or coupled social–ecological aspects. Examples of social system recovery topics included fuels management activities, housing and infrastructure (e.g., rebuilding, retrofitting), policy and planning, and community health. Examples of ecological system topics included vegetation recovery, wildlife recovery, soil conditions (e.g., moisture, nutrients), and erosion/hydrological issues. Following Schumann III *et al.* (2020), a paper was only considered coupled social–ecological if it discussed *linked* changes in social and environmental situations (i.e., human actions resulting from environmental changes or environmental changes resulting from human actions). For example, a study that documented changes in prescribed fire use post-event would be coded as social, but if it further linked prescribed fire use to changes in ecological conditions or wildlife habitat, we considered it coupled social–ecological. Alternatively, if both prescribed fire and wildlife recovery were discussed independently of one another, this source would be coded *both* social and ecological but not coupled. For each source that considered recovery, we also noted the time frame of data collection or monitoring. Each paper was coded by an assigned researcher (i.e., one of the co-authors); the research team engaged in discussion to ensure consistent application of codes and to resolve any challenges.

Our deductive review of recovery literature resulted in three main findings: (1) a quantitative summary of the prevalence of recovery literature by topic; (2) a qualitative summary of findings on social, ecological, and coupled social–ecological recovery; and also (3) summary of post-fire policy responses and interventions (Figure 3). For post-fire responses, we identified distinct types of intervention across the four fires and inductively grouped these into four categories of activity: ecological management, mitigation actions, emergency response/suppression capabilities, and social capacity (see Table 2). These categories enabled comparison of post-fire changes across our case study fires and consideration of the adaptive potential of these changes to reduce or recreate wildfire vulnerability. Development of these categories emerged organically through the literature review and multiple rounds of discussion among the research team, and were also informed by co-authors' embedded knowledge on recovery following wildfires and other natural hazards.

3. Results

3.1. *Content analysis of wildfire case literature*

Our literature review found 136 sources relevant to our study fires: 74 peer-reviewed research articles and 62 non-peer-reviewed sources (Figure 4). The number of peer-reviewed sources exceeded the number of non-peer-reviewed sources in three of the four fires (Kilmore East, the only non-US case, was the exception). Of the 74 peer-reviewed articles, 38 focused on recovery (Figure 4). While the number of available articles varied by fire, the proportion that addressed recovery was generally higher for more recent fires. For all fires, peer-reviewed recovery research emphasized ecological aspects over social aspects. Furthermore, despite widespread recognition by scholars of wildfire risk as a coupled social–ecological problem, not a single, peer-reviewed paper considered both social and ecological aspects of recovery or coupled social–ecological aspects. Roughly half (35 of 62) of non-peer-reviewed items focused on recovery (Figure 4), similar to peer-reviewed literature. However, social aspects were emphasized relative to ecological aspects in the non-peer-reviewed literature, across all four fires. Four non-peer-reviewed recovery sources from the Cedar and Bastrop fires considered coupled social–ecological aspects of fires, while two non-peer-reviewed sources from Bastrop considered distinct (non-coupled) social and ecological aspects.

3.2. *Content on recovery and post-fire outcomes*

3.2.1. 1998 Florida fires

We found nine items related to recovery, with four focused solely on ecological recovery and five on social aspects of recovery (Figure 4). All peer-reviewed studies of ecological recovery focused on short-term recovery (one to three years after the fire). Tree mortality after the 1998 fires occurred rapidly during the first year in severely burned areas and more gradually, over two years, in moderately burned areas (Hanula *et al.* 2002). Overall tree mortality was lower in areas that had experienced prescribed fire between one and two years preceding the 1998 fires (Outcalt and Wade 2004). Elevated levels of fungal growth (*Leptographium*)

