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The hazards-of-place model of vulnerability to environmental hazards posits that vulnerability has biophysical and social components. While biophysical characteristics are important in predicting locations of elevated wildfire risk, the social characteristics of human communities may help us predict locations of elevated wildfire impacts. We examine the relationship between biophysical and social vulnerability to identify places that may experience impacts from wildfire hazards more acutely. We examine whether a singular focus on either biophysical or social vulnerability will accurately represent vulnerable places and predict that areas of high wildfire do not coincide with all areas of high social vulnerability. We develop a neighborhood-level social vulnerability index using principal component analysis and intersect it with an existing measure of wildfire risk to compare areas by place vulnerability to wildfire hazards. These results were mapped and further compared by wildland-urban interface categories. We find that few areas of high wildfire risk intersect with areas of high social vulnerability, but that stronger associations exist in some portions of the coterminous US. This analysis identifies regions and states with elevated levels of place vulnerability to wildfire

hazards, places that would have otherwise have been under identified in analyses that focused on either biophysical or social vulnerability alone. These results can help inform wildfire prevention, mitigation, and recovery planning processes, ultimately decreasing the hazards associated with wildfire for vulnerable places.

Where wildfire risk and social vulnerability coincide: mapping place vulnerability to wildfire over the coterminous US

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I understand that my essay will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my essay to any reader upon request.

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1. Introduction

Wildfire researchers increasingly are examining social issues involving wildfire risk, vulnerability, and management (Cortner and Field 2007; McCaffrey *et al*. 2013), to address persistent economic, structural, and human life losses from wildfires and rising wildfire management costs (Gall *et al*. 2011; Bracmort 2014; Hoover and Bracmort 2015). Although measures of biophysical characteristics, such as climate, vegetation, and topography are all essential in predicting when and where wildfires might occur, understanding when and where wildfires might result in hazardous conditions, impact people and places, and damage valued assets and resources is also critical for wildfire management (Dondo Bühler *et al*. 2013; Hawbaker *et al*. 2013; Chuvieco *et al*. 2014). Social conditions, such as poverty, age, race, and gender, influence an individual's or a community's ability to plan for, cope with, and recover from environmental hazards (Cutter *et al*. 2003). Therefore, analyzing these social conditions in areas at risk for wildfire can reveal a community's vulnerability to hazards, and shed light on the determinants of vulnerability (Solangaarachchi *et al*. 2012). Prioritizing prevention and mitigation strategies to target the people and places with the highest vulnerability to wildfires can help ensure that hazard reduction resources and strategies are equitably distributed (Ojerio 2008; Collins 2008*b*; Gaither *et al*. 2011; Ojerio *et al*. 2011; Poudyal *et al*. 2012).

The wildland-urban interface (WUI) is part of the physical landscape that is often associated with wildfires and is a key factor in current wildfire risk management and

mitigation planning. The WUI identifies the area where the human built environment intermixes with or abuts the vegetated environment (Radeloff *et al.* 2005). The WUI is expected to expand in size in the coming decades as populations continue to migrate into vegetated landscapes and convert previously undeveloped wildland vegetation for human settlement and use (Theobald and Romme 2007; Hammer *et al.* 2009). In addition to increased wildfire risk as a result of WUI expansion, risk is also expected to increase in response to extreme weather conditions (Bar Massada *et al.* 2009), such as those resulting from climate change. However, delineation of the WUI does not specifically identify areas of elevated exposure to wildfire risk (Radeloff *et al.* 2005). For example, even though a significant proportion of the WUI is found in the eastern US, 91% of the acreage burned by wildfire in 2007 was in the western and southeastern regions (Hammer *et al.* 2009). While the WUI describes the intersection of vegetation and housing, other biophysical characteristics, such as vegetation type, topography, and climate, contribute to wildfire risk (Hawbaker *et al.* 2013). In order to evaluate *place* vulnerability to wildfire, data describing biophysical and social conditions must be combined (Cutter 1996; Cutter *et al.* 2003). Including WUI delineations in our evaluation grounds this analysis in current wildfire risk management and planning processes.

Some studies have generated representations of the spatial distribution of wildfire risk integrated with select social and ecological values (Galiana-Martín and Karlsson 2012; Haas *et al.* 2013; Chuvieco *et al.* 2014). These studies examined the impact that wildfires may have on human settlements and populated places without an explicit consideration of how heterogeneous social conditions affect hazard outcomes. Other studies have specifically integrated measures of social vulnerability with measures of

wildfire risk in analyses of communities' adoption of and participation in wildfire mitigation, prevention, and management programs (Ojerio 2008; Gaither *et al*. 2011; Ojerio *et al*. 2011; Poudyal *et al*. 2012). These studies focused on individual states and used select indicators of social vulnerability.

We build on this previous work, by expanding the geographic coverage beyond a single state or region to examine the geographic distribution of the coincidence of social vulnerability and wildfire risk across the coterminous US. This paper presents an application of the hazards-of-place model of vulnerability and uses an inductive index creation methodology (Cutter 1996; Cutter *et al*. 2003). We demonstrate a concept for intersecting the two factors of place vulnerability to wildfires as espoused in the hazards-of-place model of vulnerability to environmental hazards: the physical exposure conditions operationalized as wildfire potential, and the social conditions operationalized as a social vulnerability index. Specifically, we create a neighborhood-level (i.e. US Census Block) index of social vulnerability that we intersect with existing wildfire risk data. We map this coincidence of social and biophysical vulnerability across the coterminous US, with particular emphasis and examination of the resulting place vulnerability to wildfires within the WUI. To test our expectation that areas of high wildfire risk do not have high social vulnerability, we examine mean social vulnerability by wildfire risk classification.

2. Literature Review

2.1. *The role of social conditions in producing vulnerability to wildfire*

Cutter (1996) proposed that place vulnerability is made up of two factors: biophysical vulnerability and social vulnerability. Vulnerability is "the likelihood of

sustaining losses from some actual or potential environmental hazard event, as well as the ability to recover from those losses" (Schmidtlein *et al.* 2008 p. 1100). The hazards-of-place model of vulnerability attempts to integrate concepts of exposure—the people or places that are at risk—and social conditions—the characteristics of people or places that predispose them to harm (Cutter 1996; Adger 2006). This holistic conception of vulnerability to environmental hazards suits wildfire hazards well, in that the occurrence and extent of wildfire is a function of biophysical characteristics, and its outcomes vary across groups and individuals. Vulnerability to wildfire, as conceptualized in the hazards-of-place model, may explain some of the variability observed in wildfire impacts, such as economic loss, health impacts, or structure loss.

Social conditions, such as poverty, race, and age have many, sometimes contrary, effects on wildfire impacts. Yet as with all environmental hazards, social conditions can influence people's preparation prior to, experience during, and response following a hazard event (Finch *et al.* 2010).

Populations with more economic and social resources are perhaps better insulated from the impacts of wildfire hazards because of their ability to prepare for, cope with and recover from loss hazards (Poudyal *et al.* 2012). New migrants, part-time residents, and those whose social and economic lives are less strongly rooted in the local landscape are less likely to perform household wildfire mitigation activities (Collins 2008*b*), either because their social status provides insulation or because of other factors, such as a lack of knowledge of local hazards (Larsen *et al.* 2010). However, household wildfire mitigation activities are also less likely to be undertaken by those with limited social and economic capacity to do so, which leads to increased wildfire risk (Collins 2005).

In the upper Midwest, greater proportions of owner-occupied (compared to renter-occupied) housing units were associated with less wildfire activity (Cardille *et al*. 2001). In a WUI region of Argentina, impoverished neighborhoods, those with high levels of unemployment, and those with a higher proportion of young people not attending school, experienced wildfires with greater frequency than neighborhoods with contrary characteristics (de Torres Curth *et al*. 2012). Wildfires that begin in poor communities are less likely to be extinguished quickly because of a lack of resources (Mercer and Prestemon 2005).

Health impacts from wildfire smoke disproportionately impact the elderly (Kochi *et al*. 2012). Ecological damage resulting from wildfires can temporarily and in some cases even permanently destroy the natural resource base from which a community derives economic value and employment (Butry *et al*. 2001). This damage, when occurring in a community that is heavily dependent on extractive industries, can also have long-lasting economic effects (Niemi and Lee 2001).

Examining a specific indicator of social vulnerability, Cutter *et al*. propose that racial and ethnic minorities are often more socially vulnerable to environmental hazards because of a "lack of access to resources, cultural differences, and the social, economic, and political marginalization that is often associated with racial disparities" (2003 p. 254). Racial and ethnic communities are often not adequately prepared for disasters, often experience a greater proportion of injuries and fatalities, and have longer psychological-social recovery (Fothergill *et al*. 1999). Perceptions about fire management and risk mitigation vary by race and ethnicity (Bowker *et al*. 2008). Caucasians agree at a higher rate than African Americans and Hispanics that homeowners should be adequately

prepared for wildfire hazards. Gaither *et al.* (2011) theorize that land ownership practices perhaps more prevalent among southern African Americans, such as property ownership or tenancy through inheritance without clear land title, result in limited involvement in wildfire mitigation programs. Communities with smaller Hispanic populations saw property values decline less than other communities in post-wildfire situations (Fu 2012). Taken together, these findings point to social conditions, such as race and ethnicity, as key determinants of social vulnerability and wildfire hazard outcomes.

