Social Vulnerability, Wildfire Risk, and Ecological Damage in the Wildland-Urban Interface: What can the Global South Learn from the San Francisco Bay Area Experience?

Amm Quamruzzaman

Ava Currie

Emma Centeno

Grace Huang

Joyce Wang

Rohith A. Moolakatt

Scott Hashimoto

Amit Sant

University of California Berkeley

Abstract

A common finding of many studies is that the expansion of the wildland-urban interface (WUI) is associated with a greater risk of wildfire and ecological damage. Yet, the issue of whether or not, or how to, regulate the expansion of the WUI remains contentious and largely unresolved. There are fewer studies that explore how wildfire risk is compounded by social vulnerability of people who reside in the fire-prone WUI. Additionally, much of the extant research is focused on the national or regional level management of ecosystems and forest fires, with a clear lack of focus on local level dynamics. To fill these gaps, our analysis outlines the preliminary steps to identify social, ecological and wildfire vulnerabilities of local communities in the fire hazard zones of the highest severity type. Utilizing GIS mapping, wildfire risk, and census data from 1990 to 2010, our analysis reveals patterns of the WUI expansion in the San Francisco Bay Area and locates the socially vulnerable communities within very high fire hazard severity zones where the residents are most at-risk of wildfires. We discuss the implications of our findings for policy and argue that countries in the Global South or elsewhere facing similar situations can learn from the Bay Area experience to address social vulnerability, wildfire risk, and ecological damage in the expanding WUI.

Keywords: wildland-urban interface (WUI); wildfire risk; social vulnerability; climate change; ecological damage; sustainable development

Introduction

Wildfires pose a great threat to social, economic, and ecological sustainability in both the Global South and the Global North. For centuries, wildfires have been an integral part of forest ecosystems but more recently, the economic, social, and ecological damage caused by extreme wildfires has increased dramatically across the globe. Many factors are responsible for the mounting damage, including climate warming that has likely increased the frequency and severity of wildfires (Allen et al. 2010; Flannigan et al. 2013; Keane 2008; Marlon et al. 2008). Although fire-prone areas have not increased in number and extent in most regions of the world, the area of human habitation near wildland vegetation areas with fire exposure or what is known as the wildland-urban interface (WUI) has increased rapidly in recent decades in every continent except Antarctica (Andela and Van Der Werf 2014; Bento-Gonçalves and Vieira 2020; Caton et al. 2017; Doerr and Santín 2016; Hanberry 2020). A common finding of many studies is that the expansion of the WUI is associated with more ignitions, leading to a greater risk of wildfire (Kramer et al. 2018, 2019; Radeloff et al. 2005, 2018; Syphard et al. 2007, 2009, 2013, 2017, 2019). The wildfire risk of the people living within and near the fire-prone WUI is often compounded by their social vulnerability arising from social conditions such as wealth, poverty, education, housing structures, race, disability, and age that often confer or limit access to material and informational resources needed to prepare for and cope with a natural hazard (Coughlan, Ellison, and Cavanaugh 2019; Palaiologou et al. 2019). At the same time, the expansion of the WUI threatens wildlife and the sustainability of forest ecosystems (Bartlett, Mageean, and O'Connor 2000; Mooney and Zavaleta 2019). Regulating the WUI expansion is, therefore, quintessentially important to reduce wildfire risk, social vulnerability, and ecological damage in communities located within and near the fire-prone WUI.

While scientific evidence on the relationship between the expansion of the WUI and the increasing risk of forest fires has grown exponentially over the past few decades, the issue of whether or not, or how, to regulate the expansion of the WUI remains contentious and largely unresolved (Bento-Gonçalves and Vieira 2020; Syphard et al. 2013). The management and regulation of natural resources are a classical problem as Hardin (1968) famously explained. One reason for the problem is that many common-pool resources such as the forest often do not have clearly defined political boundaries. Many forests and wildlands are shared within local, regional, national, or international jurisdictions. Another reason is the ownership type of these resources. At the national and regional level, regulations on the expansion of the WUI are usually met with resistance due to different legal and economic impediments in terms of private and public land ownerships. There are also "underlying" social, economic and political forces operating from the national, regional, or supralocal level that control amenity development policies, land-use, urban or spatial planning, investment patterns in housing markets, agricultural expansion programs, logging operations, and resource extraction policies in the WUI (Dennis 2005; Geist and Lambin 2002). Consequently, much of the extant research on how to regulate, monitor and manage the WUI expansion to reduce wildfire risk is focused on national or regional policies, with a clear lack of focus on local-level dynamics (Gonzalez-Mathiesen, Ruane, and March 2021; Radeloff et al. 2018; Schoennagel et al. 2017; Syphard et al. 2017, 2013). At the local level, the identification of factors such as social vulnerability of people, housing needs, diverse landscapes, fire history, and fire hazard condition may necessitate variations and modifications in national and regional regulatory policies. However, existing studies show "little consensus about how to comprehensively measure vulnerability or apply vulnerability frameworks across different scales and geographies" to assess wildfire risk in the WUI (Coughlan, Ellison, and Cavanaugh 2019: 2).

To fill these gaps, our analysis outlines the preliminary steps that need to be taken at the local level to address the increasing wildfire risk, social vulnerability and ecological damage in the expanding WUI. The analysis is focused on identifying which communities are most vulnerable and at-risk and where to target resources and investments for long-term community resilience and ecological sustainability in the fire-prone WUI.

For our study site, we choose the San Francisco Bay Area's rapidly changing WUI, where housing developments abut or are directly located within wildland vegetation. We explore wildfire risk in the Bay Area's nine counties (local administrative units) over three decades (1990–2010) by mapping the expansion of the WUI and associated social, ecological and wildfire vulnerabilities within the fire hazard zones of the highest risk type. We assume that the Bay Area's wildfire risk reflects broader national and state-wide trends in the WUI growth that makes both homeowners and forest ecosystems extremely vulnerable to wildfires. Although we aim to explore local dynamics, we believe that our analysis provides important insights about the potential strategies to address social vulnerability, wildfire risk and ecological damage in the WUI at local, regional and national levels. We provide policy recommendations that may apply to similar situations in countries of the Global South or elsewhere.

To organize this study, first we trace the current trends in the WUI expansion both globally and in the study area and then contextualize social vulnerability and wildfire risk in the expanding WUI. Next, we discuss how the expansion of the WUI poses a threat to sustainable development, followed by a description of our data and methods. By highlighting changing WUI patterns over three decades (1990–2010) and isolating areas of the highest concern, we present our results underscoring the escalating social, ecological and wildfire vulnerabilities in the Bay Area. We then discuss the implications and limitations of our findings and provide policy recommendations on how to regulate the expansion of the WUI and sustain forests' fire-adaptive ecosystems.

The Current Trends in the Expansion of the Wildland-Urban Interface

With a rapid population and market growth in recent decades, many cities across the globe have continually expanded towards forest and rural areas. There has been a continuous shift of urban population to suburban areas, resulting in an increase in urban fringes especially due to their recreational attractions and landscape beauty (Bento-Gonçalves and Vieira 2020). Housing construction in urban fringes comes with the development of other amenities such as roads, water and electricity supply, waste disposal, schools, shopping malls, clinics, golf courses, and recreation centers. Studies find that a significant portion of new development takes place in low and medium density areas that are rich in natural amenities, such as forests, lakes, and seashores, or are adjacent to protected areas (Bartlett, Mageean, and O'Connor 2000; Hammer et al. 2004; Mockrin et al. 2013; Radeloff et al. 2005). Amenity development in the vicinity of rural and wild lands attracts people of specific lifestyles and economic classes to migrate there. This type of migration is known as amenity migration and defined as the movement of predominantly "affluent urban or suburban populations to rural areas for specific lifestyle amenities, such as natural scenery, proximity to outdoor recreation, cultural richness, or a sense of rurality" (Abrams et al. 2012: 270).

There has been significant expansion of rural-urban or wildland-urban interface areas in countries such as the United States, Canada, Greece, Spain, Portugal, France, Brazil, Argentina, Paraguay, Bolivia, Peru, Chile, South Africa, Democratic Republic of the Congo, Sudan, the Central African Republic, Indonesia, China, Russia, and Australia (Bento-Gonçalves, Vieira, and Vinha 2018; Chuvieco et al. 2014; Davis 1990; Radeloff et al. 2005; Skulska 2020). In the United

States, the WUI has become the fastest-growing land-use type from 1990 to 2010 in terms of both the number of new houses (from 30.8 million in 1990 to 43.4 million houses in 2010, a 41 percent increase) and land area (from 581,000 km^2 to 770,000 km^2, a 33 percent increase). In California, the total WUI area grew 19.5 percent from 22,618 km^2 in 1990 to 27,026 km^2 in 2010, with 1.1 million new homes being built in the WUI, a 33.8 percent increase (Radeloff et al. 2018). Southern California's chaparral landscape, an ecosystem composed of shrubby plants adapted to dry summers and moist winters, attracts affluent people and developers in this ecological space, despite the heightened risk of wildfire. This trend explains disperse housing growth in rural settings with a larger area per housing unit.

The San Francisco Bay Area shows a similar trend. With approximately 18,130 km^2 of land, this area houses more than 7.7 million people in 101 cities in nine counties – Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma. This part of Northern California stretches from the Wine Country in the north to Silicon Valley in the south, from the shores of the Pacific to the edge of the Central Valley. This and surrounding areas have experienced a rapid population and economic growth leading to a rapid expansion of the WUI and at the same time, endured severe economic, social and ecological damage due to some of the worst wildfires in California's recent history.

Housing nearly 20 percent of California's 39.5 million people, the San Francisco Bay Area is driving the population growth in the most populous state of America (United States Census Bureau 2020). Although the population growth in the state has slowed down in recent years, the population of the nine-county region grew by over 600,000 people since the 2010 census with a nearly 8.5 percent increase, outpacing the growth rate in any other part of California. The development of Silicon Valley as a global hub of high-tech companies and innovation led to rapid job growth in the region. The Immigration and Nationality Act of 1965 and the expansion of the H-1B visa in 1990 allowed thousands of immigrants to come to the Bay Area and contribute to the high-tech and production workforce of Silicon Valley (Matthews 2003). The region is now struggling to accommodate its own rapid pace of job growth, resulting in an increase in housing and other amenity construction. According to census data, there were 2,785,948 housing units in the Bay Area in 2010 that grew to 2,951,860 in 2019; this is an increase of 165,912 units in 10 years or a 5.6 percent decadal change (United States Census Bureau 2020). Clearly, this increase is not enough to accommodate the growing population in the region. To meet the increasing demand for housing, the California Department of Housing and Community Development very recently has assigned 441,176 new housing units to the Bay Area for the 2023–2031 cycle of the Regional Housing Needs Allocation (Sheyner 2020). We anticipate that this allocation will lead to a further expansion of the WUI in fire-prone areas and local authorities will have to deal with more fire events in the coming years.

