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Places where wildfire potential and social vulnerability coincide in the coterminous United States

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Abstract. The hazards-of-place model posits that vulnerability to environmental hazards depends on both biophysical and social factors. Biophysical factors determine where wildfire potential is elevated, whereas social factors determine where and how people are affected by wildfire. We evaluated place vulnerability to wildfire hazards in the coterminous US. We developed a social vulnerability index using principal component analysis and evaluated it against existing measures of wildfire potential and wildland–urban interface designations. We created maps showing the coincidence of social vulnerability and wildfire potential to identify places according to their vulnerability to wildfire. We found that places with high wildfire potential have, on average, lower social vulnerability than other places, but nearly 10% of all housing in places with high wildfire potential also exhibits high social vulnerability. We summarised our data by states to evaluate trends at a subnational level. Although some regions, such as the South-east, had more housing in places with high wildfire vulnerability, other regions, such as the upper Midwest, exhibited higher rates of vulnerability than expected. Our results can help to inform wildfire prevention, mitigation and recovery planning, as well as reduce wildfire hazards affecting vulnerable places and populations.

Additional keywords: environmental hazards, socioeconomic conditions, wildfire policy, wildland–urban interface.

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Introduction

Understanding social issues involving wildfire potential, vulnerability and management (Cortner and Field 2007; McCaffrey *et al.* 2013) is necessary to address persistent economic, structural and human life losses from wildfires as well as rising wildfire management costs (Gall *et al.* 2011; Bracmort 2014; Hoover and Bracmort 2015). Although biophysical characteristics (e.g. climate, vegetation, topography) are useful for predicting where and when wildfires might occur, they have little bearing on predicting where and when wildfires are likely to impact on people or damage valued assets and resources (Dondo Bühler *et al.* 2013; Hawbaker *et al.* 2013; Chuvieco *et al.* 2014). Social conditions, including poverty, age, race and gender, can influence an individual's or a community's ability to plan for, cope with and recover from environmental hazards (Cutter *et al.* 2003). Ideally, wildfire prevention and risk mitigation efforts should prioritise assisting the most vulnerable people and places to ensure that hazard reduction resources and strategies are equitably distributed (Collins 2008*b*; Gaither *et al.* 2011; Ojerio *et al.* 2011; Poudyal *et al.* 2012).

The wildland–urban interface (WUI) is a key factor in current wildfire management and mitigation planning. The WUI identifies the area where human-built environments intermix with, or abut, wildland vegetation (Radeloff *et al.* 2005). Although many WUI delineations do not specifically assess wildfire potential (Stewart *et al.* 2009), the WUI is a major consideration in US federal wildfire management decision-making processes (Bracmort 2014). For example, a portion of federal funding for wildfire management is allocated based on how local communities define and delineate their WUI (Jakes *et al.* 2011). Inasmuch as the WUI factors in wildfire management decisions, by limiting or enhancing local capacities to respond to wildfire, it acts as an institutional constraint contributing to vulnerability (Kelly and Adger 2000). The WUI is expected to grow in the coming decades as greater numbers of houses are built in vegetated landscapes (Theobald and Romme 2007; Hammer *et al.* 2009). This growth likely will increase wildfire potential, through increased ignitions associated with housing development and increasing extreme weather conditions associated with climate change (Bar Massada *et al.* 2009).

Although the WUI describes the intersection of vegetation and housing, other biophysical characteristics, such as vegetation type, topography and climate, largely influence wildfire potential (Hawbaker *et al.* 2013). *Place* vulnerability, however, incorporates concepts of biophysical exposure, social response and the geographic context in which these issues emerge (Cutter 1996). Studies have examined the spatial distribution of wildfire potential and its outcomes against selected social and ecological conditions (Galiana-Martín and Karlsson 2012; Haas *et al.* 2013; Chuvieco *et al.* 2014). However, these studies examined wildfire impacts on human settlements without considering how heterogeneous social conditions can affect hazard outcomes. A few studies have integrated social vulnerability measures with wildfire potential to examine communities' adoption of and participation in wildfire mitigation, prevention and management programs (Gaither *et al.* 2011; Ojerio *et al.* 2011; Poudyal *et al.* 2012). However, they focussed on individual states and used selected indicators of social vulnerability.