2.2. *Human agency and wildfire hazards*

Understanding the confluence of social and biophysical vulnerability is especially relevant for wildfire. For some environmental hazards, the initiation or occurrence of the environmental condition preceding the environmental hazard is independent of local social conditions. For example, whether a hurricane occurs, and how it travels upon hitting land is unrelated to a place's social conditions. In contrast, wildfire also is, in part, a function of human agency. The frequency, severity, and pattern of wildfire is significantly related to human activities such as land use, including patterns of settlement and vegetation management (Syphard *et al.* 2007; Hawbaker *et al.* 2013; Syphard *et al.* 2013). Wildfire occurrence is positively associated with specific levels of population and housing density (Syphard *et al.* 2007; Hawbaker *et al.* 2013). Human activity is responsible for the majority of wildfire ignitions, and human land use and modifications greatly affect the extent, density, type, and condition of vegetation in ways that affect fire behavior (Prestemon *et al.* 2013).

Furthermore, the spread of human development into wildfire prone landscapes in the US has been facilitated by political and economic conditions and processes. The

result is not only biophysical but social vulnerability as well (Collins 2008*a*; Simon and Dooling 2013). For example, Collins (2008*a*) argues that some federal land exchanges have facilitated the development of upscale residential developments in wildfire prone landscapes, which can, in turn, attract migrants to these communities. These new residents, and their associated lifestyle choices, can contribute to the conversion of communities previously dependent on resource extraction as an economic base into amenity-driven economies. This economic shift may marginalize those members of the community who are unable or unwilling to adapt to the new economic reality.

In the US, public-sector fire suppression, homeowner's insurance, and disaster assistance, all of which subsidize the costs of fire risk, incentivize human settlement in landscapes with high wildfire risk (Holmes *et al*. 2003; Collins 2008*a*; Fu 2012; Simon and Dooling 2013). This illustrates a classic negative externality problem: the social costs of living in fire prone landscapes (e.g. fire suppression, recovery aid) are not solely borne by residents (O'Donnell *et al*. 2014). In addition, the responsibility for mitigating residential wildfire hazard has shifted onto the individual (Collins 2008*a*; Fu 2012). At its essence, this creates a two-tiered culture of social conditions with disproportionate risks and benefits (Collins and Bolin 2009). Less vulnerable residents, such as homeowners (particularly those who are wealthy), are more able to benefit from the socialized costs of wildfire protection and are better able to assume responsibility to mitigate wildfire risk; more vulnerable residents, such as renters and the poor, are both unable to benefit from wildfire protection subsidies and less able to assume individual responsibility to mitigate their risk (Collins 2008*a*; Fu 2012; Simon and Dooling 2013). Because the incentives to occupy high wildfire risk areas likely benefit advantaged (less vulnerable) groups, we

expect to observe that these areas will not have high social vulnerability. However, we recognize the diversity of social conditions in these landscapes (Nielsen-Pincus *et al*. 2015; Paveglio *et al*. 2015), so we also expect that there are some places where high social vulnerability occurs within high wildfire risk areas, and in these places, people may need more or different wildfire hazard management assistance.

Policy intended to mitigate vulnerability to wildfire may or may not have intended effects. Federal US appropriations for wildfire management include allocations for preparedness, suppression, hazardous fuels reduction, and rehabilitation (Steelman and Burke 2007; Hoover and Bracmort 2015). Federal wildfire management activities are broad and are used to achieve a number of different policy objectives (Steelman and Burke 2007). Calkin *et al*. (2014) suggest that in order to reduce home destruction, one of many wildfire hazard management goals, policies should focus on reducing the susceptibility of homes to ignition rather than on the control of wildfire. They note that wildfire is inevitable, and that focusing on activities within the home ignition zone, activities that are commonly considered the responsibility of the individual property owner, will reduce structure losses. Some federal policies indirectly support individuals in protecting their homes, mitigating their fire risk, and reducing their vulnerability to wildfire.

The Healthy Forests Restoration Act of 2003 provides communities the opportunity to develop Community Wildfire Protection Plans with the goal of improving their adaptive capacity to wildfire hazards (Grayzeck-Souter *et al*. 2009; Jakes *et al*. 2011; Williams *et al*. 2012). These plans are developed collaboratively, identify and prioritize lands for fuels reduction, and contain recommendations for reducing the

ignitability of structures, though individual responsibility for private property remains the

norm (Jakes *et al*. 2011). These plans can be useful and effective at producing adaptive

capacity and community resilience (Jakes and Sturtevant 2013).

Facilitating Community Wildfire Protection Plan development in vulnerable

communities could help reduce their susceptibility to the impacts of wildfire hazards and

increase their adaptive capacity and resilience, though Jakes *et al*. (2011) question

whether the ability of some communities to access the resources needed to develop these

plans may limit opportunities for their development. Evidence demonstrates that socially

vulnerable communities are less engaged in these, and other, wildfire mitigation

programs (Gaither *et al*. 2011), even when they are exposed to high levels of wildfire risk

(Ojerio *et al*. 2011).

Wildfire policy in the US is not exclusively the domain of the federal government

and state and local governments are increasingly involved in wildfire management (Davis

2001). For example, state and local laws and regulations govern land-use planning, which

in turn informs where residences may be built. Reams *et al*. (2005) identify and evaluate

a number of local governmental wildfire management programs and find that direct

homeowner assistance, such as free defensible space clearing, is one of the more effective

management activities. Targeting these locally initiated, direct intervention activities at

vulnerable communities could help bypass some of the implementation difficulties

associated with federal protection and mitigation programs. State agencies can play a role

in identifying and reaching out to at-risk communities (Titus and Hinderman 2006).

Implementing efficient and equitable wildfire management policies increasingly requires

the efforts of a multitude of stakeholders.

When wildfire policy targets at-risk communities, these communities are identified and defined in a variety of ways. Creating typologies or archetypes of properties or communities within the WUI can help structure policy to achieve specific and targeted goals (Nielsen-Pincus *et al*. 2015; Paveglio *et al*. 2015). At the federal level, evaluations of select social conditions have been incorporated into recent wildfire management planning efforts, demonstrating increasing awareness of the role that these conditions have in influencing how environmental hazards can disproportionately impact communities (Wildland Fire Executive Council 2014). Policy targeting and implementation must be flexible and cognizant of community-level differences in order to encourage and facilitate the adoption and implementation of sustainable strategies and plans (Grayzeck-Souter *et al*. 2009; Champ *et al*. 2012; Williams *et al*. 2012; Olsen and Sharp 2013; Fischer *et al*. 2014). Our process of identifying the places most vulnerable to wildfire hazards can support the future development of tailored and context-specific policies at different jurisdictional levels.

3. Materials and methods

We applied methods developed by Cutter *et al*. (2003) to estimate neighborhood-level social vulnerability. We then combined these data with existing data characterizing biophysical vulnerability to wildfire to examine the distribution of place vulnerability to wildfire across the coterminous US.

3.1. Social vulnerability

Social vulnerability is not a characteristic that can be measured directly: single demographic or economic variables (e.g. Collins 2009), additive indices (e.g. Gaither *et al*. 2011), and inductive indices (e.g. Ojerio *et al*. 2011) have all been used as

representations of social vulnerability. Cutter *et al.* (2003) popularized the creation of inductive indices of social vulnerability by using principal component analysis to examine a broad set of demographic and place-based indicators which in theory represent the antecedents of social vulnerability. Principal component analysis is a statistical technique that distills a large set of variables into fewer, related components which allows for results to be more easily interpreted.

Components can be combined into one or more composite indices. Summing components allows for negative values (low vulnerability) to compensate for positive values (high vulnerability). Social vulnerability indices are not considered absolute but rather relative metrics that compare social vulnerability between units of observation, making them potentially useful for identifying priority locations or regions for hazard management efforts. Moreover, Cutter *et al.*'s (2003) method has proven to be robust, particularly with regard to variable selection and spatial scale, for estimating and describing social vulnerability (Schmidtlein *et al.* 2008). These attributes make it well suited to the evaluation of social vulnerability to wildfire risk.

Our study population consisted of terrestrial census blocks (i.e. water blocks were excluded) containing housing units in the coterminous US, as represented in the 2010 version of the Radeloff *et al.* (2005) WUI maps. We constructed our social vulnerability index using census block group data from the 2010 US Census and from the 2006-2010 American Community Survey, the continuous survey that replaced the long form version of the decennial US census after 2000 (MacDonald 2006). Census block groups are the second smallest census unit of analysis and are aggregates of census blocks. Block groups are the smallest unit for which data relevant to this analysis are published.

We selected 26 socioeconomic and demographic variables (Table 1) based upon theoretical foundations established in Cutter *et al*. (2003), subsequent applications of their methodology (Wood *et al*. 2009; Tate 2011; Solangaarachchi *et al*. 2012), and other, wildfire-specific studies of social vulnerability (Gaither *et al*. 2011; Ojerio *et al*. 2011; Poudyal *et al*. 2012). When constructing hazard-specific social vulnerability indices, analysts should use socioeconomic and demographic variables representing those social conditions that produce vulnerability to the particular hazard of interest (Tate 2011). There is evidence, however, of some universality with regard to the social conditions affecting the ability of communities to plan for, cope with, and recover from environmental hazards (Newman *et al*. 2014). Thus, we consider the selected variables adequate for accurately reflecting the social conditions that produce vulnerability to wildfire. Although we used some raw population parameter estimates directly as variables (e.g. median age), most population parameters were transformed into proportions of the block group population.