Social Vulnerability and Wildfire Risk in the Wildland-Urban Interface

Although globally the majority of wildland is under the federal or national government control, increasing private ownership of it especially makes people vulnerable to wildfires in the WUI where landowners build houses, farms, and infrastructures (Dennis et al. 2005; Wigtil et al. 2016). In the U.S., about 56 percent (more than 420 million acres) of forests are privately owned and managed by about 11 million private owners, nearly 8 million of whom have relatively small holdings of fewer than 50 acres each, while a quarter of private forestland is owned by private corporations, organizations, and individuals who have large holdings of 5,000 acres or more (Butler 2008; Smith et al. 2004; Stein et al. 2009). In California, the federal government owns nearly 58 percent of the state's 33 million acres of forestland, while the state owns only 3 percent, with the rest 39 percent being owned by private individuals or companies and Native American groups (Office of Governor 2020). While private landowners are key stewards of forests, they are under pressure to sell their land for real estate development and other uses as the costs for managing their forests can be high (Alig 2007; Stein et al. 2009). The further sale of forestland to different individuals, industries, and developers results in the parcelization, alteration, and fragmentation of forest ecosystems in the WUI (LeVert, Colgan, and Lawton 2007). Smaller, more fragmented parcels create barriers for others to access major ecosystem services and increase the risk of wildfire from human activities (Smail and Lewis 2009; Stein et al. 2005, 2009). Studies also find that the size of forest holdings is highly correlated with behaviors and attitudes of owners in terms of their management objectives and wildfire adaptation and mitigation plans (Butler 2008). A recent study, using a landowner survey in the southern United States, finds that most private landowners did nothing to respond to wildfire risk, while some of them used diverse adaptation and mitigation strategies (Gan, Jarret, and Gaither 2015).

Of course, all landowners are not the same and they are not the only people who live in the fire-prone WUI. There are many other people who work, commute from, or reside within and near fire hazard zones. Because of the diversity of population living in the growing WUI, not every individual is equally vulnerable to wildfire events. Proponents of the political ecology of hazard vulnerability assert that social inequalities in terms of wealth, race, disability and age shape vulnerability of different groups of people and affect their capacities to cope with a hazard (Blaikie et al. 2014; Collins 2008a; Wigtil et al. 2016). Institutional arrangements such as insurance coverage, land use regulations, emergency response, and disaster relief subsidies enable residential development in amenity-rich areas that are subject to destructive events (Davis 1999; Fulton

1995). These social factors are "linked with social vulnerability to wildfires and describe a community's: capability to quickly react to and escape from an emergency (e.g., too young or too old, lack of vehicle, disability and single-parent households); ability to absorb losses and enhance resilience to hazard impacts (e.g., poverty, income and education); diversity (e.g., minority status, poor ability to speak … [an official language]); housing status and affordability (e.g., multi-family residential units, manufactured homes, overcrowding in housing, and group quarters); and predominant occupations (natural resources, service, and government jobs, unemployment rates)" (Palaiologou et al. 2019: 100).

Social vulnerability as an "effect of social inequalities on sensitivity to hazards" makes some groups of people "more susceptible to harm than others while limiting their ability to adapt to changing risks" (Coughlan, Ellison, and Cavanaugh 2019: 6). For example, nearly 34 million people in the Amazon are exposed to dangerous air pollution from forest fires. Within this region, over 380 Indigenous groups suffer acutely, despite contributing little to the cause of local wildfires and the climate crisis itself (Viana 2020). Similarly, wildfires within Indonesian forests put over 31,000 Indigenous villages in danger of wildfire and the associated health impacts of smoke (Sagala, Sitinjak, and Yamin 2015). In the U.S., over 29 million people reside in the fire-prone WUI, with 12 million living in census tracts that are majority Black, Hispanic or Native American, experiencing about 50 percent greater vulnerability to wildfire compared to other census tracts (Davies et al. 2018). In California, many individuals living within and near fire-prone areas do not have capacities to pay for necessary insurance and home-hardening materials, thereby increasing their vulnerability to wildfire (Collins 2008b). These disparities became very clear as the Tubbs Fire broke out in October 2017 in parts of Napa and Sonoma counties in the Bay Area. The second most destructive wildfire in California's history, the Tubbs Fire burned 36,807 acres, destroyed 5,636 structures, and killed 22 people, inflicting its greatest losses in the city of Santa Rosa in Sonoma County (CAL FIRE 2020). Socio-economically disadvantaged people suffered disproportionately from these losses, and even in the aftermath of the destructive event, they were the people to suffer the most due to a rapid increase in house rents by the wealthy landlord amidst an already dire housing shortage in Sonoma County (Fixler 2018).

Napa and Sonoma counties also experienced other devastating fires in recent years, making it hard for many people to live in and near fire-prone areas. The Kincade Fire broke out in Sonoma County in October 2019 that burned 77,758 acres, completely destroyed 374 buildings, and damaged 60 others. In September 2020, the Glass Fire broke out in Napa and Sonoma counties that burned at least 67,484 acres and destroyed 1,555 structures including at least 19 wineries, restaurants, and resorts in Santa Rosa (CAL FIRE 2020). Many individuals lost their livelihood and became further vulnerable to wildfire.

Other wildfires such as the 1991 Tunnel Fire in the Oakland and Berkeley Hills in Alameda County are a glaring reminder of the direct danger of residing in WUI spaces. The Tunnel Fire is the third most destructive fire in the history of California that burned over 1,600 acres, completely destroying 2,900 structures and claiming 25 lives (CAL FIRE 2020). Yet, nearly 75 percent of buildings destroyed by wildfires in California are located in the WUI; this number is 69 percent in the entire United States (Kramer et al. 2018). About 90 percent of the WUI growth has occurred in high severity forest fire regimes in the western United States, especially in California (Radeloff et al. 2018; Theobald and Romme 2007). Human activities in the WUI, such as leaving campfires unattended, losing control of prescribed burns or crop fires, burning debris, discarding cigarettes, playing with fireworks, and intentionally setting fire as an act of arson, were responsible for 84 percent of all wildfires and 44 percent of total area burned in the U.S. between 1992 to 2012 (Balch et al. 2017). Sparks from railroads, motor vehicles, and power gridlines also often cause wildfires. Comparatively, a large percentage of fires in the forests of the Rocky Mountains and the Southwest in the U.S. is caused by lightning.

Both human-induced and lightning-ignited wildfires have grown larger and more severe since 1992 but human-induced wildfires have tripled the length of the wildfire season (Balch et al. 2017). Human-induced wildfires have accounted for just 44 percent of the total area burned despite the high number of incidents because many of them occurred in relatively wet environments and near WUI areas where firefighters extinguished the fires before they spread. However, firefighting has become extremely difficult within WUI communities because of high housing density and the rapid spread of wind-blown embers (Hill and Kakenmaster 2018). There are more homes to protect in the event of wildfire but foresters and firefighters often lack the necessary resources and training to fight against high-intensity fires in the artificial environment of the WUI, leading to a high rate of firefighter fatalities (Davis 1990; Radeloff et al. 2018). The lack of firefighters can also make individuals residing in the WUI especially vulnerable to the effects of wildfires (Glickman and Babbitt 2001).

A greater likelihood of ignitions from human activity coupled with artificial fuels from combustible building materials results in more frequent and destructive fires that pose a direct threat to lives and properties in the fire-prone WUI (Stec and Hull 2011). Apart from the direct threat, wildfires pollute the air that travels far and wide, indirectly affecting health of many people in the surrounding areas. Embers or firebrands born out of intense heat associated with wildfires can also travel with the wind within one mile and start new fires if they land on a combustible fuel source. This creates vulnerability for people who live within and near fire-prone WUI areas.

Millions of acres of fires used to burn each year in prehistoric California, whereas only thousands are allowed to burn today to protect houses that are being built in places where they should not have been built (Kramer et al. 2018; Theobald and Romme 2007). As a result, the vegetation has grown much thicker, increasing competition for water that has left California's forests vulnerable to droughts, bark beetles, grasslands, and shrubs, making them one of the most naturally flammable landscapes on the planet. Many of California's destructive fires have occured on the shrubby chaparral landscapes, not forests (Quinton and Brown 2020). Consequently, scaling up prescribed burns did not work effectively as the grass and shrubs grew back quickly in the wet season.

Ecological Damage in the Wildland-Urban Interface

Urban expansion, amenity development, and frequent wildfires threaten the niche chaparral ecosystem in California, but similar ecosystem threats from fire and urban development are observed around the world. The Amazon, for example, faces threats of elimination because of the telling advances of anthropogenic deforestation in the region, much of which is driven by forest fire, forest clearing and fragmentation, climate change, and droughts (Nobre and Borma 2009). The Amazon rainforest is predicted to have its tipping point at 20-25 percent of deforestation, at which the precipitation cycles withing the region would be disrupted and may lead to the drying out of the Amazon (Viana 2020). This disruption would also increase its vulnerability towards further wildfires, leading to the predicted transformation of the forest into a savanna ecosystem (Lovejoy and Nobre 2018). This conversion would have devastating effects both regionally and globally, as the Amazon gives the region climate stability, a beneficial agricultural condition, a critical refuge for biodiversity, and a natural carbon sink for the entire planet.

A constant encroachment into the wildland for human settlement and amenity development obviously poses a great threat to the sustainability of both the ecosystem and human society. The encroachment causes the loss and fragmentation of habitat essential for sustaining wildlife and biodiversity (McKinney 2002; Theobald, Miller, and Hobbs 1997). As homes and associated infrastructures are increasingly being built within forests and shrublands, they threaten and endanger many wild species. According to an estimate, urbanization is responsible for more than half of all federally listed threatened and endangered species in the U.S. (Czech, Krausman, and Devers 2000). A recent report from the World Wildlife Fund (WWF) claims that globally there has been a 68 percent drop in more than 4,392 monitored species between 1970 and 2016 due to habitat destruction, over-exploitation of nature, invasive species, pollution, and climate change (WWF 2020). The report says that this huge drop has connection to the latest sprawling wildfires across the globe, including those in California. One of the coping mechanisms for many mobile species is just to flee the fire, but due to the expansion of the WUI, they have fewer places to go in the event of a fire. As many species are being extinct and their population sizes getting shrunk, humans are losing vital ecosystem services such as oxygen, soil fertility, water purification in natural sources, and pollination from insects and birds.