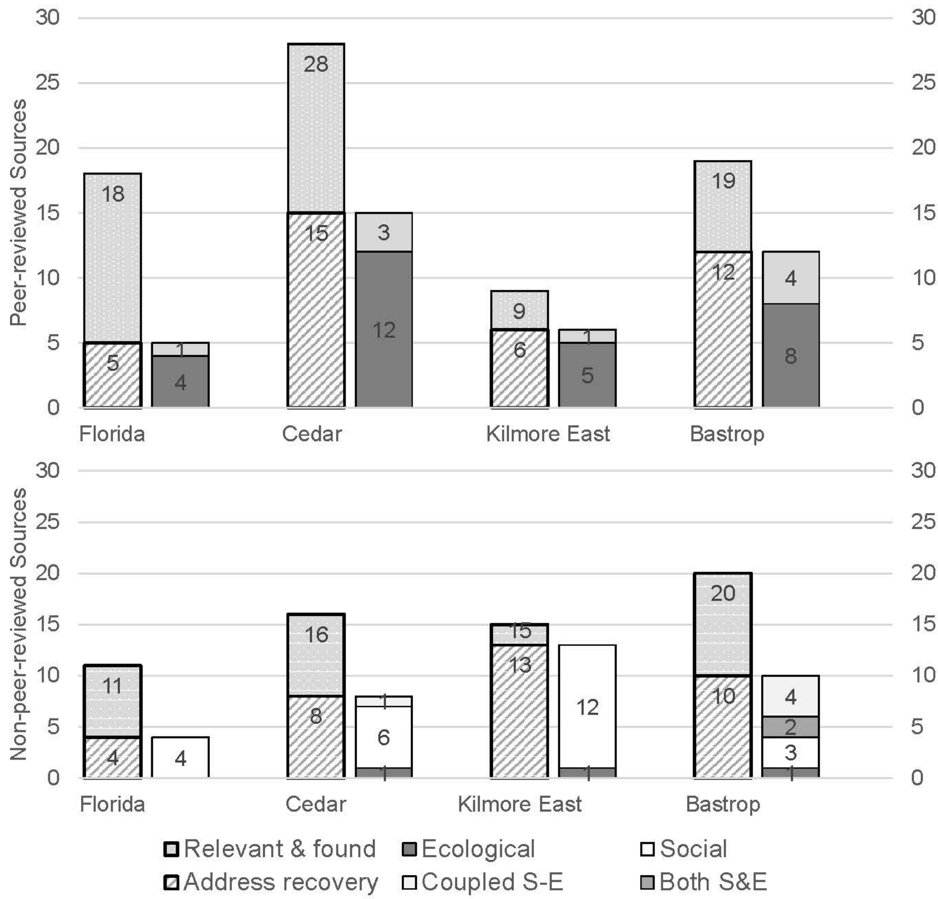

Fig. 4. Review of Peer-Reviewed Articles (Top) and Non-peer-Reviewed Sources (Bottom). For Each Fire, the First Column Shows the Proportion of Relevant Sources Focused on Recovery, While the Second Column Notes the Recovery Aspects Detailed

in tree roots within the burn scar indicated higher potential for insect infestation over the medium term (Hanula *et al.* 2002), but no follow up studies were conducted to examine actual infestation levels. Similarly, Grace (2000) noted the potential for invasive plant species introduction along timber removal corridors in the medium term but found no evidence of this in the first year after the fire. Because many species of concern in Florida's natural communities are fire-adapted, they fared well immediately after the 1998 fires (Breringer *et al.* 1999; Grace 2000). Following catastrophic wildfire, long-term forest restoration and prescribed fire are seen as valuable tools to stabilize habitat for endemic and endangered species like the Florida scrub jay (Breringer *et al.* 1999).

Only one peer-reviewed article detailed changes in human systems following the 1998 fires. In 2001, responding to citizen concerns, a new ordinance was enacted in the city of Palm Coast that required owners of vacant lots to reduce fuel loads, pay the city to clear undergrowth, or face fines and have a lien placed on the property (Jakes *et al.* 2007). The ordinance, enacted after many years of deliberation and at the suggestion of a new fire chief, prompted additional concerns from some residents about impingement on personal property rights. Investments in emergency response and communications tools were less controversial (Jakes *et al.* 2007).

Additional non-peer-reviewed sources extend our understanding of social system recovery locally and regionally. Local fire departments added brush trucks to aid in reaching wildland fires (Pulver 2018). Flagler County spent $7 million on new equipment, including a helicopter (Pulver 2018). Palm Coast, after voting out its fire commissioner later in 1998, increased fire department staffing from 5 to 72 (Jakes 2003). Immediately after the 1998 fires, Flagler County passed an ordinance requiring owners of vacant lots that bordered developed lots to create defensible space around adjacent structures (Jakes 2003). This ordinance was later expanded within the City of Palm Coast by the 2001 ordinance described above (Jakes *et al.* 2007).

At the state level, the Governor established an interagency committee to review wildfire causes and recommend improvements to wildfire response and mitigation (FDACS 2010). Accordingly, the Florida Division of Forestry updated its wildfire response and mitigation structure. By 1999, Florida had established four regional fire management teams specifically charged with fuel management in the WUI. In their first 10 years, the fire management teams treated over 38,000 hectares (94,000 acres), mostly with prescribed fire (FDACS 2010). New legislation at the state level also intended to increase prescribed burning by providing landowners greater protection against liability (Brenner and Wade 2003). The 1998 fires also led to increased wildfire outreach and education (FDACS 2010).

