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Social Vulnerability, Wildfire Risk, and Ecological Concerns Over the American Wildland-Urban Interface in the San Francisco Bay Area: A Sustainable Development Perspective

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Abstract

Building more homes and amenities in the wildland-urban interface (WUI) is not a sustainable practice as it is associated with a greater risk of wildfire, social vulnerability, and ecological damage. Yet, the issue of whether or how to regulate the expansion of the WUI remains contentious and largely unresolved in understanding sustainable development. There are fewer studies that explore how wildfire risks are 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 vulnerability, ecological damage, and wildfire risk in the WUI fire hazard zones of the highest severity type. Utilizing GIS mapping, wildfire risk, and census data on social vulnerability, our analysis reveals patterns of the WUI expansion in the San Francisco Bay Area from 1990 to 2010 and provides policy recommendations from a sustainable development perspective to address social vulnerability, wildfire risk, and ecological concerns over the WUI.

Keywords

wildland-urban interface (WUI) – wildfire risk – social vulnerability – climate change – ecosystem services – sustainable development – United States

Introduction

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 (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 (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, 2018a; Syphard et al. 2007, 2009, 2012, 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 and affordability, race, disability, and age that often confer or limit access to financial, material, and informational resources needed to prepare for and cope with a natural hazard (Coughlan et al. 2019; Palaiologou et al. 2019). At the same time, the expansion of the WUI threatens wildlife and the sustainability of forest ecosystems (Bartlett et al. 2000; Mooney and Zavaleta 2019). Regulating the WUI expansion is, therefore, quintessentially important to reduce wildfire risk, social vulnerability, and ecological concerns over the 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 how to regulate the expansion of the WUI remains contentious and largely unresolved (Bento-Gonçalves and Vieira 2020; Hardin 1968; Syphard et al. 2013). At the national and regional levels, 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 monitor or 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 and regulatory mechanisms (Gonzalez-Mathiesen et al. 2021; Radeloff et al. 2018a; Schoennagel et al. 2017; Syphard et al. 2013, 2017). 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 regulate the expansion of the WUI and "comprehensively measure vulnerability or apply vulnerability frameworks across different scales and geographies" to assess wildfire risk of different communities in the WUI (Coughlan et al. 2019: 2). To fill these gaps, our analysis outlines the preliminary steps to identify which communities are most socially vulnerable and at-risk of wildfires and where to target resources and investments for long-term community resilience and ecological protection in the fire prone WUI.

We argue that regulatory policies or institutional mechanisms play a key role in strengthening the three pillars of sustainable development – economic, social, and environmental – as explained in the framework developed by the United Nations Division for Sustainable Development (2001). Policies focused primarily on economic development by allowing, for example, the expansion of the WUI for new amenity development and housing settlement projects at the cost of increasing social vulnerability, wildfire risk, and ecological damage undermine the prospects for sustainable development. In the context of this study, we define sustainable development as the development perspective important for recognizing locally contextualized understanding of natural resources development that make housing more affordable and vital ecosystem services equally accessible to all. 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).

As our study site, we choose the San Francisco Bay Area's rapidly changing WUI, where housing developments adjoin or are directly located within wildland vegetation. We explore wildfire risks 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 vulnerabilities, ecological damage, and wildfire risks within very high fire hazard severity zones. Although we aim to explore local dynamics, we believe that our analysis provides important insights about the potential strategies to locate and address social vulnerabilities, wildfire risks, and ecological damage in the WUI at regional and national levels. We provide policy recommendations from a sustainable development perspective that may also apply to similar situations in countries of the Global South or elsewhere.

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

Studies find that a significant portion of new housing 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 et al. 2000; Hammer et al. 2004; Mockrin et al. 2013; Radeloff et al. 2005). Housing development in the vicinity of wildland attracts people of specific lifestyles and economic classes, limiting others' access to those natural amenities and ecosystem services (Abrams et al. 2012). 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 km² to 770,000 km², a 33 percent increase). In California, the total WUI area grew 19.5 percent from 22,618 km² in 1990 to 27,026 km² in 2010, with 1.1 million new homes being built in the WUI, a 33.8 percent increase (Radeloff et al. 2018a). 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 km² 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. To meet the increasing demand for housing, the California Department of Housing and Community Development has recently assigned 441,176 new housing units to the Bay Area for the 2023–2031 cycle of the Regional Housing Needs Allocation (Sheyner 2020). This is good news, but if there are no allocations for affordable housing and no regulations on building new housing units in the fire prone WUI, we anticipate that local authorities will have to deal with further widening social inequality and more damaging wildfire events in the coming years.