Protecting nature against the increasing human settlement into the wildland is essential to ensure the sustainable supply of and equitable access to vital ecosystem services, which is also necessary for achieving the Sustainable Development Goals (SDGs), as agreed by nations worldwide (DeClerck et al. 2016). Sustainable development requires a balance between economic development and the long-term safeguarding of life-sustaining ecosystem services, with a commitment to social responsibility towards future generations (Brundtland 1987). From a sustainable development framework, present actions at the local level can have effects on global-level actions for a sustainable future (Christmann et al. 2012).

Forest ecosystems are crucial for a sustainable future and offer a natural solution to climate change, as the chiefs of FAO, UNDP, and UN Environment recently said in a joint statement: "Forests are a major, requisite front of action in the global fight against catastrophic climate change – thanks to their unparalleled capacity to absorb and store carbon. Stopping deforestation and restoring damaged forests could provide up to 30 percent of the climate solution" (Da Silva, Steiner, and Solheim 2018). Deforestation can be stopped but unfortunately, the restoration of damaged forests lags far behind the rate of deforestation caused by agriculture, forestry, housing settlement, urban development, and other types of land use that increase wildfire risk and global greenhouse gas emissions. Deforestation (an indicator of land-system change), along with extinction rate (an indicator for biosphere integrity), atmospheric carbon dioxide deposit (an indicator for climate change), and the flow of nitrogen and phosphorus (an indicator of biogeochemical flows), has already crossed the planetary boundaries necessary for the Earth system to operate safely (Steffen et al. 2015). Land-system change occurs on a local scale but the aggregated impacts can have consequences for Earth system processes on a planetary scale. It is, therefore, necessary to regulate the land use at the local level to limit our ecological footprint and ensure sustainable development in the WUI.

A major challenge of adopting an integrated sustainable development framework to WUI regulation is estimating the benefits of ecosystem services – not in economic terms alone, but also in terms of planetary functioning. Another challenge is that we lack appropriate data on the extent of ecological damage in the WUI. Given this limitation, our analysis only uses vegetation cover and housing density in proximity to large patches of wildland vegetation as indicators of ecological damage. We describe our materials and methods in details in the next section.

Materials and Methods

We have used the term wildland-urban interface (WUI) from different perspectives. From a natural resource perspective, the wildland-urban interface is defined as an area where increased human influence and land-use conversion change natural resource goods, services, and management techniques (Macie and Hermansen 2002). From a wildfire perspective, the wildland-urban interface is an area where humanmade infrastructure is in or adjacent to areas prone to wildfire. From a vulnerability perspective, the wildland-urban interface is an area where social conditions can make a community vulnerable to a wildfire disaster. While all these definitions are good, we need an operational definition from a geographical-spatial perspective to fit our empirical analysis. From this perspective, the wildland-urban interface is divided into intermix and interface areas. Intermix areas are more vegetated areas where wildland fuels are continuous and settlements are dispersed with a housing density of over 1 house per 40 acres. Interface areas are more densely settled areas that have less vegetation than intermix areas but are at most 2.5 km or 1.5 miles away from an area with 75 percent or more wildland vegetation (Radeloff et al. 2018). As already mentioned, lacking appropriate data, we use the loss of vegetation areas due to housing settlement in the WUI as a measure for ecological damage. That is, ecological damage is measured here as a proportion of total acreage and housing units located in the WUI.

In our analysis, fire hazard refers to the physical conditions that generate the possibility that a location will burn "over a 30 to 50-year period without considering modifications such as fuel reduction efforts" (CAL FIRE 2007). We use the term wildfire risk to refer to the probability of exposure to wildfire events based on geographic locations and distinguish it from social vulnerability which refers to "the socially constructed potential or susceptibility of people (as individuals, households, or communities) to be negatively affected by hazard events, such as wildfires" (Coughlan, Ellison, and Cavanaugh 2019: 1). We assume that wildfire risk is compounded by social vulnerability as social conditions often influence the extent of wildfire damage and preparation and mitigation activities (Palaiologou et al. 2019).

Our assessment of the WUI in the Bay Area is based on three main geospatial datasets: California WUI change data from 1990 to 2010 produced by the SILVIS Lab (Radeloff et al. 2017) at the University of Wisconsin-Madison, Fire Hazard Severity Zones (FHSZs) from CAL FIRE (2021), and the boundaries of Bay Area counties acquired from the California State Geoportal (2021). The SILVIS wildland-urban interface maps and data are created using decadal U.S. Census Bureau block-level data and wildland vegetation areas derived from the National Land Cover Database (USGS 2021). WUI areas are classified based on three main components: housing unit density, vegetation cover, and proximity to large patches of adjacent wildland vegetation (Radeloff et al. 2018; Radeloff, Mockrin, and Helmers 2018). Although the SILVIS maps are some of the most widely used for WUI assessments, the relatively coarse spatial scale of the census blocks and the decadal update interval are key limitations that are taken into account in our analysis. Based on a combination of factors such as fuel loads, the slope of the land, fire history, and blowing embers, the FHSZ layer provides identification of areas in which wildfire hazards can be more severe and thus of higher concern (CAL FIRE 2007). FHSZs are located in both State Responsibility Areas (SRAs) where the state is financially responsible for fire protection and Local Responsibility Areas (LRAs) where local jurisdictions have the responsibility to protect. Based on the levels of fire hazard, FHSZs are categorized as moderate, high, and very high. Though there are three zones, we focus primarily on areas with the greatest hazard potential as they are where communities are most at-risk of wildfires.

With the three datasets, we set out to track the overall WUI change in the Bay Area from 1990 to 2010 and determine the patterns of the WUI change in very high FHSZs. We begin by establishing a study area polygon comprising the boundaries of the San Francisco Bay Area's nine counties. We then clip the California WUI layer to our Bay Area study region. With this new Bay Area WUI layer, we classify the WUI polygons into their two subtypes – intermix and interface – for each available time scale of 1990, 2000, and 2010. Utilizing the attribute table, we calculate the total acreage of the intermix and interface regions at the three time points. Again, using the attribute table, we sum the total number of housing units within each WUI type by decade. We then calculate the percent change in each of these categories within the decadal intervals.

The next step of our analysis is to map the extent of intermix and interface located within very high FHSZs and track how this area of overlap has changed since 1990. We first clip the FHSZ layer to our study area and then isolate the polygons representing very high FHSZs for both SRAs and LRAs. Utilizing the FHSZ layer's attribute table, we calculate the total acreage of WUI areas located directly within very high FHSZs in both SRAs and LRAs from 1990 to 2010. Then, we sum the number of housing units located in this overlap. We do this analysis for the entire Bay Area by calculating the total acreage and housing units by county in order to identify which counties face the highest wildfire risk.

To identify the Bay Area counties that face the highest wildfire risk based on the social vulnerability of the residents, we use the Centers for Disease Control and Prevention Social Vulnerability Index, or simply SVI, created by the Agency for Toxic Substances and Disease Registry's Geospatial Research, Analysis, and Services Program (CDC/ATSDR 2018). Using census data, SVI ranks census tracts on 15 social factors including poverty, unemployment, lack of vehicle access, minority status, age, disability, and housing situation. These factors are further grouped into 4 related themes: Socioeconomic Factors, Household Composition and Disability, Minority Status and Language, and Housing Type and Transportation. Tract rankings are based on percentiles, the values of which range from 0 to 1, with higher values indicating greater social vulnerability. For each census tract, the CDC/ATSDR generated its percentile rank among all tracts for the fifteen individual factors and the four themes, as well as an overall ranking. Since census tracts are subdivisions of counties for which the U.S. Census Bureau collects statistical data, tract-level rankings also correspond to county-level rankings.

For our analysis, we reorganize census data for a clear depiction of the fifteen factors that make up the Social Vulnerability Index for each of the nine Bay Area counties. We match census tract-level boundaries with block-level WUI polygons from the SILVIS Lab. Then, we intersect SVI layer with 2010 WUI regions to visualize differential social vulnerability in these areas. Finally, we intersect SVI layer with 2010 WUI regions that overlap with very high FHSZs.

Results

The change of total acreage and housing units in both intermix and interface WUI in the Bay Area from 1990 to 2010 is presented in Table 1. We find that a widespread growth of both intermix and interface WUI regions has occurred from 1990 to 2010, with the exception of a 6.62 percent decrease in intermix housing units from 2000 to 2010. The total acreage of intermix area more than doubled, with a 100.24 percent increase, from 2000 to 2010. As of 2010, the intermix WUI growth amounts to a total of 1,457,682 acres, while the interface WUI has reached 700,087 acres. In terms of housing units, there are 71,754 units within the intermix WUI and 984,145 units within the interface WUI. The growth of housing settlement accordingly shows the increase in ecological damage in the expanding WUI.

Table 1. The growth of intermix and interface WUI in the Bay Area from 1990 to 2010

	Intermix				Interface			
Decade	Total Area (in 1000s Acres)	% Increase from Previous Decade	Total Housing Units (1000s)	% Increase from Previous Decade	Total Area (in 1000s Acres)	% Increase from Previous Decade	Total Housing Units (1000s)	% Increase from Previous Decade
1990	722.52		74.69		631.71		807.19	
2000	727.98	0.76	76.84	2.88	662.33	4.85	916.40	13.53
2010	1457.68	100.24	71.75	-6.62	700.09	5.70	984.15	7.39

There is an overall growth of the WUI in very high FHSZs in areas under both state and local responsibility. The two exceptions to this trend are the interface WUI within very high FHSZs in SRAs during 1990–2000 with a 0.23 percent decrease (Table 2) and the intermix WUI within very high FHSZs in LRAs during the same period with a 6.64 percent decrease (Table 3).