We normalized the variables using z-score standardization, which resulted in zero means and standard deviations of one for all variables. Since a principal component analysis cannot include observations with missing data, we assigned the mean value (i.e. zero) of the variable to any block groups with missing values in order to produce social vulnerability scores for all blocks. Tate (2011), diverging from Cutter *et al*. (2003), adjusted the directionality of variables for which high values indicate lower levels of social vulnerability prior to the application of principal component analysis, providing consistency in inputs so that high levels of all variables indicate high levels of social vulnerability. Thus, we generated the additive inverse of standardized variables for

percent of households earning greater than \$200,000 annually, per capita income, median house value, and median gross rent. Similarly, since both high and low values of median age conceivably would indicate high vulnerability (Tate 2012), we used the absolute value of this standardized variable. These pre-analysis variable directionality adjustments eliminated the need for post-analysis component directionality adjustments.

We performed principal component analysis using the 26 variables. Cutter *et al.* (2003) used Kaiser's criterion (i.e. eigenvalues greater than one) to select the number of components to retain. We used this criterion but also confirmed the number of components to retain using parallel analysis, an alternative and preferable component-retention decision mechanism (Patil *et al.* 2008; Tate 2011). To aide qualitative interpretation, we applied varimax rotation to the selected components. This procedure simplifies component structure by minimizing the number of highly loading variables on each component.

To create a composite social vulnerability score for each block group, we weighted component scores by each component's proportion of explained variance and summed the resulting weighted components (Schmidtlein *et al.* 2008; Wood *et al.* 2009). This weighting scheme diverges from Cutter *et al.*'s (2003) use of equally weighted component scores. Without *a priori* knowledge about the relative influence of individual components on composite vulnerability, any weighting scheme, such as equal weights or proportional weights, is subjective. We believe that using proportional weights complements the use of principal components analysis, which mathematically emphasizes those components explaining a greater proportion of the variation observed among the input variables (Schmidtlein *et al.* 2008). We normalized social vulnerability

scores using z-score standardization. We classified census block groups with z-scores less than -1.0 as having "low" social vulnerability; those with z-scores greater than 1.0 were classified as "high"; the remaining block groups were classified as "moderate". Finally, we assigned the components, normalized score, and social vulnerability class to the census blocks contained within each respective census block group, in order to match spatial scales of analysis between datasets. Had we aggregated WUI data up from the block to the block group level, we would have overestimated the land area that is designated as WUI because of the relatively coarser scale of the block group level (Zhang and Wimberly 2007).

3.2. Biophysical vulnerability

We obtained data for wildfire risk from the 2012 Wildland Fire Potential raster dataset, covering the coterminous US at 270 meter resolution (Fire Modeling Institute 2012). The wildfire potential map represents the relative potential for difficult-to-suppress wildfires based on past fire occurrence, fuels data, and estimates of wildfire likelihood and intensity. The classified version of the dataset categorizes each cell according to one of seven wildfire potential values: very low, low, moderate, high, very high, water, and non-burnable. Wildfire potential data are unavailable for 1,627 of the census blocks included in the initial study population, because the dataset does not completely align with census boundary designations. So, the final study population consisted of 6,623,461 census blocks for which both social vulnerability and wildfire potential data were available.

We summarized the wildfire potential data for each census block by calculating the proportion by area of the wildfire potential values within the boundaries of each

census block. We assigned the wildfire potential value with the greatest area proportion to the census block. We then recoded wildfire potential classifications: water, non-burnable, very low, and low categories were coded as "low" wildfire risk; the moderate category remained as "moderate"; and the high and very high categories were coded as "high" which is consistent with other applications of this dataset (e.g. Kline *et al*. 2013).

We evaluated the coincidence of social vulnerability and wildfire risk through qualitative cross-tabulation (Haas *et al*. 2013; Chuvieco *et al*. 2014). For various combinations of social vulnerability and wildfire risk, we calculated housing unit counts, presenting information by WUI category and for each state. To test our expectation that areas of high wildfire risk do not have high social vulnerability, we calculated mean social vulnerability by wildfire risk classification.

4. Results

The study population represented 54% of the census blocks in the 2010 WUI map, 57% of the area, nearly 100% of the housing units (31,730 of approximately 131 million are not represented), and 99% of the population in the coterminous US. Within the study population, non-WUI census blocks encompassed 83% of the area and 64% of the housing units and population (Fig. 1). WUI interface blocks encompassed 4% of the area and 23% of the housing units and population. WUI intermix blocks encompassed 13% of the area, 14% of the total housing units, and 13% of the population. Hereafter, we will focus on statistics related to housing units rather than population. There is a strong correlation (Pearson's correlation $\rho = 0.90$) between housing units and population and housing units are the focus of wildfire hazards management.

We calculated social vulnerability scores (Fig. 2) for each of the 215,271 census block groups containing the study population census blocks. Following principal component analysis on the 26 transformed variables, we retained the first seven components. These seven components cumulatively accounted for 62.77% of the total variance (Table 2). Each rotated component explained between 12.17% and 4.67% of the total variance and was named to reflect the dominantly loading variables. The components of vulnerability varied spatially; some regions exhibited high values (high vulnerability) of some components and low values (low vulnerability) of other components (Fig. 3). Comparing how the components and the resulting composite score varied illustrates how this methodology allows the values of different components to compensate for each other in the composite index.

Ranking states (including the District of Columbia) by number of housing units with high social vulnerability generally tracked broader population trends. Texas, California, Florida, and New York were the top-ranked states in this characterization of vulnerability (Fig. 4a). New Mexico, the District of Columbia, Arizona, Mississippi, Texas, and Louisiana were top-ranked in proportion of housing units with high social vulnerability (Fig. 4b).

Summarization of the wildland fire potential dataset at the census block group level reshaped the data from grid format into polygons (Fig. 5). Recoding and generalization of the data resulted in the classification of 224,915 blocks as having high (encompassing the high and very high initial classifications) wildfire risk. Blocks with low (encompassing the water, non-burnable, very low, and low initial classifications) wildfire risk represented nearly all housing units (92%). Wildfire risk classified far fewer

housing units as highly vulnerable compared to the social vulnerability index (3% and 13%, respectively; Fig. 6).

Ranking states by number of housing units with high wildfire risk revealed California as the top-ranked state, nearly doubling the number of housing units with high social vulnerability of second-ranked Florida (956,047 to 516,914; Fig. 4*c*). States of the Southeast and West were ranked highest in proportion of housing units with high wildfire risk (Fig. 4*d*).

Social vulnerability scores did not vary dramatically by wildfire risk and WUI classifications, though the mean social vulnerability score for interface blocks (.06) was slightly higher than for non-WUI (-.01) and intermix blocks (-.05). The components of social vulnerability did vary by WUI classification and wildfire risk, however (Fig. 7). From low to high wildfire risk the Hispanic/Education and Female components trended lower while the Native American and Age components trended higher. There was heterogeneity among non-WUI and interface blocks, while intermix blocks had lower scores for the Hispanic/Education and Female components and higher scores for the Native American and Age components.

To examine how a singular focus on wildfire risk represents place vulnerability, we examined the distribution of social vulnerability among the top ten states with the highest number of housing units in high wildfire risk areas (Fig. 8). For these states, we calculated the percentage of housing units in each social vulnerability class among those in the high wildfire risk class. The percentage of housing units with high social vulnerability was generally small (ranging from 6%-12%) and the percentage of housing units with low social vulnerability was also generally small (ranging from 2%-9% for

eight of the ten states). Two states, however, contained large percentages of housing units with low social vulnerability: Florida with 27% and Mississippi with 38%. In these states, focusing exclusively on wildfire risk would misrepresent place vulnerability to wildfires.

The coincidence of high social vulnerability and high wildfire risk encompassed nearly 372,000 housing units (Fig. 9). Non-WUI and WUI intermix blocks contained a similar number of housing units (about 148,000 and 142,000, respectively) while WUI interface blocks contained the remaining units (Fig. 10). Nearly 78% of these housing units were contained in seven states, California, North Carolina, Florida, South Carolina, Georgia, New Jersey, and New York (Fig. 4*e*). South Carolina, North Carolina, Mississippi, South Dakota, New Jersey, and Georgia were ranked highest in proportion of housing units with high social vulnerability and high wildfire risk (Fig. 4*f*). The proportion of housing units with high social vulnerability declined going from areas of low to high wildfire risk (Fig. 11). Of blocks with high wildfire risk, WUI intermix blocks exhibited the smallest proportion (7%) of housing units with high social vulnerability (Fig. 12).

Moderate wildfire risk blocks had the highest mean social vulnerability (0.10) and high wildfire risk blocks had the lowest mean social vulnerability (-0.01). The subset of WUI blocks exhibited the same trend. We determined the wildfire risk class with the highest mean social vulnerability for each state, for all blocks (Fig. 13*a*) and for the subset of WUI blocks (Fig. 13*b*), to examine whether this trend varied throughout the coterminous US. Generally, the high wildfire risk areas of the states of the northern half of the West, the upper Midwest, and states in the Appalachian region exhibited higher social vulnerability than moderate or low wildfire risk areas.