We sought to build on previous work by explicitly considering social conditions and by expanding the geographic coverage to the coterminous US. We developed a concept for combining the two factors of place vulnerability as espoused in the hazards-of-place model of vulnerability to environmental hazards (Cutter 1996; Cutter *et al.* 2003), including: (1) the physical exposure conditions operationalised as wildfire potential; and (2) the social conditions summarised in a social vulnerability index. We created a place-based (i.e. US census block) index of social vulnerability and combined this with wildfire potential data at the US census block level. We analysed the relationships between social vulnerability and its components, wildfire potential and WUI designations. Following landscape typology methods (e.g. Nielsen-Pincus *et al.* 2015; Paveglio *et al.* 2015), we then mapped the coincidence of social and biophysical vulnerability for the coterminous US. Finally, we examined whether and by how much coincidence differed from the result that would be expected had we treated social and biophysical vulnerabilities as independent processes.

Literature review

Social conditions and vulnerability to wildfire

Cutter (1996) proposed that place vulnerability to environmental hazards comprises both biophysical and social vulnerability. This holistic conception of vulnerability well applies to wildfire hazards, because wildfire occurrence and extent largely depend on biophysical characteristics, but outcomes can vary among individuals and groups. The hazards-of-place model of vulnerability potentially explains some of the variability observed in people–wildfire interactions, including preparation before, experience during and response following a wildfire.

Social conditions, including wealth, poverty, race and age can often influence wildfire preparation and mitigation. People with greater economic and social resources potentially are better insulated from wildfire impacts, because they are better able to prepare for wildfire hazards (Collins 2005; Poudyal *et al.* 2012). Conversely, recent in-migrants, part-time residents and people whose social and economic lives are less strongly tied to the local landscape are less likely involved in wildfire mitigation activities (Collins 2008*b*), potentially because their social status provides insulation, they lack knowledge of local hazards, or other factors (Larsen *et al.* 2011). Some populations are less involved in wildfire mitigation programs because of their property ownership characteristics, which can reflect racial or geographic biases (Gaither *et al.* 2011). Perceptions about wildfire management and mitigation can vary by race and ethnicity, with Caucasians agreeing more than African Americans and Hispanics that homeowners should be prepared to accept wildfire risks (Bowker *et al.* 2008).

Wildfire prevalence and impacts also can vary with social status. In the upper Midwest, for example, greater proportions of owner-occupied (versus renter-occupied) housing are associated with less frequent wildfire activity (Cardille *et al.* 2001). In Argentina, impoverished neighbourhoods – those with high unemployment and few children attending school – experience more frequent wildfires (de Torres Curth *et al.* 2012). In the US, wildfires that begin in poor communities are less likely to be extinguished quickly for lack of resources (Mercer and Prestemon 2005). Health impacts from wildfire smoke disproportionately affect the elderly (Kochi *et al.* 2012). Moreover, ecological damage resulting from wildfires can harm the natural resource base from which communities derive economic activity and employment (Butry *et al.* 2001). Such damage in extractive industry-dependent communities can have long-lasting economic effects (Niemi and Lee 2001). Communities with large proportions of Hispanic populations have stronger declines in property values after wildfires than others (Fu 2013). Taken together, these findings suggest that social conditions can be key determinants of social vulnerability and wildfire hazard outcomes. Understanding how these vulnerability components vary can help hazard managers develop protection and mitigation strategies appropriate to specific places and populations (Solangaarachchi *et al.* 2012).