Table 2. The growth of intermix and interface WUI within very high Fire Hazard Severity Zones (FHSZs) in State Responsibility Areas (SRAs) from 1990 to 2010

	Intermix				Interface			
Decade	Total Area (in 1000s Acres)	% Increase from Previous Decade	Total Housing Units (1000s)	% Increase from Previous Decade	Total Area (in 1000s Acres)	% Increase from Previous Decade	Total Housing Units (1000s)	% Increase from Previous Decade
1990	90.56		14.25		8.84		14.25	
2000	91.61	1.16	15.31	7.44	8.82	-0.23	18.08	26.88
2010	110.46	20.58	16.70	9.08	8.91	1.02	18.68	3.32

Table 3. The growth of intermix and interface WUI within very high Fire Hazard Severity Zones (FHSZs) under Local Responsibility Areas (LRAs) from 1990 to 2010

	Intermix				Interface			
Decade	Total Area (in 1000s Acres)	% Increase from Previous Decade	Total Housing Units (1000s)	% Increase from Previous Decade	Total Area (in 1000s Acres)	% Increase from Previous Decade	Total Housing Units (1000s)	% Increase from Previous Decade

1990	10.69		10.45		26.92		71.84	
2000	9.98	-6.64	10.97	4.98	27.69	2.86	77.77	8.25
2010	10.39	4.11	11.65	6.20	27.83	0.51	79.69	2.47

When analyzing the data by county, we see that Sonoma, Napa, and Santa Clara counties have the most WUI acreage in SRAs and Sonoma, Contra Costa, Alameda, and Santa Clara counties have the most WUI acreage in LRAs that are directly located within very high FHSZs (Tables 4 and 5). Consequently, all these counties face high wildfire risk and ecological damage in both SRAs and LRAs. San Francisco and Solano counties have the least amount of WUI lands in both SRAs and LRAs within very high FHSZs, making them least at-risk of wildfire events and ecological damage. Additionally, Alameda County has most housing units within the interface WUI with nearly 50,000 housing units in LRAs, making it one of the most vulnerable counties in the Bay Area to wildfires and ecological damage (Table 5).

Table 4: WUI areas in Bay Area counties within very high Fire Hazard Severity Zones (FHSZs) in State Responsibility Areas (SRAs)

	Intermix		Interface			
County	**Area in Acres**	**Housing Units**	**Area in Acres**	**Housing Units**	**Total Area in Acres**	**Total Housing Units**
Alameda	878.24	690	149.20	3714	1027.44	4404
Contra Costa	1373.74	4573	679.61	3188.00	2053.35	7761
Marin	1,270.46	2295	893.46	6260	2163.92	8555
Napa	18748.45	4569	602.47	646	19350.92	5215
San Francisco	0	0	0	0	0	0
San Mateo	7978.25	2655	1147.86	5796	9126.11	8451
Santa Clara	14533.75	4379	1519.89	3589	16053.64	7968
Solano	100.075	24	0	0	100.08	24
Sonoma	23414.22	4364	566.00	1481	23980.22	5845

Table 5: WUI areas in Bay Area counties within very high Fire Hazard Severity Zones (FHSZs) in Local Responsibility Areas (LRAs)

County	Intermix		Interface		Total Area in Acres	Total Housing Units
	Area in Acres	Housing Units	Area in Acres	Housing Units		
Alameda	1736.21	1833	9160.46	48044	10896.67	49877
Contra Costa	2597.32	6872	8459.09	30730.00	11056.41	37602
Marin	298.97	2027	936.41	7199	1235.38	9226
Napa	390.86	669	212.61	428	603.47	1097
San Francisco	0	0	0	0	0	0
San Mateo	1860.98	2120	2911.16	9116	4772.14	11236
Santa Clara	2822.51	2515	5405.31	15382	8227.82	17897
Solano	0	0	0	0	0	0
Sonoma	687.7	671	740.91	3226	1428.61	3897

The intermix and interface WUI areas located within very high FHSZs are the areas where wildfire risk and ecological damage are the highest. In terms of the total WUI areas in both SRAs and LRAs that overlap with very high FHSZs, Sonoma County faces the most widespread wildfire risk and ecological damage, with 25,409 acres located directly within these zones. Santa Clara and Napa counties follow with totals of 24,281 acres and 19,954 acres, respectively. Areas of significant overlap are also found in San Mateo, Contra Costa, and Alameda counties. Although there is a significant amount of WUI area in Solano County, there are not many FHSZs that are designated as very high, which results in a very small portion of overlap (in SRAs only) in our analysis. In San Francisco County, there are no hazard zones classified as very high, so there was no area of overlap, although it may have high or moderate FHSZs that are not included in our analysis.

To see how wildfire risk is compounded by social vulnerability, we present the Social Vulnerability Index or SVI scores in Table 6 for each county. In terms of socioeconomic factors (e.g., poverty, unemployment, income, and education), Solano County has the highest SVI (0.35) and Marin County has the lowest (0). Whereas, in terms of housing type (e.g., living in multi-unit structures, mobile homes, crowded houses, and group quarters) and transportation (e.g., having access to a vehicle), Solano County has the second lowest SVI (0.25) after Contra Costa (0.11) and Alameda and San Francisco counties have the highest SVI (0.84 and 0.82, respectively). In terms of all four themes (as presented in Table 6), Solano County has the highest SVI (0.44) followed by Alameda County (0.37) and Napa County (0.33).

Table 6. Social Vulnerability Index (SVI) overview of Bay Area counties

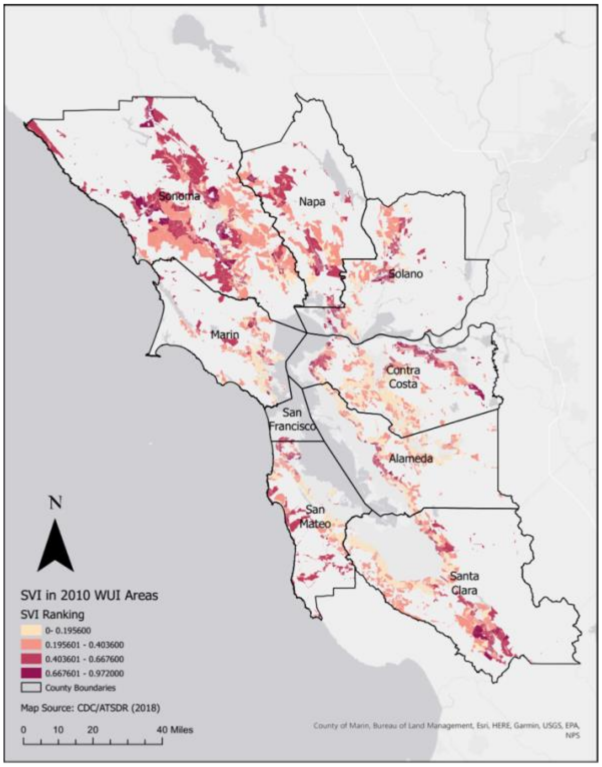
Key Themes	Indicators for SVI	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma
Socio-economic Factors	% Below Poverty	10.6	9.1	7.6	8.1	10.9	7	7.9	10.4	10.3
	Unemploy-ment Rate	5.1	6.1	3.8	5	4.7	4.1	4.8	7	5.1
	Income (per capita)	44283	45524	69275	42677	64157	57375	52451	33700	39929
	% With No High School Diploma	12	10.6	6.8	14.9	11.5	10.8	11.9	12	12
Theme SVI	On 0-1 scale	0.1754	0.1053	0	0.1579	0.1228	0.0351	0.0526	0.3509	0.2281
Household Composi-tion and Disability	Aged 65+	13.1	15	21	18	15.1	15.4	12.8	14.7	18.2
	Aged 17 or Younger	21	23.1	20.3	21.3	13.4	21.1	22.5	22.5	20.1
	Aged 5+ with Disability	9.4	11.2	8.9	11.8	10.3	8.5	7.9	12.4	12.1
	Single-Parent Households	7.1	8.1	6.2	7	3.8	5.7	6.2	10.2	7.3
Theme SVI	On 0-1 scale	0.0702	0.4211	0.1228	0.2982	0.0175	0.0877	0.0351	0.614	0.2456
Minority Status and Language	Minority (except non-Hispanic White)	68.2	55.6	26.8	47.2	59.4	60.4	68	61.5	36.5
	Aged 5+ Who Speak English “Less Than Well”	8.4	6.5	4	8.4	11.6	7.5	9	4.9	5.6
Theme SVI	On 0-1 scale	0.7544	0.5614	0.3509	0.5263	0.8246	0.5965	0.7719	0.5614	0.4386

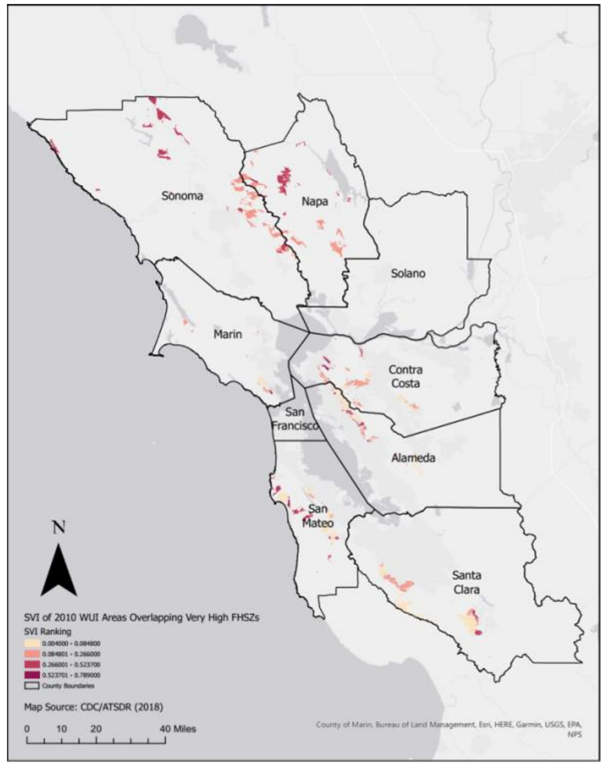
Housing Type and Transport-ation	Multi-unit Structures (% house with 10 or more units)	21.5	12.4	13.6	8.9	36.8	20.2	21.7	8.6	8.9
	% Living in Mobile Homes	1.2	1.7	1.2	6.4	0.2	1.1	2.9	2.8	4.8
	Crowding (% housing more people than rooms)	7.7	4.8	4.1	6.3	6.4	7.8	8.1	5.2	5.2
	% With a Vehicle	9.6	5.5	4.9	5	30.6	5.4	5.1	5.1	4.9
	% Living in Group Quarters	2	0.9	2.9	2.9	2.4	1.3	1.9	2.4	1.7
Theme SVI	On 0-1 scale	0.8421	0.1053	0.3333	0.6316	0.8246	0.3509	0.5789	0.2456	0.2982
Overall SVI	On 0-1 scale	0.3684	0.1754	0.0877	0.3333	0.2632	0.1228	0.2281	0.4386	0.2105

We map social vulnerability for each county, first, in the entire WUI (see Figure 1), and then, in the 2010 WUI that overlaps with very high FHSZs (see Figure 2). From these vulnerability maps, we see that except Solano and San Francisco counties, the entire Bay Area is facing high degree of wildfire risk compounded by social vulnerability, especially in the WUI that overlaps with very high FHSZs. Fortunately, Solano and San Francisco counties do not have much WUI area that overlaps with very high FHSZs (as shown in Tables 4 and 5). This small portion of overlapping area reduces their wildfire risk despite the fact that Solano County has a moderate overall SVI (0.44) and San Francisco County has a very high SVI (0.84) in two of the four themes: Minority Status and Language, and Housing Type and Transportation.