5. **Discussion**

We found that around 372,000, or 0.3%, of the housing units in the coterminous US were in places that exhibited both high wildfire risk and high social vulnerability, and that a singular emphasis on either wildfire risk or social vulnerability would inaccurately represent or overgeneralize place vulnerability to wildfires. Further, we found that few areas of high wildfire risk exhibited higher than average social vulnerability, perhaps reflecting political and economic processes and conditions that have incentivized the settlement of some areas of high wildfire risk (Holmes *et al*. 2003; Collins 2008*a*; Fu 2012; Simon and Dooling 2013). We recognize, however, that high social vulnerability and wildfire risk do intersect in some areas, emphasizing the need to evaluate wildfire management policies with regard to social conditions.

While 372,000 housing units represented only a small fraction of the total housing units in the coterminous US, it was more than two orders of magnitude greater than the average number of residences burned in wildfires annually between 1999 and 2011 (1,354; National Interagency Fire Center 2011). Nine percent of housing units in areas of high wildfire risk had high social vulnerability. Coupled with evidence that communities with higher social vulnerability participate less often in wildfire mitigation programs (Gaither *et al*. 2011; Ojerio *et al*. 2011), this study identifies those communities that could benefit from additional wildfire management assistance.

We found that about 40% of housing units with both high social vulnerability and wildfire risk were in non-WUI blocks. Radeloff *et al*. used federal definitions to delineate the WUI, and they note that this definition "does not assess wildland fire risk specifically" (2005 p. 803). While communities creating Community Wildfire Protection

Plans under the Healthy Forests Restoration Act are able to define the WUI using flexible criteria (Grayzeck-Souter *et al*. 2009), these plans often fail to encompass adjacent areas that contribute to wildfire risk (Ager *et al*. 2015). Thus, reliance on the federal WUI definitions alone may lead some communities to underestimate areas vulnerable to wildfire. This is especially important in light of the fact that some federal funding for fuels reduction is allocated based on how these plans delineate the WUI (Jakes *et al*. 2011). While Jakes *et al*. (2011) suggest that the adaptability of these plans yields local benefits, wildfire managers might consider examining whether the resources allocated as a result of these plans are distributed efficiently and equitably (Holmes *et al*. 2007). Similarly, these plans do not require the evaluation of social conditions that produce vulnerability. Considering social conditions in local wildfire planning efforts may improve communities' capacity to respond and adapt to wildfire.

Social vulnerability is a phenomenon that touches all corners of the coterminous US. Some states, mostly in the southern half of the country, exhibited greater rates of social vulnerability, however. Wildfire risk is concentrated in the western and southeastern regions. Our mapping of the intersection of social vulnerability and wildfire risk identifies vulnerable places, like the Southeast, that may not be associated with the greatest wildfire threats. We submit, however, that the coincidence of wildfire risk and social vulnerability identifies places that are more likely to be disproportionately *impacted* by wildfire, rather than simply experience wildfire.

High wildfire risk areas in parts of the Southwest, South-central, and Southeast exhibited lower social vulnerability. Case studies may help explain this divergence of biophysical and social vulnerability. In some parts of California, political and economic

processes have incentivized the settlement of high wildfire risk areas (Fu 2012; Simon

and Dooling 2013). For example, Fu (2012) suggests that some architectural restrictions

meant to reduce home ignitability are only feasible for the advantaged (less vulnerable).

Rather than providing complete protection, these restrictions may provide the pretense of

safety, and consequently exacerbate wildfire risk. Those less vulnerable are the ones who

are typically able to take advantage of political and economic incentives. In the political

ecology tradition, marginalization produces vulnerability, though Collins (2008*a*)

suggests that facilitation, the antithesis of marginalization, may be the more relevant

concept for wildfire hazards in the US. Further study may reveal additional processes that

differentially promote either the facilitation or marginalization of wildfire vulnerability.

Our study is temporally and spatially static. Social conditions and wildfire risk

will inevitably change over time, such as when people migrate into wildfire prone areas

and as land use practices and climates change (Theobald and Romme 2007; Hammer *et

al*. 2009; Syphard *et al*. 2013). These changes will invariably influence the distribution of

social vulnerability. Scale similarly influences evaluations of social vulnerability. While

our study focused on the distribution of social conditions across the coterminous US,

state or region-specific evaluations of vulnerability have produced different results

(Gaither *et al*. 2011; Ojerio *et al*. 2011; Poudyal *et al*. 2012). Wildfire risk managers

should be cognizant of these differences and select risk evaluation methods appropriate to

the situation at hand.

Our use of an established methodological approach was not without limitations.

Social vulnerability metrics may only provide a limited representation of the realities of

vulnerability. While social vulnerability indices efficiently describe broad scale

vulnerability, they fail to capture some of the richer, localized information related to

exposure, sensitivity, and adaptive capacity that is often better collected through

qualitative methods (Fischer *et al*. 2013). These indices are useful, however, for

supporting broad scale planning using a modicum of resources. They allow managers to

quickly assess areas perhaps requiring additional support or evaluation. The

compensatory logic inherent in the design of social vulnerability indices has not yet been

thoroughly tested (Jones and Andrey 2007; Wood *et al*. 2009; Tate 2011), and other

analysts have used Pareto rankings of social vulnerability components to avoid this as-of-

yet unresolved concern (Rygel *et al*. 2006). In future analysis, margins of error provided

by the American Community Survey could be used to analyze the uncertainty associated

with our social vulnerability index (Tate 2013). As social vulnerability indices are

applied more widely, these concerns, as well as others yet unforeseen, must continue to

be examined, debated, and resolved.

Testing the validity of social vulnerability indices could inform both their

construction and application. Validation is possible if post-hazard outcomes are

compared to pre-hazard vulnerabilities (Cutter *et al*. 2008). Flood events in Texas,

Hurricane Katrina, and the 1995 Chicago extreme heat event are examples of

environmental hazards that have proven useful for validating social vulnerability indices

(Zahran *et al*. 2008; Finch *et al*. 2010; Johnson *et al*. 2012). While the presence or

absence of wildfire prevention and mitigation programs has been used to validate

regional indices of social vulnerability to wildfire hazards (Gaither *et al*. 2011; Ojerio *et

al*. 2011), more direct post-hazard measures of response such as economic loss (e.g. Ash

et al. 2013), health impact, fire extent, or structure loss and rebuilding (e.g. Alexandre *et

al. 2014) data have not yet been applied. While rebuilding rates vary, they do not appear to follow easily identifiable geographic or ecological patterns (Alexandre *et al.* 2014). Rebuilding may be related to social conditions, local policies, or individual-level resources (Mockrin *et al.* 2015). Measures such as these would aid in refining both the indices themselves, and our broader understanding of social vulnerability to wildfire.

6. Policy implications

As federal spending on wildfire management and protection continues to increase and as wildfire managers search for ways to minimize loss of life and damage to property, difficult policy decisions will have to be made (Bracmort 2012). A more complete measure of vulnerability, one that incorporates a robust estimation of social vulnerability, can inform such decisions. In the short term, prioritizing programs and funding for those places that not only face the greatest wildfire risk but also lack the capacity to prevent or mitigate that risk may help improve outcomes associated with wildfire hazards.

Any redistribution of resources would affect those who currently benefit from existing wildfire management programs and may be a politically intolerable proposition for some. Policymakers may wish to understand more clearly who benefits from existing programs and whether these programs achieve efficient and equitable outcomes. Holmes *et al.* (2007) suggest that providing assistance only to those who have taken steps to mitigate risk may disproportionately impact vulnerable populations. Thinking about wildfires as a natural hazard allows us to examine why some people fail to take action to reduce their own risk (McCaffrey 2004). Some fail to recognize the risk they face, others refuse or delay taking action to reduce their risk, and others may be unable to take action.

Ultimately, no matter how governments choose to manage wildfire hazards, diverse populations will seek to hold them accountable for how those policies are implemented. In multi-jurisdictional societies like the US, people have multiple opportunities to seek out and receive assistance, if and when it is needed. The opportunity for rethinking the current distribution of resources exists at the federal, state, and local levels. State and local governmental assistance can supplement when federal wildfire management programs fail to provide needed mitigation assistance (Reams *et al*. 2005; Titus and Hinderman 2006).

In the long term, land management policies and political and economic incentives could be evaluated to assess their contribution to wildfire vulnerability. Migration and climate trends indicate that society will face wildfire hazards for the foreseeable future, but policymakers can continue to examine the acceptability of policies that facilitate and incentivize the settlement of wildfire prone landscapes.

7. Conclusion

While the processes producing social and biophysical vulnerability are largely independent, we found that social vulnerability and wildfire risk intersect in discrete and identifiable places. The WUI is not uniform in biophysical or social conditions, but rather represents a mosaic of community types, and policy flexibility and adaptability will be necessary to confront wildfire hazards affecting these communities (Paveglio *et al*. 2009). This research complements existing WUI community typologies or archetypes (Wildland Fire Executive Council 2014; Nielsen-Pincus *et al*. 2015; Paveglio *et al*. 2015) by including a robust estimator of social vulnerability. Thorough understanding of on-the-

ground characteristics of people and places will improve our ability to confront the

challenges associated with wildfire hazards.