3.2.2. Cedar fire

We found 23 items related to recovery, with 13 focused solely on ecological recovery, nine on social aspects of recovery, and one item on coupled social–ecological aspects of recovery (Figure 4). Peer-reviewed studies of ecological recovery after the Cedar fire primarily emphasized short-to-medium-term changes, generally occurring in the first five years post-fire. Ecological studies detailed soils, erosion, vegetation recovery, and wildlife recovery. Runoff and erosion diminished greatly after the second-year post-fire but remained elevated for several more years (Hubbert *et al.* 2012; Robichaud *et al.* 2013). Among vegetation communities, native sage scrub and chaparral regenerated rapidly, although recovery varied with burn intensity. For example, six years after the fire, shrub cover in the most intense part of the fire was substantially lower than in other sites (Rachels *et al.* 2016); this is likely due to a confluence of factors, including fire behavior, moisture availability, past land use, historical wildfire activity, and presence of invasive species. Many small wildlife species were able to find refuge in unburned vegetation; four years post-fire, no residual effects were observed in small mammal abundances or community composition in chaparral (Diffendorfer *et al.* 2012).

Type conversion and invasive species emerged as challenges in ecological recovery. Based on recovery patterns three years post-fire, there may be some long-term tree-to-shrub conversion in montane conifer areas (Franklin 2010). Within shrublands, repeated short-interval fires are contributing to a type conversion to invasive annual grasses (Keeley *et al.* 2005). These flashy herbaceous fuels increase landscape flammability, in turn increasing the potential for further vegetation type conversion (Lippitt *et al.* 2013; Syphard *et al.* 2019). Such changes in vegetation composition and availability raised concerns about long term, cumulative implications for wildlife species and biodiversity (Diffendorfer *et al.* 2012). For example, as grasses replace diverse scrub and chaparral communities, herpetofauna become less diverse (Rochester *et al.* 2010).

Two media publications, both written a decade post-fire, profiled challenges of restoration in oak and conifer forests on state and federal lands (Johnson 2012; Brennan 2013). Ten years post-fire, forests that had experienced high intensity fire were still recovering slowly, and reforestation efforts had met with uneven success. However, ambitious restoration efforts at one state park were coupled with public education programs to increase wildfire awareness (Johnson 2012); this was the lone example of linked social–ecological recovery efforts profiled in the Cedar fire.

Peer-reviewed articles on the social aspects of recovery all pertained to a project that studied post-wildfire civic action, a period of intense debate about post-fire fuels management, requirements for defensible space and mitigation, and emergency response/suppression (Goldstein 2007, 2008; Goldstein and Hull 2008). The San Diego Fire Recovery Network (SDFRN), a coalition of conservationists and resource professionals, emerged following the Cedar fire. Grounded in ecological awareness, collective capacity building, adaptation to place, and self-reliance in rural residents, SDFRN focused on a message of living with wildfire for about a year, after which a lack of funding and conflicts with fire management agencies in the region led them to largely stop operating (Goldstein 2007, 2008). We found limited information on short-term housing recovery in one non-peer-reviewed source: according to Medina (2017), newspaper articles from two years post-fire reported that approximately 35% of residents had returned. Housing was facilitated by production-style grouped rebuilding and many of the modest original homes were rebuilt larger (Medina 2017). We found no information on longer-term social, economic, or health impacts of the fires.

Non-peer-reviewed sources, in combination with Goldstein (2007, 2008), provide insight into an array of post-fire policy changes and investments in vegetation management. After the 2003 fire season, a 2003 state-wide “Blue Ribbon Panel” review, and subsequent fires in San Diego County in 2007, there were numerous changes in wildfire management at the state and local level. Many of these changes were focused on suppression and emergency response: improvements after the Cedar Fire included creating a unified county fire department for unincorporated areas (rather than many separate volunteer departments), enhancing evacuation planning, instituting reverse 911, providing training for emergency response and firefighting across urban and rural settings, and improving environmental monitoring (e.g., new weather stations and cameras to allow earlier detection and provide real time information on fire spread) (Jones 2013). New codes require 100 feet of defensible space to be cleared around structures in the City and County (Mainar 2013; Miller 2013). The city of San Diego employed additional inspectors to conduct comprehensive code compliance inspections of 45,000 properties on canyon rims (Mainar 2013). However, state-wide, 10 years after the Cedar fire there were still concerns about the risk of future wildfire losses, including a lack of funding for inspection efforts, retrofitting, and vegetation thinning (Miller 2013).