Wildfire hazards and human agency

Understanding the confluence of social and biophysical vulnerability is especially relevant for wildfire. Wildfire is, in part, a function of human agency. The frequency, severity and pattern of wildfire are significantly related to human activities, including land use, settlement patterns and vegetation management (Syphard *et al.* 2007; Hawbaker *et al.* 2013; Syphard *et al.* 2013). For example, wildfire occurrence is positively associated with population and housing density (Syphard *et al.* 2007; Hawbaker *et al.* 2013), because people cause the majority of wildfire ignitions and human land uses greatly influence vegetation patterns and thus fire behaviour (Prestemon *et al.* 2013). Development in fire-prone landscapes in the US is facilitated by political and economic conditions and processes. Environmental amenities raise property values in these locations and are an important pull factor (Stetler *et al.* 2010).

Additionally, factors such as public-sector fire suppression, homeowners' insurance that is indiscriminate with regard to wildfire hazard and disaster assistance incentivise human settlement by subsidising the costs that homeowners face from wildfire risk (Holmes *et al.* 2007; Collins 2008*a*; Fu 2013; Simon and Dooling 2013). In many ways, wildfire is 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 the residents at risk (O'Donnell *et al.* 2014). Although the relationship between residential mitigation activity and social costs of wildfire is complex (e.g. Prante *et al.* 2011), individuals still bear responsibility for wildfire mitigation activities on private property (Collins 2008*a*; Fu 2013). This creates a two-tiered culture of social conditions featuring disproportionate risks and benefits (Collins and Bolin 2009). Less vulnerable residents, such as homeowners and the wealthy, benefit from socialised costs of wildfire protection and are better able to assume responsibility for mitigating wildfire potential. More vulnerable residents, such as renters and the poor, are less able to benefit and less able to assume responsibility for mitigating risk (Collins 2008*a*; Fu 2013; Simon and Dooling 2013).

Because the incentives that encourage development in fire-prone landscapes tend to benefit advantaged (less vulnerable) groups, we expect that such locations have lower social vulnerability. Using a null hypothesis that wildfire potential and social vulnerability are not associated, we can test an alternative hypothesis that they are related and that high-wildfire-potential locations exhibit lower social vulnerability. However, we recognise the diversity of social conditions in these landscapes (e.g. Nielsen-Pincus *et al.* 2015; Paveglio *et al.* 2015), and also expect that there are some places where high social vulnerability does occur within high-wildfire-potential areas.

Policies intended to mitigate biophysical vulnerability to wildfire also can vary in their effectiveness. Federal appropriations provide funds for preparedness, suppression, hazardous fuels reduction, rehabilitation and wildfire management activities (Steelman and Burke 2007; Hoover and Bracmort 2015). However, Calkin *et al.* (2014) suggested that to reduce home (or structure) losses, policies should focus on reducing home susceptibility to ignition – commonly considered the responsibility of individual property owners. In large part, this view stems from the idea that wildfires are inevitable in some locations, making reductions in home ignitability an effective strategy. State and local governments also increasingly are involved in wildfire management (Davis 2001; Titus and Hinderman 2006), and there are numerous local governmental wildfire management and direct homeowner assistance programs, including free defensible space clearing (e.g. Reams *et al.* 2005).

Indeed, some federal policies indirectly support individuals in reducing their vulnerability to wildfire. For example, the Healthy Forests Restoration Act of 2003 provides communities opportunities to develop Community Wildfire Protection Plans to improve their adaptive capacity to wildfire (Grayzeck-Souter *et al.* 2009; Jakes *et al.* 2011; Williams *et al.* 2012), and these have been shown to improve community resilience (Jakes and Sturtevant 2013). Although plans identify and prioritise lands for fuels reduction, they often include recommendations for reducing the ignitability of structures (though individual responsibility for private property remains the norm) (Jakes *et al.* 2011). Facilitating the development of Community Wildfire Protection Plans in vulnerable communities could help to reduce their susceptibility to wildfire impacts, but this depends on communities having access to adequate resources (Jakes *et al.* 2011). Socially vulnerable communities are generally 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).

Federal wildfire management planning efforts seek to incorporate evaluations of selected social conditions (Wildland Fire Executive Council 2014). Policy targeting and implementation ideally 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). A process of identifying those places most vulnerable to wildfire would support developing tailored and context-specific policies at different jurisdictional levels.