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Table 1. Variables used to create the social vulnerability index.

All data sourced from 2006-2010 American Community Survey except percent of population living in nursing and skilled-nursing facilities sourced from 2010 US Census.

Median Gross Rent
Median House Value
Median Age
Per Capita Income
People Per Unit
Percent of Population Under 5 Years or 65 and Older
Percent Asian
Percent Black or African American
Percent Civilian Unemployment
Percent of Population Aged 25 Years or Older with Less Than 12th Grade Education
Percent Speaking English as a Second Language with Limited English Proficiency
Percent Employment in Extractive Industries
Percent Female
Percent Female Participation in Labor Force
Percent Female-Headed Households
Percent Hispanic
Percent Mobile Homes
Percent Native American
Percent of Housing Units with No Cars
Percent of Population Living in Nursing and Skilled-Nursing Facilities
Percent Poverty
Percent Renters
Percent of Households Earning Greater than $200,000 Annually
Percent Employment in Service Industry
Percent of Households Receiving Social Security
Percent Unoccupied Housing Units

Table 2. Social vulnerability components, based on a principal component analysis with a varimax rotation.

Component	% of variance explained	Dominant variables	Variable Loading
Hispanic/Education	12.17	Percent Speaking English as a Second Language with Limited English Proficiency	+.5112
		Percent Hispanic	+.4639
		Percent with Less than 12th Grade Education	+.3325
Material Resources	12.12	Percent of Households Earning Greater than $200,000 Annually[A]	+.5209
		Median House Value[A]	+.5021
		Per Capita Income[A]	+.4664
		Median Gross Rent[A]	+.3621
Socioeconomic Status	10.37	Percent Black	+.4915
		Percent Civilian Unemployment	+.4560
		Percent Female-Headed Households	+.4108
		Percent Poverty	+.3271
Age	8.68	Percent of Population Under 5 Years or 65 and Older	+.5831
		Percent of Households Receiving Social Security	+.5631
		Median Age[B]	+.3538
Housing	7.54	People Per Unit	−.6054
		Percent Unoccupied Housing Units	+.4497
		Percent Renters	+.3865
		Percent of Housing Units with No Cars	+.3193
Female	7.21	Percent Female	+.5961
		Percent Female Participation in Labor Force	+.5717
Native American	4.67	Percent Native American	+.7203
		Percent Employment in Extractive Industries	+.3399
		Percent Mobile Homes	+.3269

[A]The additive inverse of this standardized variable was used in the principal component analysis.
[B]The absolute value of this standardized variable was used in the principal component analysis.

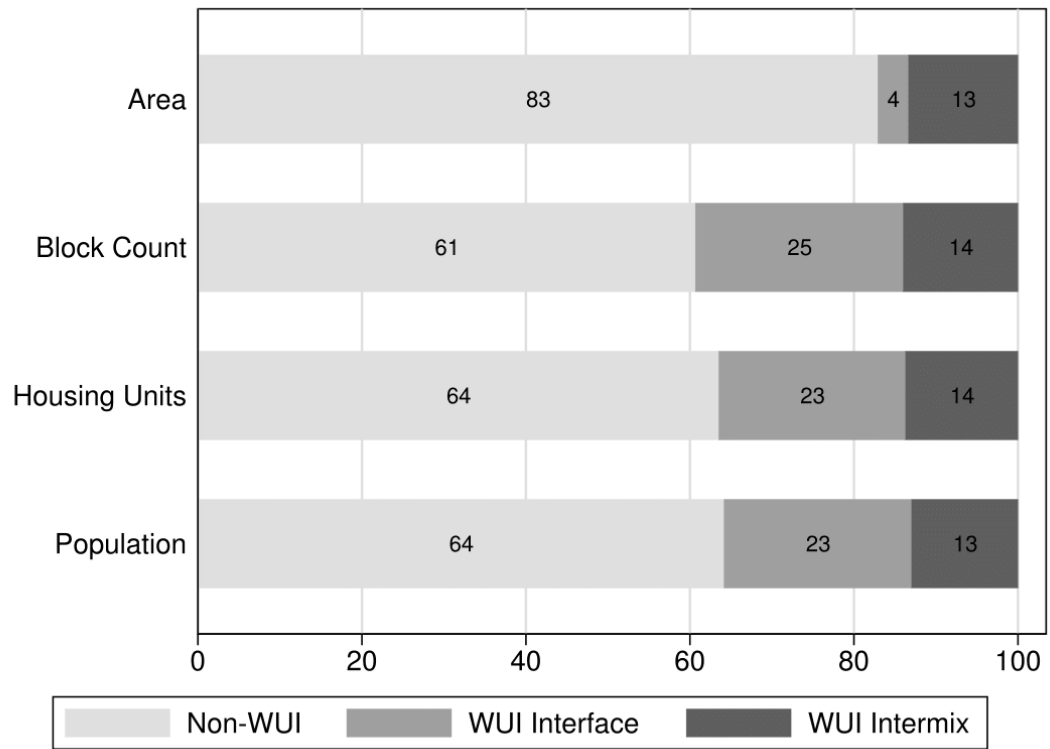**Figure 1. Percentage of the study population by WUI category.**

Figure 2. Social vulnerability scores for the coterminous US.
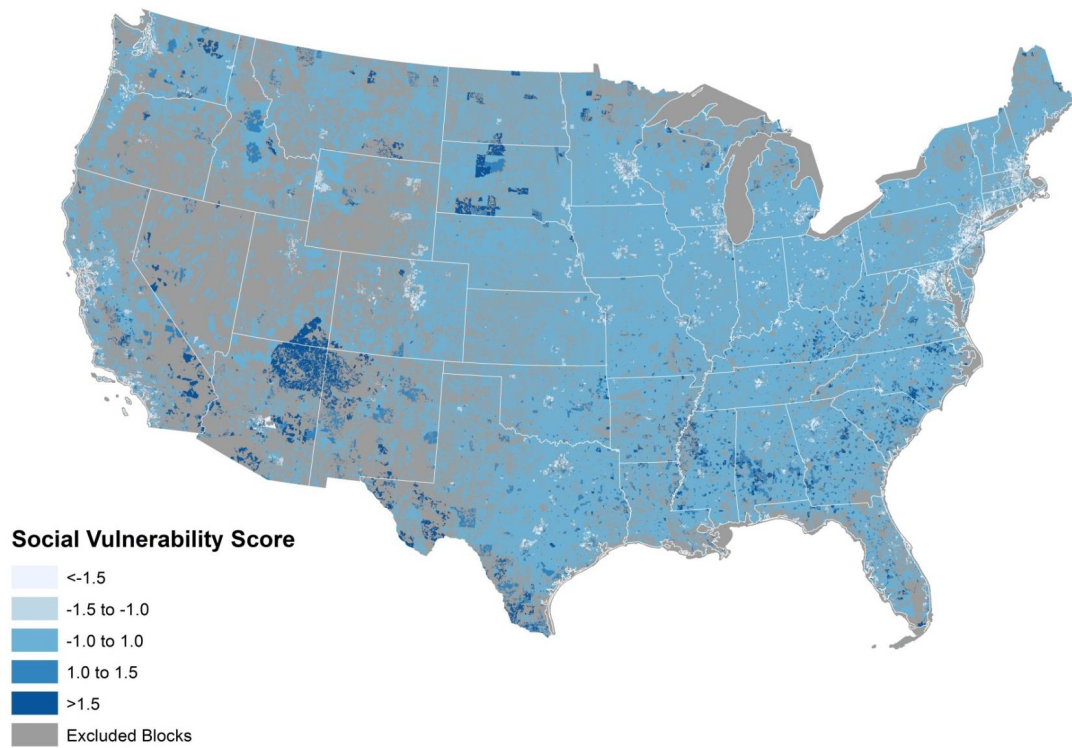
Figure 3. Spatial variability of component and social vulnerability scores for a fire prone portion of the state of Arizona.

Figures *(a)-(h)* represent the same geographic area as delineated by the extent border in the overview map. The overview state map and figure *(h)* depict the composite social vulnerability scores. Figures *(a)-(g)* depict standardized component scores for each of the seven components retained from the principal component analysis: *(a)* Hispanic/Education; *(b)* Material Resources; *(c)* Socioeconomic Status; *(d)* Age; *(e)* Housing; *(f)* Female; and *(g)* Native American. Figure *(h)* includes burn perimeters (red) from wildfires occurring from 2006 through 2010, sourced from the Monitoring Trends in Burn Severity database.