Figure 1. Social vulnerability in the 2010 Wildland-Urban Interface (WUI) in nine Bay Area counties

Figure 2. Social vulnerability in the 2010 WUI that overlaps with very high Fire Hazard Severity Zones in Bay Area counties





Discussions

Our results provide convincing evidence that significant expansion into densely vegetated fire-prone ecosystems has occurred in the Bay Area, despite the extent of ecological damage and the risk that wildfires pose to lives and homes in interface and intermix communities. In alignment with broader national and state-wide trends, our findings confirm the growth of the WUI on a more localized scale. Our mapping locates the interface and intermix communities within very high fire hazard severity zones where Bay Area residents are most vulnerable to wildfires which is compounded by their social vulnerability. Substantial expansion into wildland spaces suggests that the demographic, social and economic factors driving WUI growth remain significant and relevant in the Bay Area. For this reason, reducing wildfire risk and social vulnerability as well as ecological damage in the WUI requires appropriate spatial, social and economic planning, more importantly at the local level. While national and regional-level plans, regulations and policies guide local-level planning, local jurisdictions may need to modify and change those regulations and policies based on their enforcement capacity and local dynamics such as their diverse landscapes, fire history and fire hazard, economic opportunities in the real estate market, infrastructure and amenity development projects, and housing and other local land-use needs. Local-level policy variations are generally considered a strength but sometimes they may result in gaps and inconsistencies if they undermine risk reduction objectives and increase social vulnerability and ecological damage in the WUI (Mowery and Punchard 2021).

As wildfire problems are expected to be exacerbated by climate change, droughts, and extreme weather events in the coming years, Bay Area homeowners will be left increasingly vulnerable (Goss et al. 2020; Schoennagel et al. 2017). Our findings of overall WUI growth into very high FHSZs thus underscore the urgent need to address WUI growth, social vulnerability, and climate change by establishing social, economic, spatial and management plans and regulatory policies. We emphasize on regulatory policies as they are important to limit new housing settlements in very high FHSZs to ensure the sustainability of both human communities and forest ecosystems.

In need of immediate attention are mapping efforts, which should focus on producing updated and more accurate maps to locate social, ecological and wildfire vulnerabilities in intermix and interface communities. As the SILVIS WUI maps rely on census data, they have been limited by the decadal intervals in which the census occurs. Finalized in 2018, the maps were based on the best available data from the 2010 Census and have not yet incorporated the recently released 2020 Census data. Though they remain some of the best WUI maps available, much has changed in the past ten years in terms of population growth and increased wildfire risk. Since the 1980s, the size and intensity of wildfires in California have significantly increased. Fifteen of the 20 largest wildfires in California's history have occurred since 2000, and ten of the most destructive fires have occurred since 2015 (CAL FIRE 2020). Consequently, our analysis of Bay Area WUI patterns could not calculate changes in both housing development and wildfire occurrences after 2010. Lacking appropriate data, we also could not accurately calculate the extent of ecological damage in the WUI. However, as WUI growth is predicted to continue increasing across the state, our results still hold significant value by highlighting the need for regulation, monitoring and mitigation efforts on a more localized scale. To account for key changes from the past ten years and allow for more accurate WUI analyses in the future, the SILVIS WUI maps should be promptly updated with 2020 Census data, especially incorporating information on the fifteen social factors that make up the Social Vulnerability Index. Lacking updated mapping data, we had difficulty getting accurate information on various socioeconomic factors of residents living within WUI areas and areas overlapping FHSZs due to the varied spatial scales of the different layers. Yet, we have included an important visual of differential social and wildfire vulnerabilities in the Bay Area WUI by each county. The comprehensive table of SVI variables by county (Table 6 above) can also be used to understand the overall vulnerability of Bay Area residents living in the fire-prone WUI.

Additionally, CAL FIRE's fire hazard severity maps, last updated in 2007, consider factors such as vegetation, topography, and fire history, but do not yet account for future risk based on extreme weather events, droughts, and climate change. Moving forward, CAL FIRE must update their maps on a more frequent and consistent basis with these factors to more accurately depict fire hazard zones. We believe these updated maps will prove invaluable for future research investigating if extreme weather, drought, and climate change increase wildfire risk in the WUI.

We consider local-level mapping as the first step to investigate how the expansion of the WUI increases social vulnerability, wildfire risk, and ecological damage. Based on local dynamics, national and regional policies should be modified, reformed or enacted to effectively monitor and regulate land-use practices in the WUI. We are aware of the fact that wildfires never respect the boundaries of local jurisdictions but our hope is that more accurate and informative vulnerability maps can help better social, economic and spatial planning, wildfire preparedness, and the management of ecosystem services at the local level. Based on local-level vulnerability mapping, there can possibly be a call for social, ecological, and wildfire vulnerability mapping efforts at the global level. We believe that our analysis provides important insights that can help address similar situations facing countries in the Global South and elsewhere.

We advocate for an integrated approach to sustainable management of ecosystem services and wildfires to ensure well-being for all while protecting the environment. The sustainable development framework for ecosystem services management can offer ways to limit the expansion of the WUI and reduce wildfire risk in this space by incorporating social, economic, political and ecological dimensions of sustainability, moving beyond sectoral approaches (Díaz et al. 2015; Maes et al. 2012; Poschen 2017; Renard, Rhemtulla, and Bennett 2015; Wood et al. 2018). A sectoral approach to aggressively suppress wildfires near homes has only promoted increased intensity of wildfires in California due to fuel accumulation over time (Biswell 1989). A sectoral approach that focuses exclusively on the economic growth potential of housing development can undermine the wildfire risk in the WUI by changing the very definition of the wildland-urban interface. A recent assessment shows that over 40 percent of structures threatened by wildfire are not being included in current definitions of WUI (Kramer et al. 2018). The sectoral approach of privatization of forest lands and resources can lead to social vulnerability of certain groups such as the Indigenous and other socio-economically disadvantaged communities who reside within and near the WUI with high wildfire risk. In contrast, a sustainable development approach can boost the economy, reduce social vulnerability and wildfire risk, and help restore ecosystem services in the WUI. The integrated sustainable development framework guides our policy recommendations that we provide below.

Policy Recommendations

Our findings of persistent growth of the WUI from 1990–2010 and projections for its continued expansion suggest that slowing further development in the high fire severity zones will be a significant challenge for local authorities and surely will take time. In the meantime, we recommend Bay Area counties continue efforts to implement pre-fire mitigation strategies and wildfire preparedness measures to reduce vulnerability. The implementation of state fire codes will be essential in mitigating wildfire risk in the Bay Area. Individuals living within high fire hazard severity zones under state jurisdiction are required by California state codes to take proactive steps to protect their properties against fire risk. Homeowners are required to build structures with fire-resistant materials and create defensible spaces around homes by clearing fuels within 100 feet of their properties (California Fire Code 2016). Though these are important measures, there is often a concerning lack of follow-through on wildfire preparedness measures among homeowners, which poses great risk for extensive damage among WUI communities (Safford, Schmidt, and Carlson 2009). As inadequate fuel management poses a great danger for heightened wildfire risk, it will become increasingly important to strengthen fire codes and incentivize Bay Area homeowners to create more resilient properties. Areas that do not have a well-defined fire code should develop one and strictly implement it. Globally, however, bolstering the capacity and strength of environmental regulations on the expansion of the WUI and other significant drivers of forest fires, such as land clearing, logging, and forest conversion, would be necessary to reduce anthropogenic fire and ecological damage.

Wildfires are a natural mechanism to maintain forest ecosystems. Since increased wildfire risk is strongly tied to fire suppression as well as current land-use and fuel management techniques, we do not recommend focusing on fire suppression and fuel reduction in the WUI as key solutions to wildfire problems. Rather, we agree with Jerry Williams, the former National Director of Fire and Aviation Management, United States Forest Service, that "protecting people and sustaining natural resources can no longer rely on suppression capabilities, alone; protection will become more dependent on how we manage the forests where high-impact mega-fires incubate" (Williams 2013, cited in Adams, Shadmanroodposhti, and Neumann 2020: 3756). We recommend for the management of forest ecosystems by limiting human settlements within very high fire hazard severity zones in the WUI. Though mechanical fuel reduction and prescribed fires are common solutions to reducing fuel build-up, many forests' geographic boundaries such as areas on steep slopes and inventoried roadless areas are "off-limits" to mechanical fuel reduction and prescribed burns (Steel, Safford, and Viers 2015). Given such challenges with prescribed burning and space limitations for heavy machinery used in thinning on slopes, there should be stricter regulations on construction especially in steep slope areas of the WUI. Existing homeowners and their insurance providers must also be informed of the dangers of unregulated fire behaviors if their buildings sit atop such slopes.

For more accessible areas, we recommend for mechanical thinning over prescribed burns because prescribed burns are a source of significant carbon emissions. In contrast, mechanical thinning is labor-intensive but important for climate protection of valuable carbon sinks and wildlife in the WUI in addition to fire prevention. However, debates over whether thinning should be subsidized by the government, or funded by sales of harvested merchantable timber, may impact the extent and rate of such fuel treatments (Collins et al. 2010). Prescribed burns are also costly and usually met with resistance due to ownership issues over private, state, and federal lands (Quinn-Davidson and Varner 2011). Yet, California's current governor has recently proposed $2 billion – the largest in California history – to support wildfire suppression, improve forest health and build resilience in communities. "Investments include $48.4 million to phase in 12 new CAL FIRE HAWK helicopters and seven large air tankers; $143.3 million to support 30 additional fire crews; and an additional $708 million to restore landscape and forest health to be more resilient to wildfires" (Office of Governor 2021). Although $708 million is allocated to improve forest health and build resilience in communities, there is no allocation to address social vulnerability of residents. It is also not clear how resilient communities can be built without addressing their social vulnerability. We recommend developing proper regulations and pre-fire mitigation plans to ensure equal access to material and informational resources for all residents so they are better prepared to tackle wildfire risk.