There are a variety of ways to identify and define vulnerable communities. Creating typologies or archetypes of private lands or communities could help structure policy to achieve specific and targeted goals (Nielsen-Pincus *et al.* 2015; Paveglio *et al.* 2015). Given the diversity of social and biophysical conditions across the landscape, mapping their coincidence would enable identifying vulnerability typologies. Using a null hypothesis that social vulnerability and wildfire potential are independent phenomena, we can test an alternative hypothesis that they are not independent, to examine relative incidence rates of vulnerability typologies.

Materials and methods

We examined the distribution of place vulnerability to wildfire in the coterminous US by developing neighbourhood-level social vulnerability measures following methods developed by Cutter *et al.* (2003) and combining these with existing data characterising biophysical vulnerability to wildfire. We mapped these data to show the coincidence of social vulnerability and wildfire potential, and their spatial pattern relative to WUI designations. We examined all terrestrial census blocks (i.e. excluding water blocks) containing housing units, as represented in the 2010 version of the WUI maps of Radeloff *et al.* (2005) (SILVIS Lab 2012). We assigned WUI designations at the block level: either WUI or non-WUI. Some of the census blocks in the dataset differed from US-designated census blocks, because they have been divided into sub-blocks containing either public lands or housing units. These adjusted census blocks are a more precise representation of inhabited areas, because they analyse large areas of uninhabited public lands and human settlements separately. We focussed on housing units as a measure of human habitation, rather than population, because housing generally is the focus of wildfire hazards management. Moreover, housing and population are strongly correlated (Pearson's correlation $\rho = 0.90$).

Social vulnerability

Cutter *et al.* (2003) pioneered the development of inductive social vulnerability indices based on principal component analysis, to examine various demographic and place-based indicators presumed to indicate likely social vulnerability. Principal component analysis is a statistical technique that distils a large set of variables into fewer related components to

Table 1. List of variables used to create the social vulnerability index
All data sourced from 2006–10 American Community Survey except 'percentage 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
Percentage of population under 5 years or 65 and older
Percentage Asian
Percentage Black or African American
Percentage civilian unemployment
Percentage of population aged 25 years or older with less than 12th grade education
Percentage speaking English as a second language with limited English proficiency
Percentage employment in extractive industries
Percentage female
Percentage female participation in labour force
Percentage female-headed households
Percentage Hispanic
Percentage mobile homes
Percentage Native American
Percentage of housing units with no cars
Percentage of population living in nursing and skilled-nursing facilities
Percentage poverty
Percentage renters
Percentage of households earning greater than US$200 000 annually
Percentage employment in service industry
Percentage of households receiving social security
Percentage unoccupied housing units

enhance their interpretability. Components also can be combined into one or more composite indices. Resulting social vulnerability indices are relative metrics that rank social vulnerability among observational units, making them useful for identifying priority locations for hazard management. Although the social vulnerability index of Cutter *et al.* (2003) was created at the county level for the US using 42 variables, their method has proved to be statistically robust, particularly in regard to changes in spatial scale and variable selection (Schmidtlein *et al.* 2008). These characteristics suggested that the methodology was well suited for application both at the census block level and including variables associated specifically with wildfire hazards.

We constructed our social vulnerability index using census block group data from the 2010 US Census and the 2006–10 American Community Survey. Census block groups – the second-smallest census unit of analysis – are aggregates of census blocks, and are the smallest unit for which data relevant to this analysis are published. We selected 26 socioeconomic and demographic variables (Table 1) based on theoretical foundations established by Cutter *et al.* (2003), subsequent applications of their methodology (e.g. Wood *et al.* 2010; Tate 2011; Solangaarachchi *et al.* 2012), and other wildfire-specific social vulnerability studies (Gaither *et al.* 2011; Ojerio *et al.* 2011; Poudyal *et al.* 2012).