3.2.3. Kilmore East fire

We found 19 items related to recovery, with 13 focused solely on social aspects and six on ecological aspects (Figure 4). In contrast to other fires, most of these sources were not peer-reviewed, but similar to other fires, ecological recovery was addressed almost exclusively in the peer-reviewed literature. Peer-reviewed studies of ecological recovery after Kilmore East included studies of vegetation and wildlife recovery, largely conducted within a few years after the fire, however, one study was conducted seven years post-fire. Dry forests, mostly comprising tree species that resprout after fire, experienced considerable understory mortality, but were recovering well seven years post-fire, with fuels and shrub layers equal to or exceeding pre-fire levels (Cawson *et al.* 2018). In wet forests, while there was also high re-establishment via seed post-fire (Smith *et al.* 2016), there was concern that, because this forest requires an inter-fire period of greater than 100 years, the next planned or unplanned fire could eradicate the mountain ash (Cawson *et al.* 2018). The fire also had major impacts on fauna and their critical habitat. For example, small mammal populations were reduced by at least 80% (Banks *et al.* 2011a). Arboreal possums fitted with radio transmitters survived the fire, but 80% of nesting (hollow bearing) trees were removed (Banks *et al.* 2011b). Bird populations were reduced by 40% in the two to three years after the fire (Robinson *et al.* 2014). An additional non-peer-reviewed study of herpetofauna found that the combined impact of extended drought and the fire negatively affected two threatened frog species (Howard *et al.* 2010).

Nearly all information on social recovery came from non-peer-reviewed sources, with one only one peer-reviewed publication (Whittaker 2020) overviewing changes in policy and post-fire outcomes. We found limited information on rebuilding, all from non-peer-reviewed sources. A survey conducted four years post-fire found that 44% of households had rebuilt, 7% were in the process of rebuilding, and 36% had purchased a new property (Fire Recovery Unit 2012). News articles characterized strong growth in property prices over time and noted in-migration of younger families seeking rural lifestyles, even in areas where many casualties occurred (Wells 2018; Hersher and Rizzo 2020; Realestate.com.au 2020). There was one attempt to revisit residential land use through buyouts, but the number of properties purchased (116 in total) represented a tiny proportion of the total properties at risk in Victoria. The buyout program was created two years after the fire, which may have limited participation (Hersher and Rizzo 2020). Purchased properties were primarily resold to owners of adjoining parcels (to remain open space), while a few were retained by the government as public land (BRCIM 2014).

An array of policy changes occurred after Black Saturday, many of them stemming from recommendations from a Royal Commission (Teague *et al.* 2010; BRCIM 2014). Major changes to safety policy and community education included greater emphasis on early evacuation, clearer communication about the preparation required to stay and defend houses, and the introduction of additional ratings to communicate risks to life and property when fire danger is greatest (Whittaker 2020). In response to an identified need for a range of community shelter and relocation options (BRCIM 2014), the Victorian government introduced "Neighbourhood Safer Places" (designated locations that may provide protection from direct flame and heat during a fire, but do not guarantee safety) and "Community Fire Refuges" (purpose-built or modified buildings that can provide protection from radiant heat and embers) as places of last resort during a fire (CFA 2020). Land use planning was also strengthened through restrictions on new developments in high-risk areas; more stringent requirements for subdivisions, building siting, bushfire protections, defensible space, water storage, and access; and greater power to the Country Fire Authority in planning decisions. Construction standards for buildings in bushfire-prone areas were strengthened (Standards Australia 2009). Additionally, guidelines were created for retrofitting older buildings

(Building Commission and CFA 2011; Victorian Building Authority 2015), and standards were developed for building private-use shelters of last resort (Australian Building Codes Board 2014). Despite these changes, 10 years after the Black Saturday fires, an estimated 90% of houses in bushfire risk areas throughout Australia were not "bushfire hardened" (Mannix *et al.* 2019).

Since Kilmore East and the Black Saturday fires, $650 million AUD has been invested in electrical asset protection and control equipment (DELWP 2020). However, doubts remain about the effectiveness of these technologies: a decade after the fires, a significant number of fires were still being caused by faulty electrical infrastructure, and new technologies themselves were associated with ignition risks (Carey 2018; Hobday and Robb 2019). Finally, the Victorian Government adopted a program of prescribed burning, with an annual rolling target of 5% minimum of public land (Teague *et al.* 2010). However, after scientists raised concerns that this program would damage the environment without necessarily reducing risk, the government shifted to a "risk-based" approach, focused on strategic areas where fires posed the greatest threat to life and property (Handmer and Keating 2015; Penman 2015).