Figure 3.
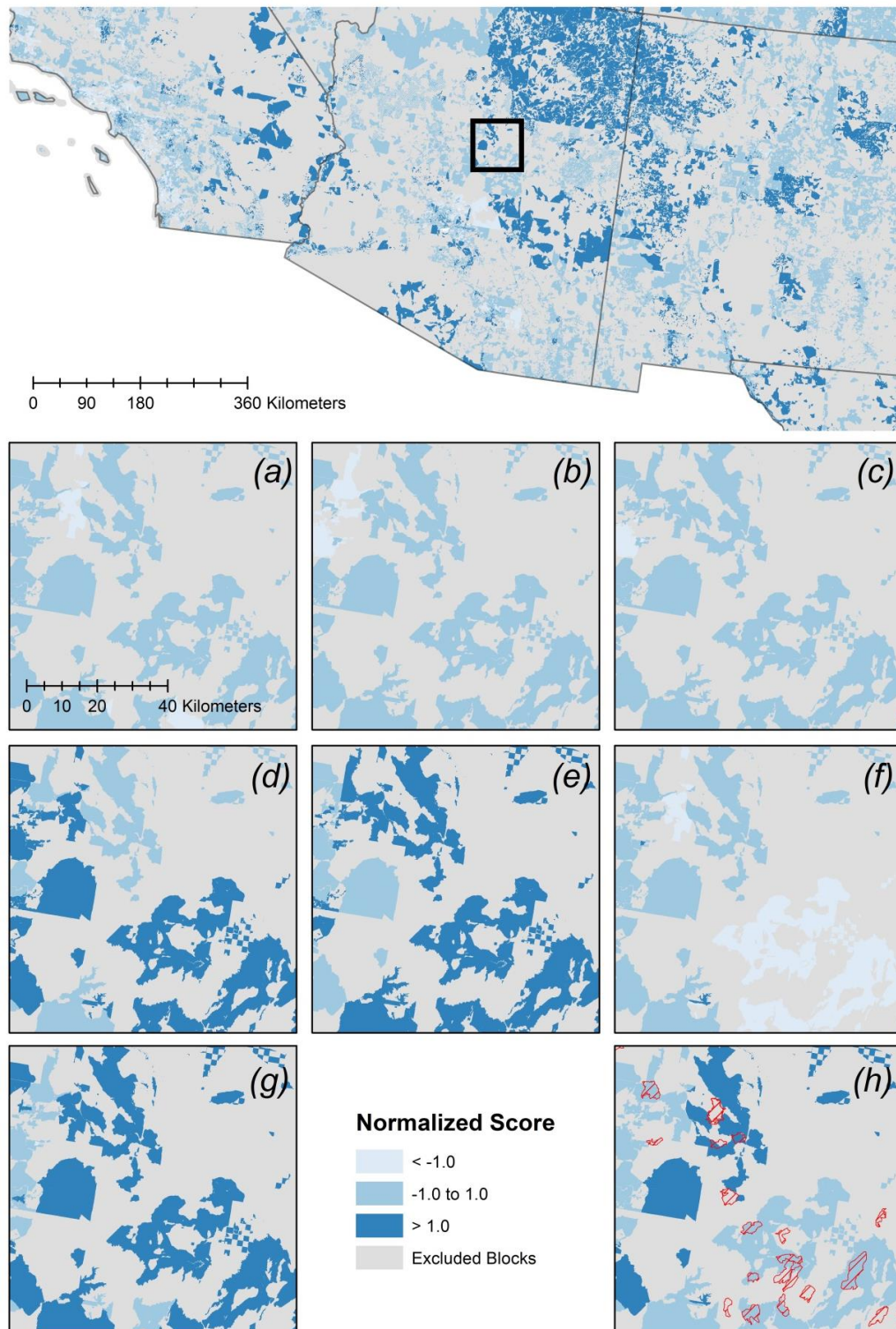
Figure 4. Housing with high vulnerability.

Housing units in areas of and proportion of housing units in areas of, respectively, *(a)-(b)* high social vulnerability, *(c)-(d)* high wildfire risk, *(e)-(f)* and high social vulnerability and high wildfire risk.
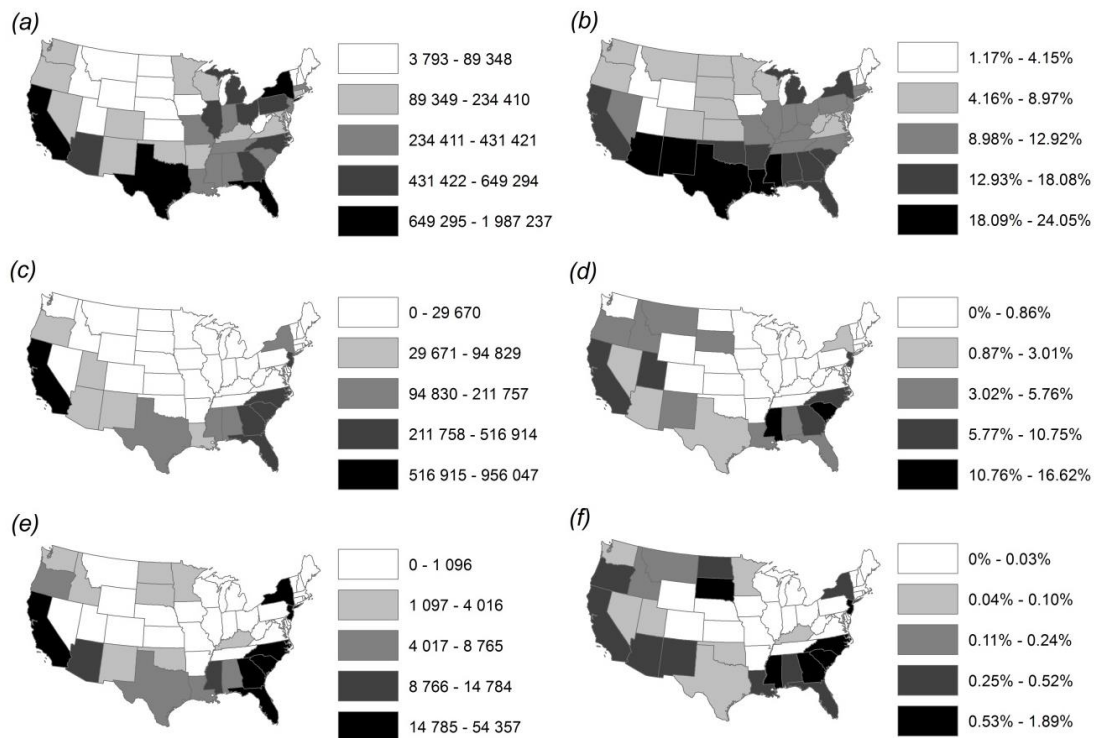
Figure 5. Wildfire potential for the coterminous US.