Wildfire Risk in the Wildland-Urban Interface

Nearly 75 percent of buildings destroyed by wildfires in California are 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. 2018a; Theobald and Romme 2007). Human activities in the WUI, such as campfires, fireworks, prescribed burns or crop fires, burning debris, and acts of arson, were responsible for 84 percent of all wildfires and 44 percent of total area burned in the United States between 1992 to 2012 (Balch et al. 2017). 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. At the same time, firefighting has become extremely difficult within WUI communities because of high housing density and the rapid spread of wind-blown embers, leading to a high rate of human fatalities and property destruction (Davis 1990; Hill and Kakenmaster 2018; Radeloff et al. 2018a).

A greater likelihood of ignitions from human activity coupled with artificial fuels from combustible building materials results in more frequent and destructive fires in the WUI (Stec and Hull 2011). 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 over time, 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 occurred 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.

Social Vulnerability and Wildfire Risk in the Wildland-Urban Interface

Increasing private ownership of wildland 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 in some cases private landowners are key stewards of forests, they are often under pressure to sell their land for real estate development and other usage as the costs for maintaining the forestland 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 et al. 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 et al. 2015).

Landowners are not the only people who live in the WUI. There are others who work, commute from, or reside within and near fire hazard zones in the WUI. 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).

Thus, 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 et al. 2019: 6). For example, nearly 34 million people in the Amazon basin were exposed to dangerous air pollution from forest fires in recent years, but over 380 Indigenous groups suffered 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 et al. 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 wildfires (Collins 2008b).

Sustainable Development and Ecological Concerns Over the Wildland-Urban Interface

As homes and associated infrastructures are increasingly being built within forests and shrublands, they cause the loss and fragmentation of habitat essential for sustaining wildlife and biodiversity (McKinney 2002; Theobald et al. 1997). According to an estimate, urbanization is responsible for more than half of all federally listed threatened and endangered species in the U.S. (Czech et al. 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.

Forest ecosystems are crucial for a sustainable future and offer a natural solution to climate change due to "their unparalleled capacity to absorb and store carbon" (Da Silva et al. 2018). 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 risks 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 change in the WUI to limit our ecological footprint and ensure sustainable development.

However, 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. Most people, including many policymakers and politicians, cannot see the bigger picture, the connection between local ecosystem destruction and climate change at the planetary level. Another challenge is that we lack appropriate data on the extent of ecological damage in the WUI. Given this limitation, our analysis also uses only the proportion of housing density to vegetation cover in proximity to large patches of wildland as an indicator of ecological damage. We describe our materials and methods in detail in the next section.

Materials and Methods

In this study, we use 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 activities and land use affect 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. From a geo-spatial 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 of land. 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. 2018a).

Our assessment of the WUI in the Bay Area is based on three main geospatial datasets: (1) California WUI change data from 1990 to 2010 produced by the SILVIS Lab (Radeloff et al. 2017) at the University of Wisconsin-Madison, (2) Fire Hazard Severity Zones (FHSZS) from CAL FIRE (2021), and (3) 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. 2018a; Radeloff et al. 2018b). We measure WUI expansion as a change in interface and intermix acreages and ecological damage as a proportion of total acreage and housing units located in the WUI.

Fire hazards refer 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). Based on a combination of factors such as fuel loads, the slope of the land, fire history, and blowing embers, the fire hazard severity zone 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 to identify which counties face the highest wildfire risk.