3.2.4. Bastrop fires

We found 22 items related to recovery, with nine focused solely on ecological aspects and seven focused solely on social aspects (Figure 4). Six sources, all non-peer-reviewed, considered both social and ecological aspects together, and four of these sources considered these aspects in a coupled way. Peer-reviewed studies documenting ecological recovery after the 2011 Bastrop fires focused on the short-to-medium term (up to four years post-fire). In terms of vegetation recovery, post oak regenerated faster than loblolly pine in areas of highest burn severity (Booth *et al.* 2019). Studies found the transpiration rates and overall health of regrown pines to be more sensitive to shallow soil moisture, relative to regrown oaks, and suggested that hydroseed for erosion control delayed first-year regeneration of pine seedlings (Booth *et al.* 2019; Cooper *et al.* 2019). Several studies examined differences in forest microclimate (e.g., air temperature, humidity, soil temperature, soil moisture) between burned and unburned areas.

Brown *et al.* (2014b) detected no differences in these parameters, apart from increased wind in burned areas. Two studies differed in their conclusions on soil moisture variation (Cardenas and Kanarek 2014; Brown *et al.* 2014b).

A few studies reported on post-fire faunal recovery, including Goldstripe Darter fish (*Etheostoma parvipinne*) (Dautreuil 2016), red imported fire ant (*Solenopsis invicta*) (Brown *et al.* 2013), and the endangered Houston toad (*Bufo houstonensis*) (Brown *et al.* 2014a). In the short term, no significant population changes were observed, but concerns were raised about longer-term impacts to the Houston toad. For instance, while stability within the forest microclimate bodes well for the toad's post-fire recovery (Brown *et al.* 2014b), reduced canopy cover may ultimately increase populations of invasive fire ants who prey on juvenile toads (Brown *et al.* 2013).

Relative to the other fires, the peer-reviewed literature on the Bastrop fires contained more coverage on social aspects and focused on the first four years post-fire. Two focused on wildfire mitigation efforts in response to the 2011 fires. Bastrop County's Office of Emergency Management, with support from FEMA, initiated a $3.7 million fuels reduction project (Horney *et al.* 2018). The county also contracted a private firm to map wildfire hazard areas (i.e., "fire plains"), set planning priorities, and create a web map interface for decision support (Jackson 2016).

This fire was unique in having a longitudinal survey of social recovery in the peer-reviewed literature, with data collected immediately following the fire, in 2011, and 3.5 years afterward, in 2015 (Kirsch *et al.* 2016). In 2011, 40% of households living in fire-damaged or destroyed homes had no plans to rebuild or repair; however, by 2015, 91% of households living in fire-damaged homes reported that the homes had been repaired or rebuilt. Households that received county incentives showed higher rebuilding rates (94%) than those who received none (83%). Kirsch *et al.* (2016) also documented increases in household-level wildfire evacuation planning and improvements in mental health over time; however, a news article noted the prevalence of post-traumatic stress disorder among firefighters and survivors (Trejo 2018). Another peer-reviewed study described altered gender norms during post-fire recovery (Nummi and Henderson 2016).

Non-peer-reviewed sources further detail changes to policy and practice at the state and local levels. Following the 2011 fires, the state government issued a report on lessons learned (TAMU Forest Service 2012), and began fully funding the Texas Wildfire Protection Plan (Sevilla 2016). Locally, Bastrop County received federal funding ($25 million from the US Department of Housing and Urban Development) for projects to improve emergency response capabilities and mitigate post-wildfire erosion (Huber 2016). Local aviation facilities were enhanced to support wildfire suppression (Sevilla 2016). Strategic vegetation management has increased since the Bastrop Fires. With funds from FEMA's Hazard Mitigation Grant Program (HMGP), the county piloted a mechanical vegetation management program on private lands (FEMA 2015). Efforts at Bastrop State Park have focused on maintaining defensible space around structures, decreasing ladder fuels, and designing burn lanes for better control of fires (Trejo 2019). The park has also reintroduced prescribed burning for ecosystem restoration and maintenance (TPWD 2018; Mulder 2019a,b).

Sources detailing coupled social–ecological recovery aspects described interactions between fuel treatments, conservation policies/practices, and vegetation or faunal recovery. For instance, to safeguard Houston toads during mechanical clearing projects, toads were captured by a local biologist to be released once clearing was completed (FEMA 2015). The Texas Parks and Wildlife Department (TPWD) and US Fish and Wildlife Service also implemented a Safe Harbor Agreement to engage landowners in the Houston Toad's recovery (TPWD 2018). Meanwhile, in Bastrop State Park, officials undertook several interventions to ensure post-fire ecosystem recovery. For example, they counteracted erosion-induced oxygen depletion in ponds by adding electric-powered aerators and used targeted herbicides in response to post-fire propagation of invasive, hybrid grasses designed by the agricultural industry for cattle ranching (Buchele 2013).

3.3. *Comparison of post-fire actions and changes in vulnerability*

We identified 18 distinct types of intervention across the fires, grouped into four categories of activity: ecological management, mitigation actions, emergency response/suppression capabilities, and social capacity (Table 2).