Wildfire suppression has historically diverted federal and state funding from pre-fire mitigation strategies (Miller et al. 2020). In fiscal year 2018, the U.S. Forest Service spent more than half a billion dollars on air tankers, helicopters and other firefighting aircraft alone to suppress wildfires in California (Gabbert 2021). Such big spending to save lives and homes in high fire hazard severity zones further increases taxes in this state that already has the highest tax rates in the United States. Home insurance rates in high fire hazard severity zones have also skyrocketed in recent years. Additionally, emergency services are seriously unprepared to respond to more frequent and severe wildfires. Given this situation, some wealthy people are hiring private firefighters to protect their homes (Varian 2019). While hiring private firefighters may seem an interesting idea, this highlights the extent of social vulnerability of other communities living in the WUI who are not so affluent and cannot always expect to be saved by government firefighters. Hopefully, these experiences may discourage people from building new homes in the WUI within high fire hazard severity zones.

Consequently, one of the most direct solutions to the growing wildfire risk in the expanding WUI would be to create (dis)incentive mechanisms that would decrease further housing development within high fire hazard severity zones. Greater outreach to homeowners and further awareness building through scientifically informed knowledge regarding high fire vulnerability in the WUI can be key components of these (dis)incentive mechanisms (Hill and Kakenmaster 2018). Community-based organizations, such as California's Fire Safe Councils, can play an important role in mobilizing residents to protect their homes, communities, and local environments from catastrophic wildfires. Partnered with several organizations, including the California Department of Forestry and Fire Protection and the United States Forest Service, these councils highlight the increasingly essential cross-agency collaboration necessary to ensure effective fire management strategies. Fire Safe Councils offer valuable educational materials that include information about fire risk and how to create defensible spaces and hardened homes that are prepared for wildfires and ember storms. Many local councils have already been established across the Bay Area, especially in communities with greater wildfire risk. Similar councils, if not already existing, can be formed in other fire-prone landscapes across the globe to promote information materials, assist socially vulnerable individuals, and encourage homeowners to pursue more aggressive and consistent fuel management on their properties to mitigate wildfire risk.

Cross-agency collaboration is also necessary to maintain forest ecosystems at both local and regional levels as populations in the hazardous WUI keep increasing. In California, as in many other places, the colonial practices of fire suppression and fire exclusion have hindered cultural burning (McWethy 2019). Before these colonial practices, Indigenous communities used to manage forest ecosystems through traditional ecological knowledge aka TEK (Berkes 1993). Cultural burning is more nuanced, conducted in patch-like approaches, unlike large-scale industrial burns, and often targets and revitalizes a specific plant resource in the Indigenous community. The incorporation of TEK into overall wildfire and ecosystem services management is thus essential not only for addressing catastrophic wildfires but also for addressing social vulnerability of Indigenous communities living in fire-prone landscapes. Most of all, this is part of social responsibility to preserve philosophically and spiritually significant traditions and histories of Indigenous communities (Bedsworth et al. 2018; Goode 2013; Long et al. 2020). Indeed, Indigenous communities in many states are working to restore traditional burning practices. Suggestions for increasing their participation and TEK in wildfire management in the Bay Area include establishing and funding tribal agency and academic organization research partnerships to discuss best fire mitigation strategies. An example of this kind of research partnership is the fire ecology courses and research opportunities at the University of California Berkeley that promote student involvement in, and practically learn about, cultural burns. Another example is the annual tribal-government-to-federal-government consultation summits that the U.S. federal government and various departments regularly hold (Lake et al. 2018). Such frequent meetings have resulted in signed agreements, or memorandums of understanding (MOUs), between the U.S. Forest Service and the Karuk Tribe of Northwestern California, establishing positions and roles in wildfire and ecosystem management interactions (Lake 2011). This experience can be replicated in Europe, Australia, and countries in the Global South.

Another critical opportunity for many countries, including the United States, would be to contextualize further fire prevention and mitigation efforts as green jobs that contribute to preservation and restoration of ecosystem services (Poschen 2017). Sustainable development within the United States and around the globe has often been purported to provide an economic hindrance, leading to its widespread unpopularity despite worsening environmental crises facing the world today. Fire prevention efforts offer a glimpse into an alternative path towards securing green jobs for protecting ecological resources rather than traditional sources of green jobs in renewable energy and construction (Hess 2012). Green jobs may help the restoration and maintenance of ecosystems by planting new trees to replace trees removed or damaged during logging operations and manually clearing up dead trees and bushes in the WUI to reduce fire hazards. Green jobs may, then, turn the cleared tree parts and bushes into a source of renewable energy and various products such as paper and furniture. Revenues generated from the sale of these products can also finance fuel treatments and hardening of existing homes to make them fire resistant (UNECE 2018). However, transitioning to a green economy will require a new set of skill and investments in training. It will be important to revise existing curricula and develop new ones for catering to the needs of the green economic sector. Green jobs stand as opportunities for job growth and potentially offering ways to connect communities closer to their local ecosystems.

References

Abrams, Jesse B., Hannah Gosnell, Nicholas J. Gill, and Peter J. Klepeis. 2012. "Re-creating the rural, reconstructing nature: An international literature review of the environmental implications of amenity migration." *Conservation and Society* 10(3): 270-284. DOI: 10.4103/0972-4923.101837.

Alig, Ralph J. 2007. "A United States view on changes in land use and land values affecting sustainable forest management." *Journal of Sustainable Forestry* 24(2-3): 209-227.

Allen, Craig D., et al. 2010. "A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests." *Forest Ecology and Management* 259(4): 660-684.

Andela, Niels, and Guido R. Van Der Werf. 2014. "Recent trends in African fires driven by cropland expansion and El Niño to La Niña transition." *Nature Climate Change* 4(9): 791-795.

Balch, Jennifer K., Bethany A. Bradley, John T. Abatzoglou, R. Chelsea Nagy, Emily J. Fusco, and Adam L. Mahood. 2017. "Human-started wildfires expand the fire niche across the United States." *Proceedings of the National Academy of Sciences* 114(11): 2946-2951.

Bartlett, Jay G., D. M. Mageean, and R. J. O'Connor. 2000. "Residential expansion as a continental threat to US coastal ecosystems." *Population and Environment* 21(5): 429-468.

Bedsworth, Louise, et al. 2018. *California's Fourth Climate Change Assessment: Statewide Summary Report*. Publication number: SUM-CCCA4-2018-013. Retrieved 2 April 2021, https://www.energy.ca.gov/sites/default/files/2019-11/Statewide_Reports-SUM-CCCA4-2018-013_Statewide_Summary_Report_ADA.pdf.

Bento-Gonçalves, A., and António Vieira. 2020. "Wildfires in the wildland-urban interface: Key concepts and evaluation methodologies." *Science of the Total Environment* 707: 135592.

Bento-Gonçalves, António, António Vieira, and Luís da Vinha. 2018. "Changes in mainland Portuguese forest areas since the last decade of the XXth century." *Journal of Mediterranean Geography* 130. DOI: 10.4000/mediterranee.10025.

Berkes, Fikret. 1993. "Traditional Ecological Knowledge in Perspective." In Inglis, Julian, ed., *Traditional ecological knowledge: Concepts and cases,* 1-9. Ottawa, Canada: IDRC.

Biswell, Harold H. 1999. *Prescribed Burning in California Wildlands Vegetation Management*. California: University of California Press.

Blaikie, Piers, Terry Cannon, Ian Davis, and Ben Wisner. 2014. *At Risk: Natural Hazards, People's Vulnerability and Disasters*. New York, NY: Routledge.

Brundtland, Gro Harlem. 1987. "Our common future – Call for action." *Environmental Conservation* 14(4): 291-294.

Butler, B. 2008. "Private forest owners of the United States, 2006." General Technical Report NRS-27. Newtown, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.

CAL FIRE. 2007. "Fire hazard severity zone model: A non-technical primer." California Department of Forestry and Fire Protection and Office of the State Fire Marshal. Retrieved 10 April 2021, https://www.sccgov.org/sites/dpd/DocsForms/Documents/FIreHazardZone_NonTechnical_Primer.pdf.

CAL FIRE. 2020. "Top 20 Most Destructive California Wildfires." The California Department of Forestry and Fire Protection. Retrieved 10 April 2021, https://www.fire.ca.gov/media/t1rdhizr/top20_destruction.pdf.

CAL FIRE. 2021. "Fire Hazard Severity Zones Maps." Maps and dataset. Office of the State Fire Marshal. Retrieved 10 February 2021, https://osfm.fire.ca.gov/divisions/wildfire-planning-engineering/wildland-hazards-building-codes/fire-hazard-severity-zones-maps/.

California Fire Code. 2016. "Requirements for wildland-urban interface fire areas." Chapter 49. UpCodes. Retrieved 10 April 2021, https://up.codes/viewer/california/ca-fire-code-2016/chapter/49/requirements-for-wildland-urban-interface-fire-areas#49.

California State Geoportal. 2021. "City and county boundaries." Maps. Retrieved 1 March 2021, https://gis.data.ca.gov/datasets/35487e8c86644229bffdb5b0a4164d85_0/explore?location=37.269168%2C-119.306399%2C6.34.

Caton, Sara E., Raquel S.P. Hakes, Daniel J. Gorham, Aixi Zhou, and Michael J. Gollner. 2017. "Review of pathways for building fire spread in the wildland urban interface Part I: Exposure conditions." *Fire Technology* 53(2): 429-473.

CDC/ATSDR. 2018. Social Vulnerability Index 2018 Database, California. Centers for Disease Control and Prevention/Agency for Toxic Substances and Disease Registry/Geospatial Research, Analysis, and Services Program. Retrieved 10 May 2021, https://www.atsdr.cdc.gov/placeandhealth/svi/data_documentation_download.html.

Christmann, Gabriela B., Oliver Ibert, Heiderose Kilper, and Timothy Moss. 2012. "Vulnerability and resilience from a socio-spatial perspective: Towards a theoretical framework." *Working Paper* 45. Leibniz Institute for Research on Society and Space, Germany. Retrieved 1 May 2021, http://nbn-resolving.de/urn:nbn:de:101:1-201208174763.