We normalised all variables using z-score standardisation, giving each of them a mean of zero and a standard deviation of 1. As principal component analysis cannot include observations with missing data, we assigned a mean variable value of zero to any block groups having missing values. Values for all variables were available for 181 610 of the 215 271 block groups examined, and only 899 block groups (0.42%) required imputation of two or more variables. Tate (2011) has suggested adjusting the directionality of variables for which high values indicate lower levels of social vulnerability before the application of principal component analysis, to provide consistency such that high levels of all variables indicate high levels of social vulnerability. Following Tate (2011), we reversed the directionality of the standardised variables: percentage of households earning more than US$200 000 annually, per capita income, median house value and median gross rent. Because both high and low values of median age conceivably can indicate high vulnerability (Tate 2012), we used the absolute value of this standardised variable.

We performed principal component analysis on the 26 standardised variables. Again following Cutter *et al.* (2003), we applied Kaiser's criterion (i.e. eigenvalues greater than 1) to select the number of components to retain, and confirmed our selection using parallel analysis (Patil *et al.* 2008; Tate 2011). We then applied varimax rotation to the selected components (Cutter *et al.* 2003), which aids qualitative interpretation by minimising the number of highly loading variables on each component.

We created our composite social vulnerability score for each block group by weighting component scores by each component's proportion of explained variance and summing the resulting weighted components (Schmidtlein *et al.* 2008; Wood *et al.* 2010). We did this because proportional weights can complement principal components analysis, which mathematically emphasises those components explaining a greater proportion of the variation observed among the input variables (Schmidtlein *et al.* 2008). We normalised the social vulnerability scores using z-score standardisation. 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 as 'high', and remaining block groups as 'moderate'. Finally, we assigned the components, normalised scores and social vulnerability classes to individual census blocks according to their respective census block group, to match spatial scales of analysis between the datasets.

Biophysical vulnerability

We obtained data describing wildfire potential from the 2012 Wildland Fire Potential dataset (USDA Forest Service 2012). The map shows the relative potential for difficult-to-suppress wildfires of all sizes based on past fire occurrence, fuel, and wildfire likelihood and intensity estimates. The dataset categorises each 7.29-ha cell according to one of seven wildfire potential values: very low, low, moderate, high, very high, water and non-burnable. The dataset attempts to address concerns about both large and small wildfires, resulting in some places not commonly associated with recent large destructive wildfires (e.g. New Jersey, New York) being categorised as having high wildfire potential. The data were unavailable for 1627 of the census blocks included in our initial study population, because the dataset does not entirely align with census boundary designations. The final study population consisted of 6 623 461 census blocks for which both social vulnerability and wildfire potential data were available.

We assigned the modal wildfire potential value to each census block. Various methods for aggregating spatial data exist (e.g. mean averaging, central-pixel resampling, median averaging). Although Bian and Butler (1999) suggest support for the mean and median averaging methods, the wildfire potential categories are not necessarily interval, because differences between adjacent values are not necessarily equivalent, thus precluding our use of mean averaging. Given a strongly right-skewed variable distribution, we felt it was most appropriate to assign the most typical wildfire potential value to each census block. To aid later interpretation and analysis, we collapsed the wildfire potential categories into three broader classes: (1) 'low' wildfire potential included water and non-burnable lands, very low and low categories; (2) 'moderate' included the moderate category; and (3) 'high' included the high and very high categories, consistent with other applications of this dataset (e.g. Kline *et al.* 2013).

Our choice to use census blocks as our summary unit potentially raises the modifiable areal unit problem (MAUP, Fotheringham and Wong 1991; Dark and Bram 2007). The MAUP occurs whenever administrative boundaries are used to delineate units of analysis and to summarise data. A different set of boundaries delineating the units of analysis, i.e. a different way to delineate census blocks, could have changed our results. We were not able to evaluate the extent to which the MAUP affected our results by actually changing census block boundaries, because only the Census Bureau has access to the data provided by each respondent. However, we did compare our overall assessment of wildfire potential with those compiled by others. In the summary data reported along with the wildfire potential dataset, 8 and 4% of all land in the coterminous US were classified as high and very high wildfire potential respectively (USDA Forest Service 2012). In our study, our mode classification resulted in 6.1 and 2.0% classified as high and very high wildfire potential respectively, which we deemed reasonably close to the prior estimate.