Ecological management activities included efforts intended to restore function to habitats and ecosystems. We found evidence of these activities after all US focal fires but not after the Kilmore East fire in Australia. Following the Florida fires, conservation of a threatened species (the Florida scrub jay) primarily motivated ecological restoration efforts, while after the Cedar fire, the threat of vegetation type conversion appeared to be the primary motivator. In Bastrop, we observed a confluence of both factors, including concerns about Houston toad recovery, threats posed by invasive ants, and the potential conversion of loblolly pine forest to oak woodlands. While the degree to which restored species, habitats, and ecosystems were fire-adapted often indicated the success of ecological management activities (e.g., Florida and Cedar fires), this indicator was static rather than dynamic. We found little consideration of longer-term changes in ecosystem vulnerability due to shifts in climate and fire regimes.

At a local government level, jurisdictions conducted risk assessments, which often included mapping areas of greatest wildfire risk to then prioritize mitigation efforts. Among mitigation efforts, all study areas saw increases in vegetation management programs aimed at fuels reduction, often through prescribed fire. However, differences in vegetation and fire regimes also meant that prescribed fire use was not uniformly appropriate. Specifically, after the Kilmore East and Cedar

Table 2. Policy Responses to the Four Fires Grouped by their General Purpose[a]

	Florida	Cedar	Kilmore East	Bastrop
Ecological Management				
Habitat restoration for threatened species	×			×
Strategic replanting to prevent ecosystem type conversion		×		×
Mitigation Actions				
Ignition prevention through electrical asset protection[b]			×	
Fuels reduction through new vegetation management programs	×	×	×	×
Fuels reduction through increased use of prescribed fire	×		×	×
Comprehensive risk assessment and mapping programs		×	×	×
Buyout programs for high-risk properties			×	
Strengthened land use planning and subdivision design		×	×	
New fire-resistant construction and retrofit standards	×	×	×	
Increased enforcement of construction standards		×		
Stricter defensible space requirements	×	×	×	
Increased enforcement of defensible space practices	×	×		
Emergency Response/Suppression Capabilities				
Investments in new equipment and technology	×	×	×	×
Increased planning for evacuations		×	×	
Improvements in organizational structure of response agencies	×	×		
Enhanced training for firefighters	×	×	×	
Social Capacity				
Community education on fire-adapted principles	×	×	×	×
Establishment of grassroots networks for wildfire recovery and adaptation		×		

Notes: [a]The table documents only those outcomes evidenced in our found literature. It is possible that some coupled outcomes were unpublicized via these sources and, thus, may inadvertently be omitted.
[b]After 2007 wildfires, San Diego Gas and Electric became active in wildfire prevention and mitigation activities.

fires, there were concerns about the ecological trade-offs (e.g., type conversion, invasive species) of prescribed fire.

There was less action focused on the built environment, with nearly all changes focused on new housing rather than retrofitting or enforcement of defensible space for existing housing. Buyouts occurred only after Kilmore East, but with limited participation. In California and Australia, new local regulations integrated wildfire risk into land use planning and subdivision design. At the household level, stricter requirements for fire-resistant construction, structural retrofitting, and defensible space maintenance followed all but the Bastrop fire;[3] however, rigorous enforcement of these new requirements was less widespread, potentially limiting the vulnerability reduction potential of these efforts.

Emergency response capabilities were improved after all four fires, and investments in suppression occurred in all the US fires. Many of these investments introduced new technologies and upgraded equipment, although the purpose of technologies varied to include wildfire detection, public warning, fire suppression equipment (e.g., trucks, helicopters), and improved facilities (e.g., water storage, air bases). The Cedar fire stood out among our cases as the only event that prompted a comprehensive set of changes spanning the full range of identified emergency response activities. In contrast to the US, we could find no evidence of increased investment in suppression technologies that were directly attributable to the Kilmore East fire.

The final category of activities we identified were those intending to build social capacity for future fires. While these activities may not directly reduce exposure or sensitivity, they have potential to increase the ability to cope and adapt to future fire, and therefore to counteract vulnerability. All case study sites showed an increase in community education campaigns, although the focus differed with the wildfire experience. For example, in Australia, the large number of fatalities forced a major shift in policy toward early evacuation and away from "stay and defend" (Whittaker 2020). Meanwhile in the US, education was focused on wildfire risk awareness more generally.