Chuvieco, Emilio, Susana Martínez, María Victoria Román, Stijn Hantson, and M. Lucrecia Pettinari. 2014. "Integration of ecological and socio-economic factors to assess global vulnerability to wildfire." *Global Ecology and Biogeography* 23(2): 245-258.

Collins, Brandon M., Scott L. Stephens, Jason J. Moghaddas, and John Battles. 2010. "Challenges and approaches in planning fuel treatments across fire-excluded forested landscapes." *Journal of Forestry* 108(1): 24-31.

Collins, Timothy W. 2008a. "The political ecology of hazard vulnerability: marginalization, facilitation and the production of differential risk to urban wildfires in Arizona's White Mountains." *Journal of Political Ecology* 15(1): 21-43.

Collins, Timothy W. 2008b. "What influences hazard mitigation? Household decision making about wildfire risks in Arizona's White Mountains." *The Professional Geographer* 60(4): 508-526.

Coughlan, Michael R, Autumn Ellison, and Alexander Cavanaugh. 2019. "Social vulnerability and wildfire in the wildland-urban interface: Literature synthesis." *Ecosystem Workforce Program Working Paper* 96 (Fall). Retrieved 20 April 2021, http://nwfirescience.org/sites/default/files/publications/WP_96_0.pdf.

Czech, Brian, Paul R. Krausman, and Patrick K. Devers. "Economic associations among causes of species endangerment in the United States." *BioScience* 50(7): 593-601.

Dennis, Rona A., et al. 2005. "Fire, people and pixels: Linking social science and remote sensing to understand underlying causes and impacts of fires in Indonesia." *Human Ecology* 33(4): 465-504.

Da Silva, José Graziano, Achim Steiner, and Erik Solheim. 2018. "Forests: A natural solution to climate change, crucial for a sustainable future." UN-REDD. Retrieved 2 January 2021, https://www.un-redd.org/post/2018/10/03/Forests-A-natural-solution-to-climate-change-crucial-for-a-sustainable-future.

Davies, Ian P., Ryan D. Haugo, James C. Robertson, and Phillip S. Levin. 2018. "The unequal vulnerability of communities of color to wildfire." *PloS One* 13(11): e0205825. DOI: 10.1371/journal.pone.0205825.

Davis, James B. 1990. "The wildland-urban interface: Paradise or battleground?" *Journal of Forestry* 88(1): 26-31. DOI: 10.1093/jof/88.1.26.

Davis, Mike. 1999. *The Ecology of Fear: Los Angeles and the Imagination of Disaster*. New York: Metropolitan.

DeClerck, Fabrice A.J. et al. 2016. "Agricultural ecosystems and their services: The vanguard of sustainability?" *Current Opinion in Environmental Sustainability* 23: 92-99.

Díaz, Sandra, et al. 2015. "The IPBES conceptual framework – Connecting nature and people." *Current Opinion in Environmental Sustainability* 14: 1-16.

Doerr, Stefan H., and Cristina Santín. 2016. "Global trends in wildfire and its impacts: Perceptions versus realities in a changing world." *Philosophical Transactions of the Royal Society B: Biological Sciences* 371(1696): 20150345. DOI: 10.1098/rstb.2015.0345.

Fixler, Kevin. 2018. "Marin County landlord charged with price gouging as prosecutors scour for cases after wildfires." *North Bay Business Journal*. Santa Rosa. Retrieved 2 April 2021, https://www.northbaybusinessjournal.com/article/industry-news/marin-county-landlord-charged-with-price-gouging-as-prosecutors-scour-for-c/.

Flannigan, Mike, Alan S. Cantin, William J. De Groot, Mike Wotton, Alison Newbery, and Lynn M. Gowman. 2013. "Global wildland fire season severity in the 21st century." *Forest Ecology and Management* 294: 54-61.

Fulton, William. 1995. "Burn, California, burn." *Planning* 61(6): 4-9.

Gabbert, Bill. 2021. "A 9-year USFS aerial firefighting study left many questions unanswered." *Wildfire Today*, 16 April. Retrieved 20 April 2021, https://wildfiretoday.com/2021/04/16/a-9-year-usfs-aerial-firefighting-study-left-many-questions-unanswered/.

Gan, Jianbang, Adam Jarrett, and Cassandra Johnson Gaither. 2015. "Landowner response to wildfire risk: Adaptation, mitigation or doing nothing." *Journal of Environmental Management* 159: 186-191.

Geist, Helmut J., and Eric F. Lambin. 2002. "Proximate causes and underlying driving forces of tropical deforestation." *BioScience* 52(2): 143-150.

Glickman, Dan, and Bruce Babbitt. 2001. "Urban wildland interface communities within the vicinity of federal lands that are at high risk from wildfire." *Federal Register* 66(3): 751-777.

Gonzalez-Mathiesen, Constanza, Simone Ruane, and Alan March. 2021. "Integrating wildfire risk management and spatial planning–A historical review of two Australian planning systems." *International Journal of Disaster Risk Reduction* 53: 101984.

Goode, Ron W. 2013. *Burning Down to the Village*. Clovis, CA: Eagle Eye Enterprises, Inc.

Goss, Michael, Daniel L. Swain, John T. Abatzoglou, Ali Sarhadi, Crystal A. Kolden, A. Park Williams, and Noah S. Diffenbaugh. 2020. "Climate change is increasing the likelihood of extreme autumn wildfire conditions across California." *Environmental Research Letters* 15(9): 094016.

Hammer, Roger B., Susan I. Stewart, Richelle L. Winkler, Volker C. Radeloff, and Paul R. Voss. 2004. "Characterizing dynamic spatial and temporal residential density patterns from

1940–1990 across the North Central United States." *Landscape and Urban Planning* 69(2-3): 183-199.

Hanberry, Brice B. 2020. "Reclassifying the wildland-urban interface using fire occurrences for the United States." *Land* 9(7): 225. DOI: 10.3390/land9070225.

Hardin, Garrett. 1968. "The tragedy of the commons." *Science* 162: 1243-1248.

Hess, David J. 2012. *Good Green Jobs in a Global Economy: Making and Keeping New Industries in the United States.* Cambridge, Mass.: The MIT Press.

Hill, Alice, and William Kakenmaster. 2018. "'A new normal': California's increasing wildfire risk and what to do about it." Hoover Institution, 24 May. Retrieved 20 April 2021, https://www.hoover.org/research/new-normal-californias-increasing-wildfire-risk-and-what-do-about-it.

Job Corps. 2018. "Green jobs: Integrating career technical training into the 'green' economy." U.S. Department of Agriculture, Forest Service, National Job Corps Office, and the Conservation Education Program. Retrieved 23 April 2021, https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5212120.pdf.

Keane, Robert E., Lisa M. Holsinger, Russell A. Parsons, and Kathy Gray. 2008. "Climate change effects on historical range and variability of two large landscapes in western Montana, USA." *Forest Ecology and Management* 254(3): 375-389.

Kramer, Heather Anu, Miranda H. Mockrin, Patricia M. Alexandre, and Volker C. Radeloff. 2019. "High wildfire damage in interface communities in California." *International Journal of Wildland Fire* 28(9): 641-650.

Kramer, Heather Anu, Miranda H. Mockrin, Patricia M. Alexandre, Susan I. Stewart, and Volker C. Radeloff. 2018. "Where wildfires destroy buildings in the US relative to the wildland-urban interface and national fire outreach programs." *International Journal of Wildland Fire* 27(5): 329-341.

Lake, Frank K. 2011. "Working with American Indian tribes on wildland fires: Protecting cultural heritage sites in northwestern California." *Fire Management Today* 71(3): 14-21.

Lake, Frank K., John Parrotta, Christian P. Giardina, Iain Davidson-Hunt, and Yadav Uprety. 2018. "Integration of traditional and Western knowledge in forest landscape restoration." In Mansourian, Stephanie, and John Parrotta, eds., *Forest Landscape Restoration: Integrated Approaches to Support Effective Implementation*, 198-226. New York, NY: Routledge.

LeVert, Mike, Charles S. Colgan, and Charles Lawton. 2007. "Are the economics of a sustainable Maine forest sustainable?" *Maine Policy Review* 16(2): 26-36.

Long, Jonathan W., Frank K. Lake, Ron W. Goode, and Benrita Mae Burnette. 2020. "How traditional tribal perspectives influence ecosystem restoration." *Ecopsychology* 12(2): 71-82.

Lovejoy, Thomas E., and Carlos Nobre. 2018. "Amazon Tipping Point." *Science Advances* 4(2): eaat2340. DOI: 10.1126/sciadv.aat2340.

Macie, Edward A. and L. Annie Hermansen, eds. 2002. "Human influences on forest ecosystems: The southern wildland-urban interface assessment." General Technical Report SRS55. Asheville, North Carolina: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Maes, J., M.L. Paracchini, G. Zulian, M.B. Dunbar, and R. Alkemade. 2012. "Synergies and trade-offs between ecosystem service supply, biodiversity, and habitat conservation status in Europe." *Biological Conservation* 155: 1-12.

Marlon, Jennifer R., Patrick J. Bartlein, Christopher Carcaillet, Daniel G. Gavin, Sandy P. Harrison, Philip E. Higuera, Fortunat Joos, M.J. Power, and I.C. Prentice. 2008. "Climate and human influences on global biomass burning over the past two millennia." *Nature Geoscience* 1(10): 697-702.

Matthews, Glenda. 2003. *Silicon Valley, Women, and the California Dream: Gender, Class, and Opportunity in the Twentieth Century*. Stanford, California: Stanford University Press.

McKinney, Michael L. 2002. "Urbanization, biodiversity, and conservation." *Bioscience* 52(10): 883-890.

McWethy, David B., et al. 2019. "Rethinking resilience to wildfire." *Nature Sustainability* 2(9): 797-804.

Miller, Rebecca K., Christopher B. Field, and Katharine J. Mach. 2020. "Barriers and enablers for prescribed burns for wildfire management in California." *Nature Sustainability* 3(2): 101-109.

Mockrin, Miranda H., Susan I. Stewart, Volker C. Radeloff, Roger B. Hammer, and Kenneth M. Johnson. 2013. "Spatial and temporal residential density patterns from 1940 to 2000 in and around the Northern Forest of the northeastern United States." *Population and Environment* 34(3): 400-419.

Mooney, Harold, and Erika Zavaleta. 2019. *Ecosystems of California*. California: University of California Press.