Wildland Fire Potential Class

- Very Low; Non-burnable
- Low
- Moderate
- High
- Very High
- Excluded Blocks
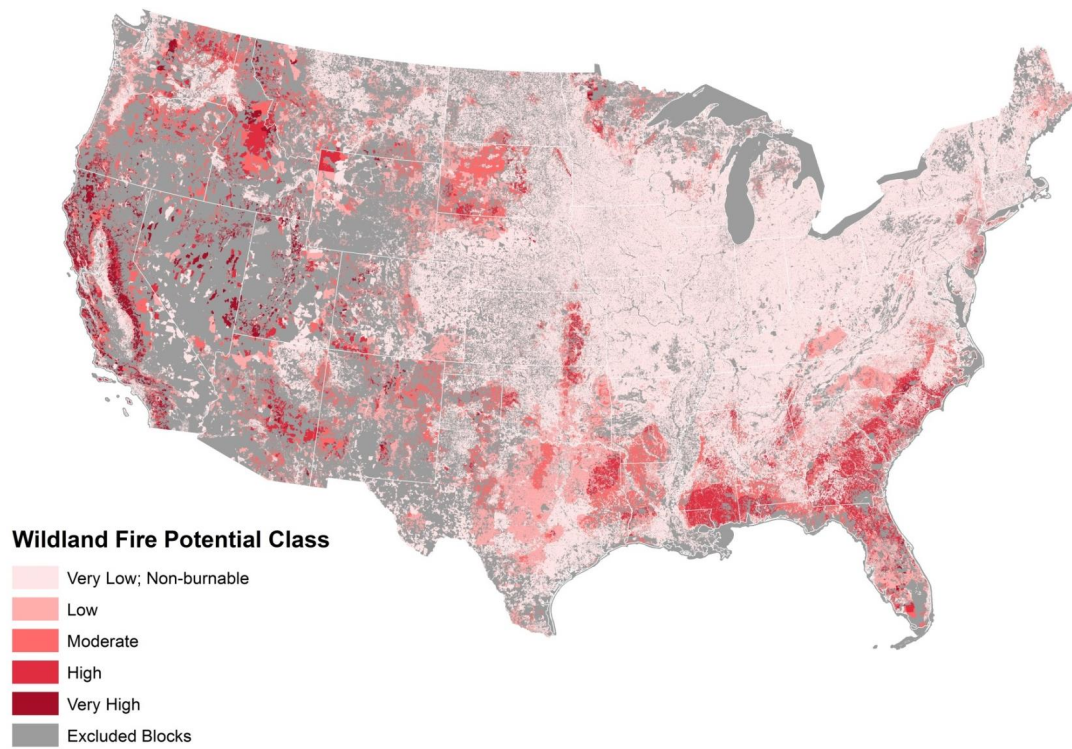
Figure 6. Percentage of housing in each class.
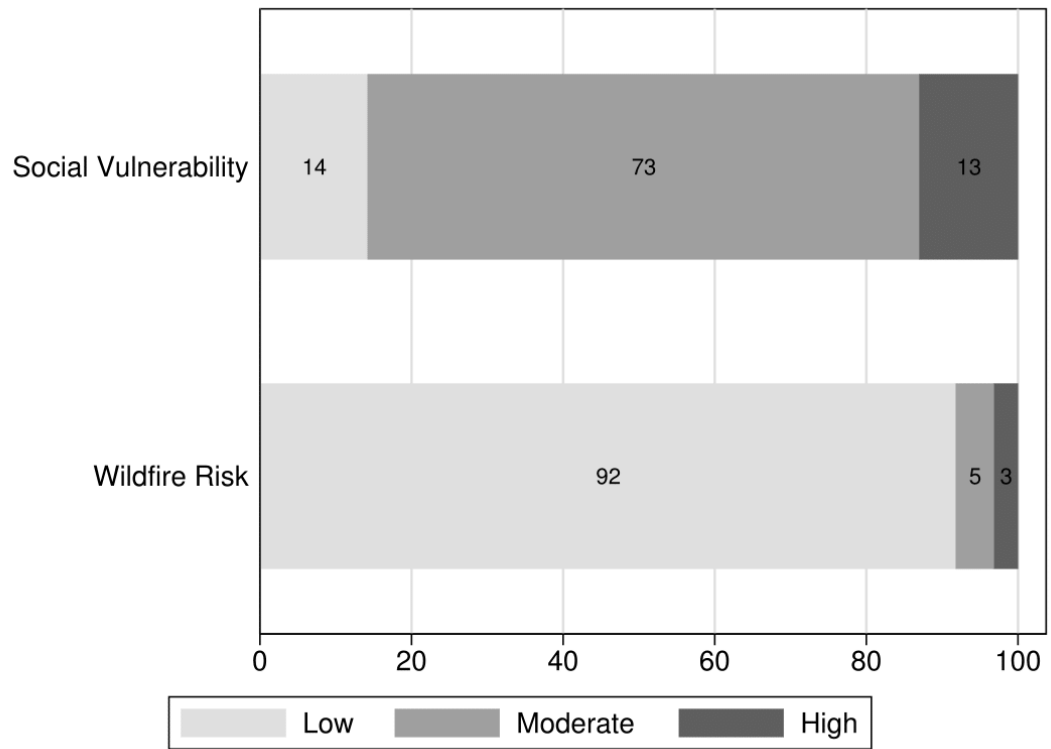
Figure 7. Mean component scores by wildfire risk class (WR) and WUI category.
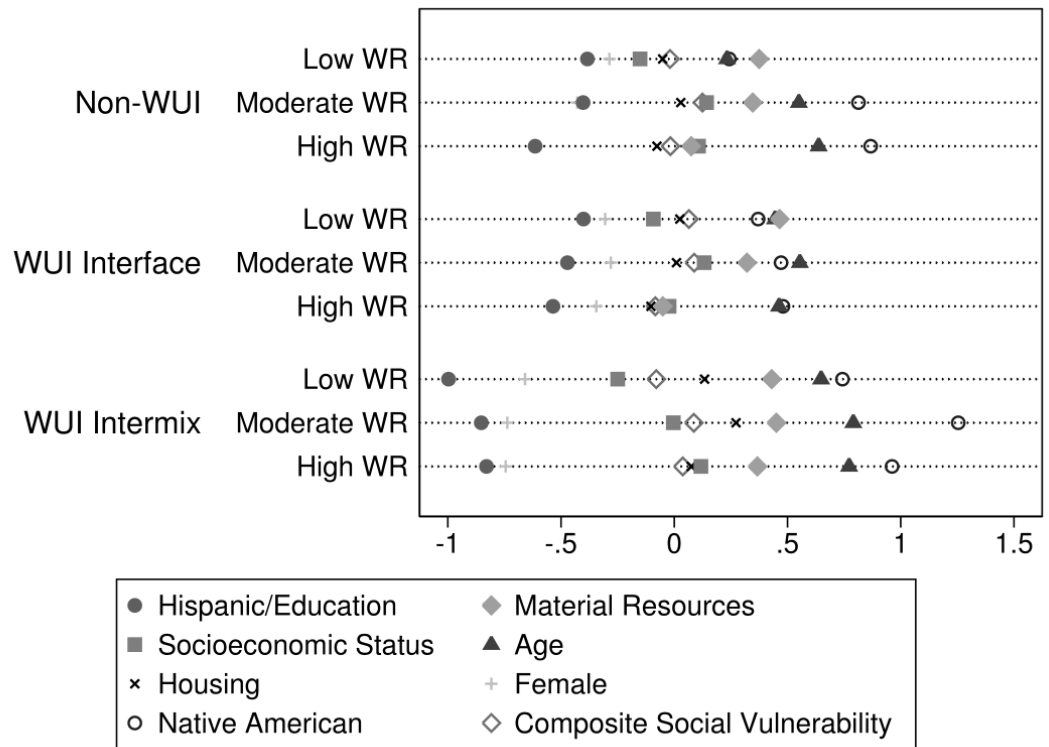
Figure 8. Percentage of housing in each social vulnerability class (SV), of those units in the high wildfire risk class.
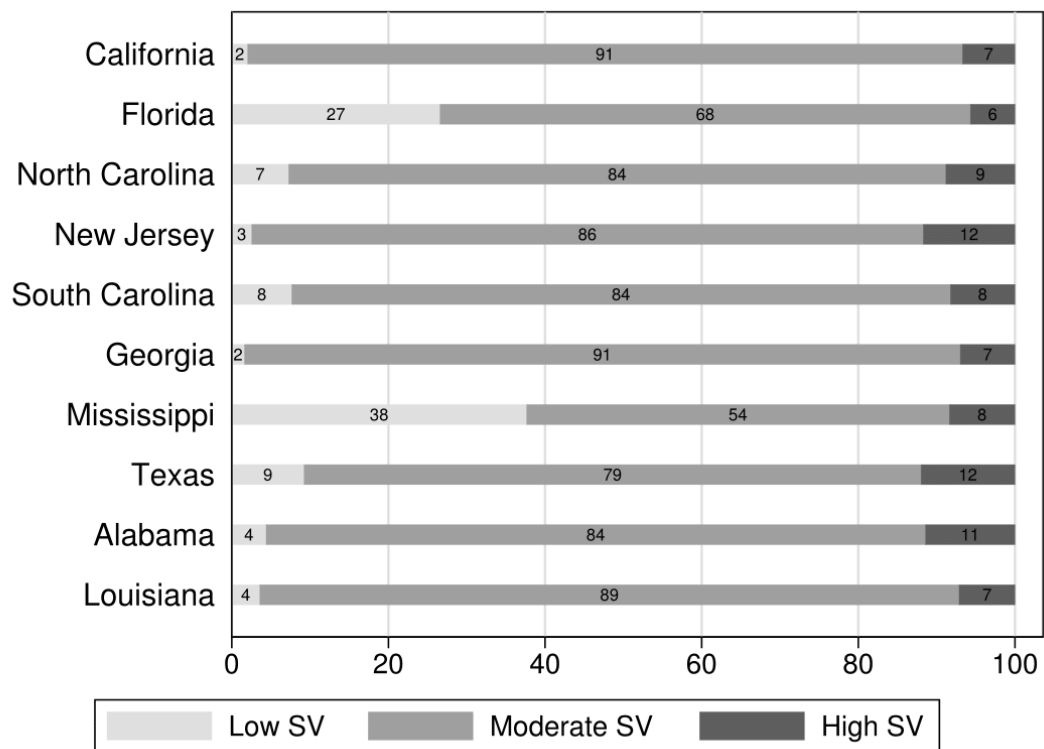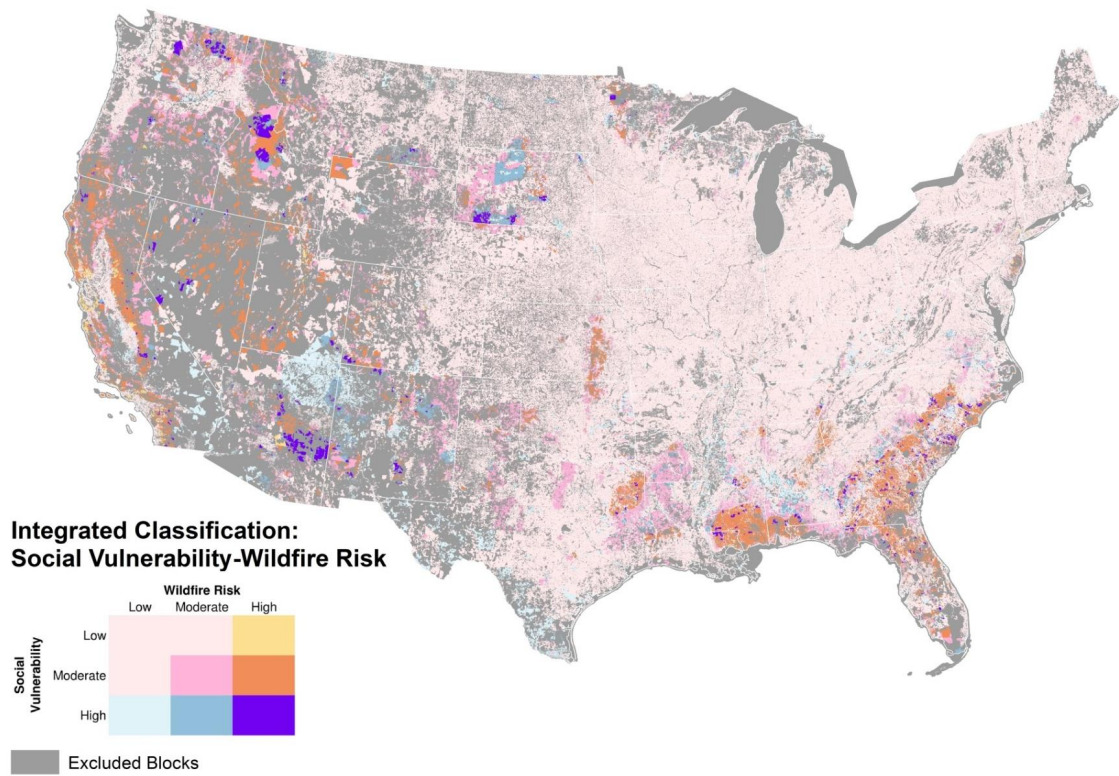
Figure 9. Intersection of social vulnerability and wildfire risk.