Although wildfire recovery has been described as an opportunity for transformative adaptation (O'Neill and Handmer 2012), without more detailed information on changing social and ecological conditions it was challenging to assess how future vulnerability might change with recovery. Only a few studies focused on these interactions, but we did find some ways in which interactions between ecological capability and human culture were restructuring post-fire landscapes. In this sense, culture refers broadly to factors shaping beliefs about what human recovery and ecological recovery from wildfire *should* look like (e.g., risk tolerance, environmental values, financial incentives, rebuilding practices). For example, in Texas, initiatives focused on preventing the complete loss of a beloved, yet fragile ecosystem may recreate the vulnerability conditions that led to the Bastrop

[3]Texas law only permits fire codes in counties of over than 250,000 population and adjacent counties. This means roughly 70% of counties are forbidden from having fire codes (Dallas Morning News 2013).

fires. In Southern California, reducing fuels around houses creates significant ecological costs and trade-offs that, while potentially reducing risk in the short term, may increase landscape flammability in the longer term through vegetation type conversion (Syphard *et al.* 2019). In both Southern California and Bastrop, therefore, despite the goal of "living with fire", vegetation management practices may be leading to recovery trajectories that are not sustainable or fire-adapted.

In contrast, vegetation management in our other two study sites appeared more likely to yield coupled human and ecological benefits. Increased prescribed burning following the 1998 Florida fires mitigated risk for people and their property, reduced vegetation mortality in wildfires, and increased habitat quality for endemic and endangered species (Breringer *et al.* 1999; Outcalt and Wade 2004). The fires themselves in Florida provided valuable evidence that prescribed fire can mitigate ecological damage and lead to quicker vegetation recovery. In Australia as well, prescribed fire use has increased, taking care to maximize risk reduction to people and property while avoiding deleterious effects on wider ecological systems (Penman 2015).

However, even in these instances where studies indicate that ecological and social benefits align, we lack systematic measurement of the interdependencies and outcomes in social–ecological conditions. All of our study sites are facing increased exposure and sensitivity through more houses/people (which may increase ignitions) and climate change (which may increase severity and extent of wildfire in many areas). Although we did find notable changes in how people build and live in wildfire risk areas, it is unclear how such efforts will affect vulnerability long term. For example, fire-resistant building design and construction techniques may be based on historical fire behavior, but longer-term climate changes could usher in fire weather conditions that supersede these strategies, ultimately increasing the exposure of people and property to wildfire.

4. Discussion

This paper used a systematic literature review to examine post-wildfire outcomes following four major wildfires in Australia and the United States, including social and ecological recovery processes and policy changes. Drawing from our collective case study results, we now consider gaps in the available information and data on wildfire recovery. We describe how these gaps limited our ability to discern how wildfire recovery may recreate vulnerability or facilitate adaptation in human and ecological systems. Finally, based on these observations, we suggest directions for further research on post-wildfire adaptation.

4.1. *Information and data gaps in wildfire recovery*

Although these were nationally significant wildfire events, we found a lack of systematic data on long-term human system recovery, including housing reconstruction (e.g., number of buildings exposed to wildfire, sensitivity/fire-resistance). Additionally, we found relatively little data on other facets of social recovery such as changes in population characteristics, prolonged adverse health effects, mitigation practices, and social networks. The sole exception was in Bastrop, where surveys conducted immediately after wildfire and 3.5 years later assessed social outcomes, including rebuilding, emergency planning, and mental and physical health outcomes (Kirsch *et al.* 2016). While peer-reviewed sources generally did not include social aspects of recovery, non-peer-reviewed sources frequently "took stock" of social recovery in ways that were more evocative than systematic. For example, news articles often focused on the social memory of disaster but were not intended to provide neighborhood or community-level information on recovery or vulnerability. Across all four fires, in both social and ecological domains, we rarely found peer-reviewed studies that extended beyond five years post-fire. Studies that focused on post-fire mitigation efforts, especially fuel treatments and changes to regulations, similarly lacked the comprehensiveness or detail to gauge changes in future vulnerability.

Peer-reviewed coverage of ecological outcomes and recovery after fire proved more systematic than coverage of social aspects, yet these studies were also limited by their short time frames of, generally, one to three years post-fire. Investigators frequently speculated on potential medium- and longer-term changes in vegetation or wildlife characteristics (Grace 2000; Franklin *et al.* 2006; Brown *et al.* 2014b) but subsequent studies rarely followed up to observe whether these anticipated changes occurred. Across all four cases, we found only five sources on ecological outcomes that considered changes beyond three years post-fire: four pertained to the Cedar fire and one pertained to the Kilmore East fire. Beyond referencing drought, studies generally did not consider how forecasted changes in local climate (e.g., precipitation frequency and duration, temperature extremes, wind patterns) and fire regimes might affect the adaptive capacity of ecosystems.