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 et al. 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). To identify the Bay Area counties that face the highest wildfire risk based on social vulnerabilities of the residents, we use the Centers for Disease Control and Prevention (CDC) Social Vulnerability Index (SVI), created by the Agency for Toxic Substances and Disease Registry's Geospatial Research, Analysis, and Services Program (CDC/ATSDR 2018). Using census data, the 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. 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 vulnerabilities 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 occurred from 1990 to 2010, except for 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 amounted to a total of 1,457,682 acres, while the interface WUI reached 700,087 acres. In terms of housing units, there were 71,754 units within the

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

Decade	Intermix				Interface			
	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

intermix WUI and 984,145 units within the interface WUI. The growth of housing settlements proportionately shows the increase in ecological damage in the expanding WUI.

There was an overall growth of the WUI in very high FHSZs in areas under both state and local responsibility. The two exceptions to this trend were 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).

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).

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

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

Decade	**Intermix**				**Interface**			
	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

Decade	**Intermix**				**Interface**			
	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

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

County	Intermix		Interface		Total Area in Acres	Total Housing Units
	Area in Acres	Housing Units	Area in Acres	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

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

TABLE 6 Social Vulnerability Index (SVI) overview of Bay Area counties (*cont.*)

Key Themes	Indicators for SVI	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma
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 (% hous-ing 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

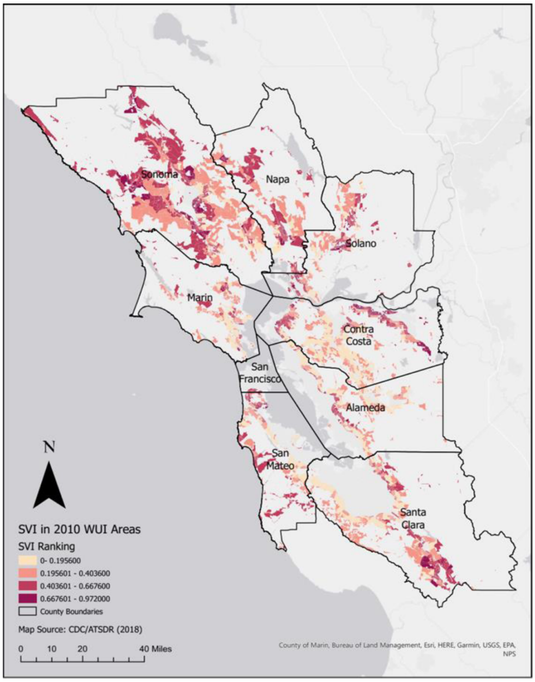

FIGURE 1 Map showing the extent of social vulnerability in the 2010 Wildland-Urban Interface (WUI) in nine Bay Area counties

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).

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 even though 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.

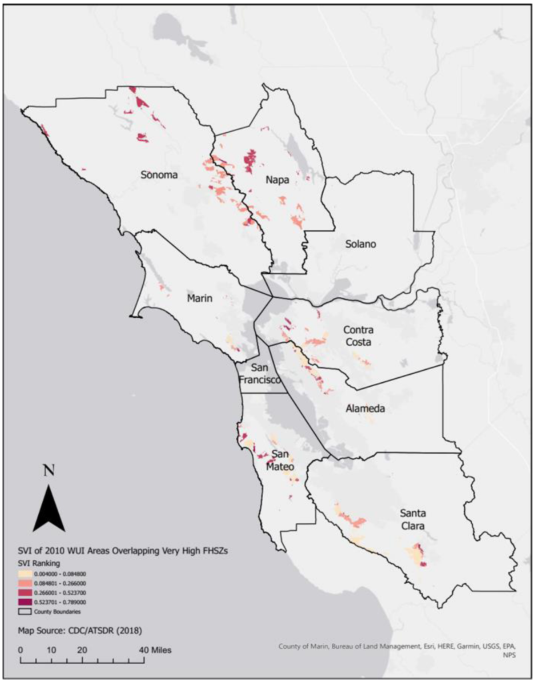

FIGURE 2 Map showing social vulnerability in the 2010 WUI that overlaps with very high Fire Hazard Severity Zones in nine counties

Discussions

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 FHSZs where Bay Area residents are most vulnerable to wildfires, which is compounded by their social vulnerability. Substantial expansion into wildland spaces threatens sustainable development in the Bay Area. For this reason, reducing wildfire risk, social vulnerability and ecological concerns over the WUI requires appropriate spatial, social, and economic planning, especially 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, the social conditions of at-risk communities, 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 we should also note that 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).