Hypothesis testing

We produced summary statistics for our social vulnerability index and wildfire potential datasets. To test our hypothesis that high wildfire potential areas exhibit lower social vulnerability, we conducted a two-way factorial ANOVA examining the effect of wildfire potential (the raw mode value rather than the aggregated categories), the WUI dummy variable and their interaction on the social vulnerability variable. We conducted similar analyses for the individual component variables of social vulnerability, but using the three collapsed wildfire potential classes and without an interaction term.

We also evaluated and mapped the coincidence of social vulnerability and wildfire potential through cross-tabulation (Haas *et al.* 2013; Chuvieco *et al.* 2014). Our three-way cross-tabulation of the three social vulnerability classes, three wildfire potential classes and two WUI designations resulted in eighteen typologies of vulnerability to wildfire. For each typology, we computed housing unit counts and expected housing unit counts given the null hypothesis that social vulnerability and wildfire potential are independent (controlling for WUI designation). To test our alternative hypothesis of dependence, we calculated chi-square test statistics for the two partial contingency tables (non-WUI and WUI).

Finally, we summarised data by state to evaluate subnational trends. For the high-social-vulnerability–high-wildfire-potential type (collapsed across WUI designations), we computed total housing units, housing units as a proportion of the state's total housing unit count, and the ratio of observed housing units to expected housing units (given the null hypothesis of independence between social vulnerability and wildfire potential at the state level). Our goal was to show examples of how vulnerability data can be summarised at a given geographic unit of analysis to identify vulnerable areas or regions for policy intervention. States, however, are just one of many potential areal units (e.g. counties, ecoregions, Forest Service regions), and so our analysis is but one of many ways that vulnerability data could be summarised.

Results

Our study population represented nearly 100% of the housing units (~32 000 of 131 million were not included), and 99% of the people in the coterminous US. Within this study population, WUI census blocks comprised 17% of the land area and 36% of the housing units and people.

Our principal component analysis of social vulnerability resulted in our retaining seven components, which cumulatively accounted for 63% of the total variance, and each rotated component explained between ~5 and 12% of the total variance (Table 2). Individual components were labelled to reflect the predominant loading variables. We generated social vulnerability scores (Fig. 1) for the more than 6 623 000 study population census blocks. The mean block social vulnerability score was 0.00 with a standard deviation of 0.86. Social vulnerability scores were distributed with skewness of 0.34 and kurtosis of 3.74. Skewness ($P < 0.01$) and kurtosis ($P < 0.01$) tests for normality indicated that the population distribution was significantly different than a normal distribution. However, the large population size and the approximately normal shape of the distribution allowed the use of parametric hypotheses tests. Nearly 10% of blocks had scores lower than -1.0 and slightly more than 11% had scores greater than 1.0. Therefore, our classification system is more centrally biased than what would result from a standard normal distribution – 16% on either end. Our classification system is similar to what Cutter *et al.* (2003) developed for social vulnerability to hazards generally at the US county level, wherein 12.5% of counties were classified at the highest vulnerability level.

Our two-way factorial ANOVA examining the effect of wildfire potential and WUI designation on social vulnerability indicated that both variables, as well as their interaction with each other, were statistically significant (F (5, 6 623 449) = 9140.29, $P < 0.0001$; F (1, 6 623 449) = 61.75, $P < 0.01$; F (5, 6 623 449) = 947.28, $P < 0.01$ respectively). Blocks with very high wildfire potential had the lowest average social vulnerability compared with other wildfire potential levels (Fig. 2). WUI blocks had lower social vulnerability than non-WUI blocks. Post hoc analysis using the Bonferroni multiple-comparison test