The lack of peer-reviewed literature considering coupled human and ecological wildfire outcomes obscured the relationship between exposure and sensitivity in the post-fire landscape, and in turn, made it difficult to diagnose the net effect on vulnerability before the next fire. Studies generally did not consider the feedbacks between ecological conditions and human responses. Understanding both the outcomes of these feedbacks (i.e., do they increase/decrease exposure or sensitivity to future fires) and their motivations (e.g., values, beliefs that motivate interventions and policy changes) are key to making progress toward vulnerability reduction. Ultimately, the extent to which recovery processes recreate vulnerability or facilitate adaptation depends on how well management strategies are tailored to fit the human-ecological context. In places like California, where fire regimes can vary widely across a single jurisdiction, developing responsive management strategies is challenging.

Finally, we note that our study and findings reflect our approach, a retrospective review of literature. Although we attempted to be systematic and exhaustive, searching peer-reviewed literature and other sources, there are likely resources we did not find (e.g., studies that used different names for study areas or fires, academic theses, reports that were not made available on the internet). We acknowledge that managers, practitioners, and academics in these regions may well be engaged in additional studies and have compiled vital information and synthesis through their own work, which is not readily available in literature sources. Documenting and making available knowledge on previous fire recoveries (e.g., Whittaker 2020) is vital if we are to learn from these events and better adapt our communities and ecosystems. In future studies, direct engagement with managers and scientists (e.g., interviews) to elicit their perspectives on wildfire recovery processes could supplement the current collective case study approach and overcome some of its limitations.

4.2. *Directions for future research*

Addressing these data gaps with systematic monitoring of long-term recovery trajectories in coupled socio-ecological systems across varied policy environments and fire regimes would seem a logical first step toward enhancing our knowledge of wildfire recovery. Accomplishing this requires sustained collaboration between ecologists and social scientists, and dissemination of research in rigorous, peer-reviewed outlets.

Our findings also suggest several ways in which the concepts of adaptation and vulnerability can be reframed. For example, ecological studies could further consider the vulnerability of ecosystem conditions to future climate, land use conditions, and potential outcomes from restoration. Cultural values motivating post-fire changes in social conditions could also be further explored. For example, could investments in mitigation (e.g., fire-resistant design and construction), evacuation planning, rapid detection and monitoring, and suppression capabilities serve to *encourage* rather than curb rebuilding in high fire risk environments (similar to the "levee effect" in flood-prone areas (Montz and Tobin 2008; Ferdous *et al.* 2019))?

Future efforts can also take a broader view of wildfire, hazards, and governmental response as compounding and interlocking events. This study, combined with the extent and pace of recent fire events, suggests additional considerations that are, as yet, not explicitly depicted in Schumann III *et al.* (2020) model. First, across our sites, we saw that destructive wildfires led to policy learning and recovery contributions on multiple scales, from national, regional, and local governments. Better understanding of the complex interplay between these levels of government will be helpful for future recovery research. For example, regional or national entities commonly made comprehensive recommendations after these high-profile events, but the power to implement such recommendations often remains with local governments. Second, we had conceived of wildfire recovery as systematic adjustments within successive cycles of policy learning after wildfire events (Schumann III *et al.* 2020). However, we have now reached a point where we are seeing multiple fires in close succession in the same areas, in a way that is perhaps augmenting political will, but also destabilizing communities. For example, northern California has experienced record-setting wildfires (in size or losses) nearly every year from 2015 to 2022, with some years containing multiple record-setting wildfires. These circumstances may further complicate the pursuit of adaptive recovery and long-term research. Under such conditions, space and time to implement changes recommended by commissions or after-action reports is limited, and long-term social and ecological recovery outcomes of specific events are challenging, if not impossible, to tease apart.

5. Conclusion

This paper conducted a systematic literature review to examine and compare social–ecological recovery following four major wildfires in Australia and the United States. First, and perhaps most importantly, the paper highlighted the limited peer-reviewed research on post-wildfire recovery, including limited longitudinal data on rebuilding, few studies of long-term vegetation recovery, and scant consideration of feedbacks between social and ecological outcomes throughout the recovery process. Second, our review revealed differences in how sources detailing human and ecological recoveries framed and considered vulnerability. Consequently, our analysis highlighted challenges in determining whether post-wildfire policy and/or management actions were reducing or recreating vulnerability. Finally, considering the data and knowledge gaps on coupled social–ecological recovery from wildfire, the paper illuminated the need for more holistic, multi-scalar, and integrative approaches to research on long-term wildfire. Given the rapidly changing landscape of wildfire risk exacerbated by climate change and the decreasing return period between wildfires that impact the same human and ecological communities, perhaps our best hope of becoming fire-adapted lies in actualizing vulnerability reduction through recovery.

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