We consider local-level mapping as the first step to investigate how the expansion of the WUI increases wildfire risk, social vulnerability, and ecological damage. We believe that 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 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 our analysis provides important insights that can help address similar situations facing countries in the Global South and elsewhere.

Our analysis, however, has some caveats. First, we used SILVIS WUI maps that rely on census data. As a result, the maps 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, housing settlements, the expansion of the WUI, and 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. Second, lacking updated mapping data, we had difficulty getting accurate information on various socioeconomic factors for residents living within the WUI and areas overlapping very high FHSZs due to the varied spatial scales of different layers. Yet, we have included an important visual of differential social and wildfire vulnerabilities in the Bay Area WUI by each county. In addition, the comprehensive table of SVI variables by county (Table 6 above) can be used to understand the overall social vulnerability of Bay Area residents living in the WUI.

Another caveat is that 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 risks 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 depict fire hazard zones more accurately. 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.

As wildfire problems are expected to be exacerbated by climate change, droughts, and extreme weather events in the coming years (Goss et al. 2020; Schoennagel et al. 2017), we believe that Bay Area residents will be left increasingly vulnerable. We advocate for an integrated approach to the sustainable management of wildfires, ecosystem services, and social vulnerability to ensure well-being for all while protecting the environment. The sustainable development framework 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 et al. 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 years. 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). Moreover, the sectoral approach of privatization of forestlands and resources can increase 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 risks. In contrast, a sustainable development approach can boost the economy, reduce social vulnerability and wildfire risk, and help restore ecosystem services in the WUI. This sustainable development framework guides our policy recommendations that we present below.

Policy Recommendations

From a sustainable development perspective, we need to acknowledge that wildfires are natural mechanisms to maintain forest ecosystems. Since increased wildfire risks are strongly tied to fire suppression as well as current land-use and fuel management techniques, we do not think these are sustainable solutions to wildfire problems. Instead, we recommend for the sustainable management of forest ecosystems by regulating amenity migration and human settlements and addressing social vulnerability 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 et al. 2015). Given such challenges with prescribed burning and space limitations for heavy machinery used in thinning on slopes, there should be stricter regulations on any new 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. Consequently, creating (dis)incentive mechanisms would discourage further housing development within high fire hazard severity zones and encourage existing homeowners to make their homes fire safe as far as possible. Greater outreach to homeowners and further awareness building through scientifically informed knowledge can be key components of these (dis)incentive mechanisms (Hill and Kakenmaster 2018).

Local authorities must identify the groups of people who are socially vulnerable to wildfire hazards. They must enhance these groups' ability to adapt to changing wildfire risks. We recommend developing and updating proper social vulnerability maps to identify vulnerable groups and implement regulations and pre-fire mitigation plans to ensure equal access to financial, material, and informational resources for all residents, so they are better prepared against wildfires.

One of the socially vulnerable groups is the Indigenous communities who used to maintain forest ecosystems more sustainably using traditional ecological knowledge (TEK) and cultural burning practices (Berkes 1993). In California, as in many other places, the colonial practices of fire suppression and fire exclusion have hindered their cultural burning (McWethy 2019). 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 hazardous 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 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). These examples can be replicated elsewhere with similar situations for encouraging the sustainable management of ecosystems, social vulnerabilities, and wildfire risks.

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 the preservation and restoration of ecosystem services and creating training and income opportunities to people who are socially vulnerable (Poschen 2017). Sustainable development within the U.S. 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. 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 or amenity construction 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). 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. This, green jobs stand as opportunities for job growth and potentially offering ways to connect communities closer to their local ecosystems.

Our findings of persistent growth of the WUI from 1990–2010 and projections for its continued expansion suggest that slowing further housing and amenity development in the high fire severity zones will be a significant challenge for local authorities. But policies and decisions must be made sooner than later as wildfires are getting more destructive, frequent, and out of control. From glaring examples and experiences related to the danger of living in the fire prone WUI, we must realize that a balance must be established between the economy, the environment, and society if we want to cope with climate change and live in harmony with nature and one another.

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