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

Component	% of variance explained	Dominant variable	Variable Loading
Hispanic/Education	12.17	Speaking English as a second language with limited English proficiency (%)	+0.5112
		Hispanic (%)	+0.4639
		Less than 12th grade education (%)	+0.3325
Material resources	12.12	Households earning greater than US$200 000 annually[A] (%)	+0.5209
		Median house value[A]	+0.5021
		Per capita income[A]	+0.4664
		Median gross rent[A]	+0.3621
Socioeconomic status	10.37	Black (%)	+0.4915
		Civilian unemployment (%)	+0.4560
		Female-headed households (%)	+0.4108
		Poverty (%)	+0.3271
Age	8.68	Population under 5 years or 65 and older (%)	+0.5831
		Households receiving social security (%)	+0.5631
		Median age[B]	+0.3538
Housing	7.54	People per unit	−0.6054
		Unoccupied housing units (%)	+0.4497
		Renters (%)	+0.3865
		Housing units with no cars (%)	+0.3193
Female	7.21	Female (%)	+0.5961
		Female participation in labour force (%)	+0.5717
Native American	4.67	Native American (%)	+0.7203
		Employment in extractive industries (%)	+0.3399
		Mobile homes (%)	+0.3269

[A]The directionality of this standardised variable was reversed before principal component analysis.
[B]The absolute value of this standardised variable was used in the principal component analysis.

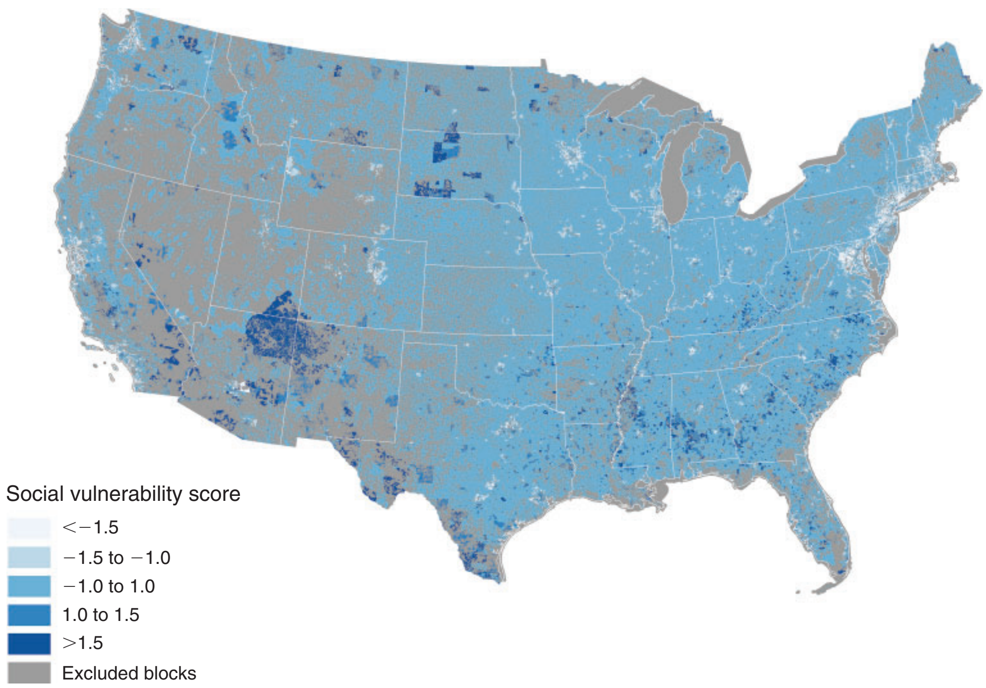

Fig. 1. Social vulnerability scores for the coterminous US.