Mowery, Molly B., and Darrin Punchard. 2021. "Land use planning approaches in the wildland-urban interface. An analysis of four western states: California, Colorado, Montana, and Washington. Community Wildfire Planning Center. Retrieved 12 June 2021, https://www.communitywildfire.org/wp-content/uploads/2021/02/CWPC_Land-Use-WUI-Report_Final_2021.pdf.

Nobre, Carlos Afonso, and Laura De Simone Borma. 2009. "'Tipping Points' for the Amazon Forest." *Current Opinion in Environmental Sustainability* 1(1): 28-36.

Office of Governor. 2020. "California, U.S. Forest Service establish shared long-term strategy to manage forests and rangelands." 13 August. Retrieved 7 June 2021, https://www.gov.ca.gov/2020/08/13/california-u-s-forest-service-establish-shared-long-term-strategy-to-manage-forests-and-rangelands/.

Office of Governor. 2021. "At McClellan Air Force Base, Governor Newsom Highlights New Firefighting Aircraft, $2 Billion in Wildfire and Emergency Preparedness Investments." 24 May. Retrieved 15 June 2021, https://www.gov.ca.gov/2021/05/24/at-mcclellan-air-force-base-governor-newsom-highlights-new-firefighting-aircraft-2-billion-in-wildfire-and-emergency-preparedness-investments/.

Palaiologou, Palaiologos, Alan A. Ager, Max Nielsen-Pincus, Cody R. Evers, and Michelle A. Day. 2019. "Social vulnerability to large wildfires in the western USA." *Landscape and Urban Planning* 189: 99-116. DOI: 10.1016/j.landurbplan.2019.04.006.

Poschen, Peter. 2017. *Decent Work, Green Jobs and the Sustainable Economy: Solutions for Climate Change and Sustainable Development*. New York, NY: Routledge.

Quinn-Davidson, Lenya N., and J. Morgan Varner. 2012. "Impediments to prescribed fire across agency, landscape and manager: An example from northern California." *International Journal of Wildland Fire* 21(3): 210-218.

Quinton, Sophie, and Alex Brown. 2020. "California may need more fire to fix its wildfire problem." *Stateline*, 18 September. Retrieved 20 April 2021, https://www.pewtrusts.org/en/research-and-analysis/blogs/stateline/2020/09/18/california-may-need-more-fire-to-fix-its-wildfire-problem.

Radeloff, Volker C., et al. 2017. The 1990–2010 wildland-urban interface of the conterminous United States – Geospatial data. 2nd Edition. Fort Collins, CO: Forest Service Research Data Archive. DOI: 10.2737/RDS-2015-0012-2.

Radeloff, Volker C., et al. 2018. "Rapid growth of the US wildland-urban interface raises wildfire risk." *Proceedings of the National Academy of Sciences* 115(13): 3314-19. DOI:10.1073/pnas.1718850115.

Radeloff, Volker C., Miranda H. Mockrin, and David P. Helmers. 2018. "Mapping change in the wildland-urban interface (WUI) 1990–2010. State summary statistics." Retrieved 10 April 2021, http://silvis.forest.wisc.edu/GeoData/WUI_cp12/WUI_change_1990_2010_State_Stats_Report.pdf.

Radeloff, Volker C., et al. 2005. "The wildland-urban interface in the United States." *Ecological Applications* 15(3): 799-805.

Renard, Delphine, Jeanine M. Rhemtulla, and Elena M. Bennett. 2015. "Historical dynamics in ecosystem service bundles." *Proceedings of the National Academy of Sciences* 112(43): 13411-13416.

Safford, Hugh D., David A. Schmidt, and Chris H. Carlson. 2009. "Effects of fuel treatments on fire severity in an area of wildland-urban interface, Angora Fire, Lake Tahoe Basin, California." *Forest Ecology and Management* 258(5): 773-787.

Sagala, Saut, Efraim Sitinjak, and Dodon Yamin. 2015. “Fostering community participation to wildfire: Experiences from Indonesia.” In John F. Shroder and Douglas Paton, eds., *Wildfire Hazards, Risks and Disasters,* 123-144. Elsevier.

Schoennagel, Tania, et al. 2017. “Adapt to more wildfire in western North American forests as climate changes.” *Proceedings of the National Academy of Sciences* 114 (18): 4582–90. DOI: 10.1073/pnas.1617464114.

Sheyner, Gennady. 2020. “Bay Area’s new growth plan eyes massive housing influx in Silicon Valley.” *Palo Alto Weekly,* 22 October. Retrieved 20 April 2021, https://paloaltoonline.com/news/2020/10/22/bay-areas-new-growth-plan-eyes-massive-housing-influx-in-silicon-valley.

Skulska, I., I. Duarte, F. C. Rego, and C. Montiel-Molina. 2020. “Relationships Between Wildfires, Management Modalities of Community Areas, and Ownership Types in Pine Forests of Mainland Portugal.” *Small-scale Forestry* 19: 231-251.

Smail, Robert A. and David J. Lewis. 2009. “Forest land conversion, ecosystem services, and economic issues for policy: A review.” General Technical Report PNW-GTR-797. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Smith, W. Brad, Patrick D. Miles, John S. Vissage, Scott A. Pugh. 2004. “Forest resources of the United States, 2002.” General Technical Report NC-241. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station.

Stec, Anna A., and T. Richard Hull. 2011. “Assessment of the fire toxicity of building insulation materials.” *Energy and Buildings* 43(2-3): 498-506.

Steel, Zachary L., Hugh D. Safford, and Joshua H. Viers. 2015. “The fire frequency-severity relationship and the legacy of fire suppression in California forests.” *Ecosphere* 6(1): 1-23.

Steffen, Will, et al. 2015. “Planetary boundaries: Guiding human development on a changing planet.” *Science* 347(6223). DOI: 10.1126/science.1259 855.

Stein, Susan M., Ronald E. McRoberts, Lisa G. Mahal, Mary A. Carr, Ralph J. Alig, Sara J. Comas, David M. Theobald, and Amanda Cundiff. 2009. “Private forests, public benefits: Increased housing density and other pressures on private forest contributions.” General Technical Report PNW-GTR-795. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Stein, Susan M., Ronald E. McRoberts, Ralph J. Alig, Mark D. Nelson, David M. Theobald, Mike Eley, Mike Dechter, and Mary A. Carr. 2005. “Forests on the edge: Housing development on America’s private forests.” General Technical Report PNW-GTR-636. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Syphard, Alexandra D., Jon E. Keeley, Avi Bar Massada, Teresa J. Brennan, and Volker C. Radeloff. 2012. “Housing arrangement and location determine the likelihood of housing loss due to wildfire.” *PloS One* 7(3): 1-13.

Syphard, Alexandra D., Jon E. Keeley, Anne H. Pfaff, and Ken Ferschweiler. 2017. “Human presence diminishes the importance of climate in driving fire activity across the United States.” *Proceedings of the National Academy of Sciences* 114(52): 13750-13755.

Syphard, Alexandra D., Avi Bar Massada, Van Butsic, and Jon E. Keeley. 2013. “Land use planning and wildfire: Development policies influence future probability of housing loss.” *PloS One* 8(8): e71708.

Syphard, Alexandra D., Volker C. Radeloff, Todd J. Hawbaker, and Susan I. Stewart. 2009. “Conservation threats due to human-caused increases in fire frequency in Mediterranean-climate ecosystems.” *Conservation Biology* 23(3): 758-769.

Syphard, Alexandra D., Volker C. Radeloff, Jon E. Keeley, Todd J. Hawbaker, Murray K. Clayton, Susan I. Stewart, and Roger B. Hammer. 2007. “Human Influence on California Fire Regimes.” *Ecological Applications* 17(5): 1388-1402. DOI: 10.1890/06-1128.1.

Syphard, Alexandra D., Heather Rustigian-Romsos, Michael Mann, Erin Conlisk, Max A. Moritz, and David Ackerly. 2019. “The relative influence of climate and housing development on current and projected future fire patterns and structure loss across three California landscapes.” *Global Environmental Change* 56: 41-55.

Theobald, David M., James R. Miller, and N. Thompson Hobbs. 1997. “Estimating the cumulative effects of development on wildlife habitat.” *Landscape and Urban Planning* 39(1): 25-36.

Theobald, David M., and William H. Romme. 2007. “Expansion of the US wildland-urban interface.” *Landscape and Urban Planning* 83(4): 340-354.

UNECE. 2018. “Green jobs in the forest sector.” *Geneva Timber and Forest Discussion Paper* 71. United Nations Economic Commission for Europe and Food and Agriculture Organization. Retrieved 20 April 2021, https://unece.org/DAM/timber/publications/DP71_WEB.pdf.

United States Census Bureau. 2020. “Census 2020. Quick facts: California.” Retrieved 20 April 2021, https://www.census.gov/quickfacts/fact/table/CA/PST045219.

USGS. 2021. “National Land Cover Database.” United States Geological Service, Department of Interior. Retrieved 10 February 2021, https://www.usgs.gov/centers/eros/science/national-land-cover-database?qt-science_center_objects=0#qt-science_center_objects.

Varian, Ethan. 2019. "While California fires rage, the rich hire private firefighters." *The New York Times*, 26 October. Retrieved 20 April 2021, https://www.nytimes.com/2019/10/26/style/private-firefighters-california.html.

Viana, Virgilio. 2020. "Health climate justice and deforestation in the Amazon." In Wael K. Al-Delaimy, Veerabhadran Ramanathan, and Marcelo Sánchez Sorondo, eds., *Health of People, Health of Planet and Our Responsibility: Climate Change, Air Pollution and Health*, 165-174. Cham, Switzerland: Springer Open.

Wigtil, Gabriel, Roger B. Hammer, Jeffrey D. Kline, Miranda H. Mockrin, Susan I. Stewart, Daniel Roper, and Volker C. Radeloff. 2016. "Places where wildfire potential and social vulnerability coincide in the coterminous United States." *International Journal of Wildland Fire* 25(8): 896-908.

Williams, Jerry. 2013. "Exploring the onset of high-impact mega-fires through a forest land management prism." *Forest Ecology and Management* 294: 4-10. DOI: 10.1016/j.foreco.2012.06.030.

Wood, Sylvia L.R., et al. 2018. "Distilling the role of ecosystem services in the Sustainable Development Goals." *Ecosystem Services* 29: 70-82. DOI: 10.1016/j.ecoser.2017.10.010.

WWF. 2020. *Living Planet Report 2020 – Bending the Curve of Biodiversity Loss*. Almond, R.E.A., M. Grooten, and T. Petersen, eds. Gland, Switzerland: World Wildlife Fund.