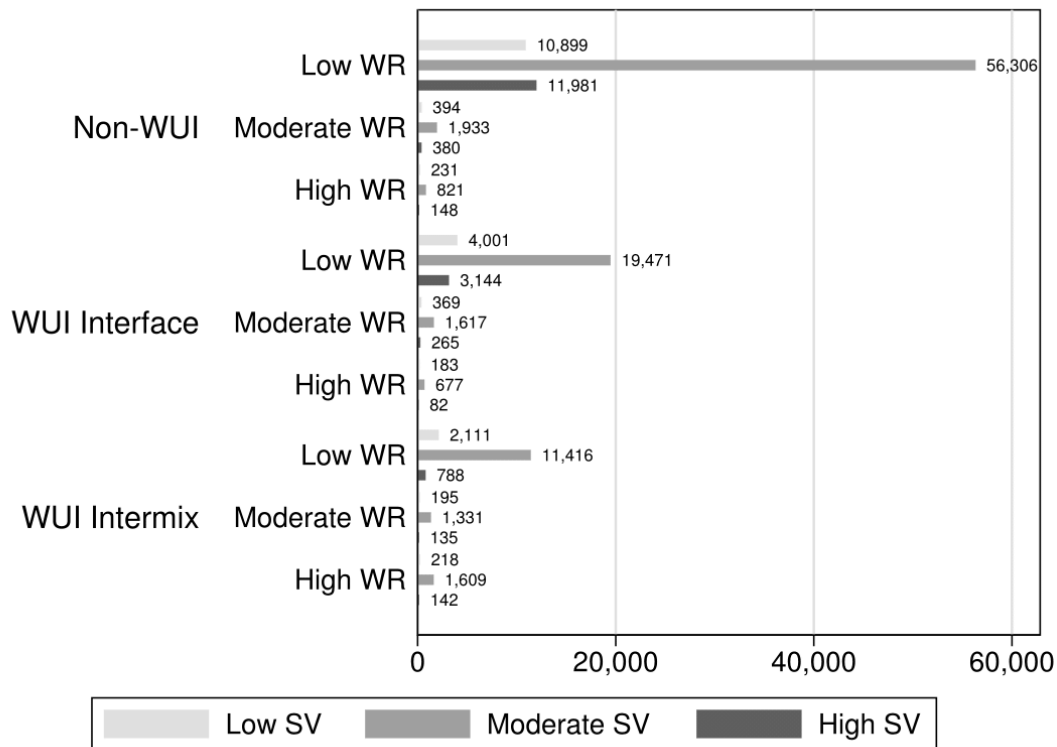**Figure 10. Housing counts (in thousands) by social vulnerability class, wildfire risk class, and WUI category.**

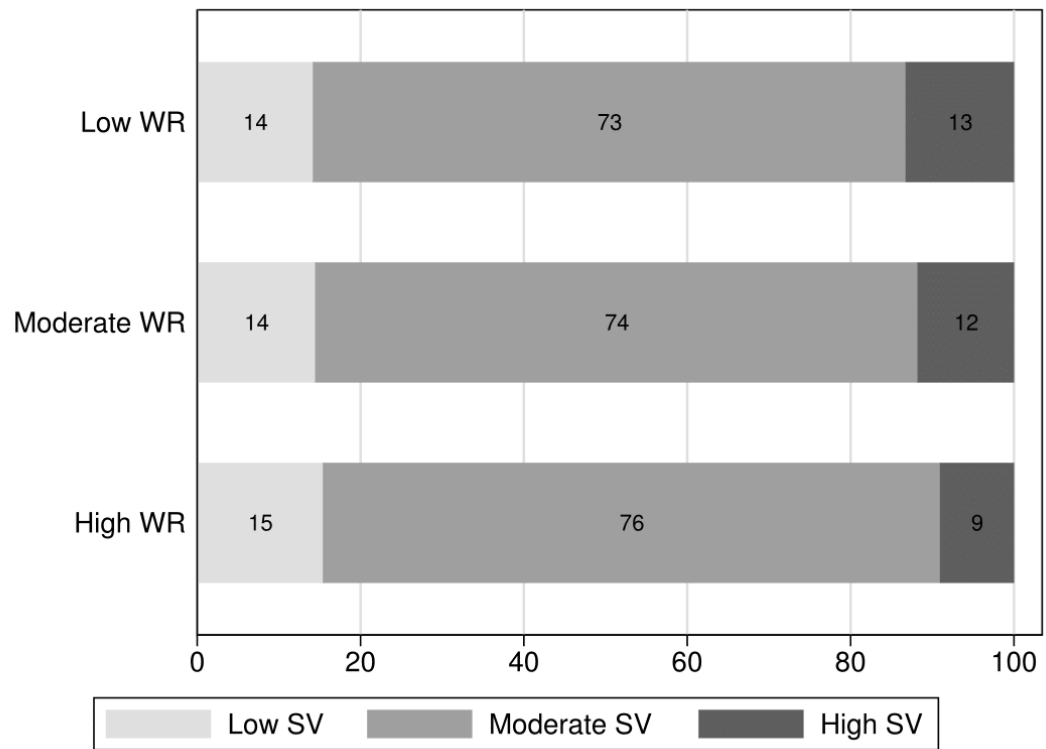**Figure 11. Percentage of housing in each social vulnerability class (SV), by wildfire risk class (WR).**

Figure 12. Percentage of housing in each social vulnerability class (SV), by wildfire risk class (WR) and WUI category.
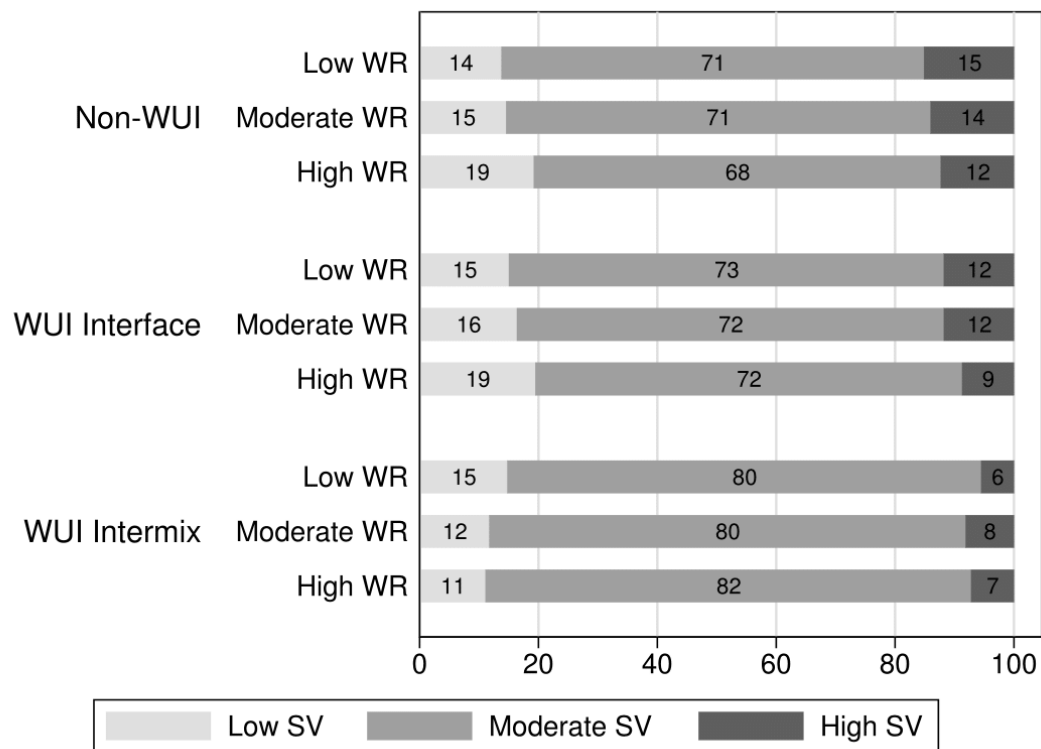
Figure 13. Wildfire risk class (WR) containing the highest average social vulnerability, for *(a)* all blocks, and *(b)* WUI blocks.