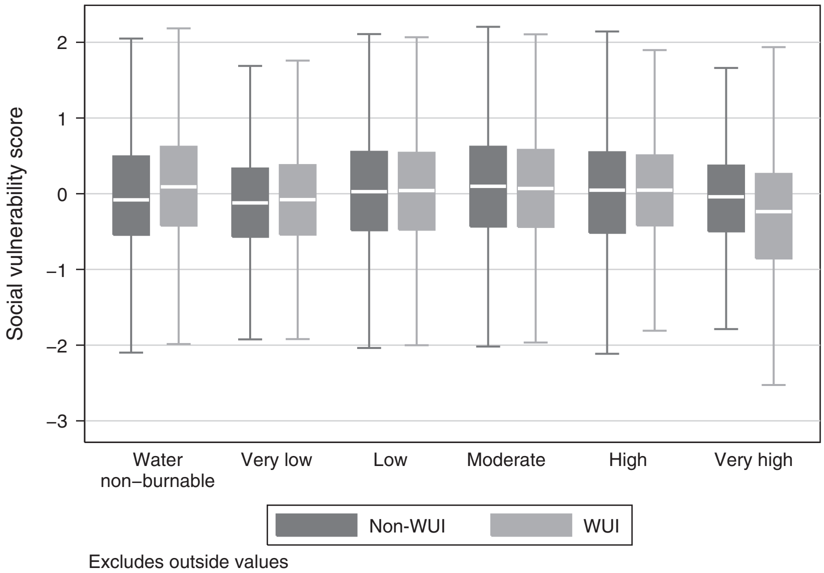

Fig. 2. Box plots of social vulnerability scores by wildfire potential values and wildland–urban interface (WUI) designation. Box plots show median value (white horizontal line), 25th and 75th percentiles (lower and upper box boundaries) and ±1.5 interquartile range (whiskers). Outside values are not shown.

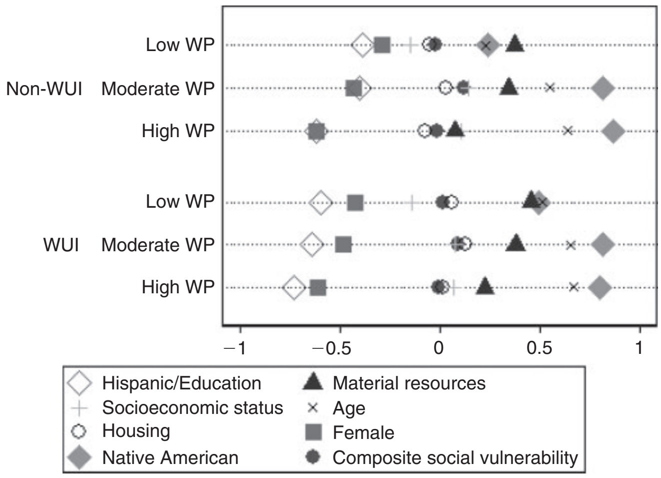

Fig. 3. Mean component scores by wildfire potential (WP) class and WUI designation.

indicated which pairwise comparisons were significant. Considering the main effect of wildfire potential, all pairwise comparisons were significant ($P < 0.01$). Considering the interaction between wildfire potential and WUI designation, very-high-wildfire-potential blocks in the WUI had the lowest social vulnerability ($P < 0.01$). Non-WUI blocks with either very high or very low wildfire potential had the next lowest social vulnerability, but the effect was not statistically significant ($P > 0.05$). Taken together, our results suggested that both wildfire potential and WUI designation are associated with social vulnerability. Specifically, high wildfire potential, whether in the WUI or not, is associated with the lowest average social vulnerability scores.

Using our collapsed wildfire potential categories, we found nearly 225 000 blocks (3%) to have 'high' wildfire potential, whereas blocks with 'low' wildfire potential represented nearly all housing units (91%). The components of social vulnerability varied by these wildfire potential classes as well as WUI designation (Fig. 3). Our two-way ANOVAs examining the effect of these collapsed wildfire potential classes and a WUI dummy variable on each component of social vulnerability indicated that blocks with high wildfire potential had the lowest average vulnerability scores for the Hispanic/Education, Materials Resources, Housing and Female components (using the Bonferroni multiple-comparison test, pairwise comparisons between the three wildfire potential classes for each vulnerability component were significant, $P < 0.01$). Low vulnerability scores for these components may represent higher rates of non-Hispanics, higher income populations, fewer renters and gender

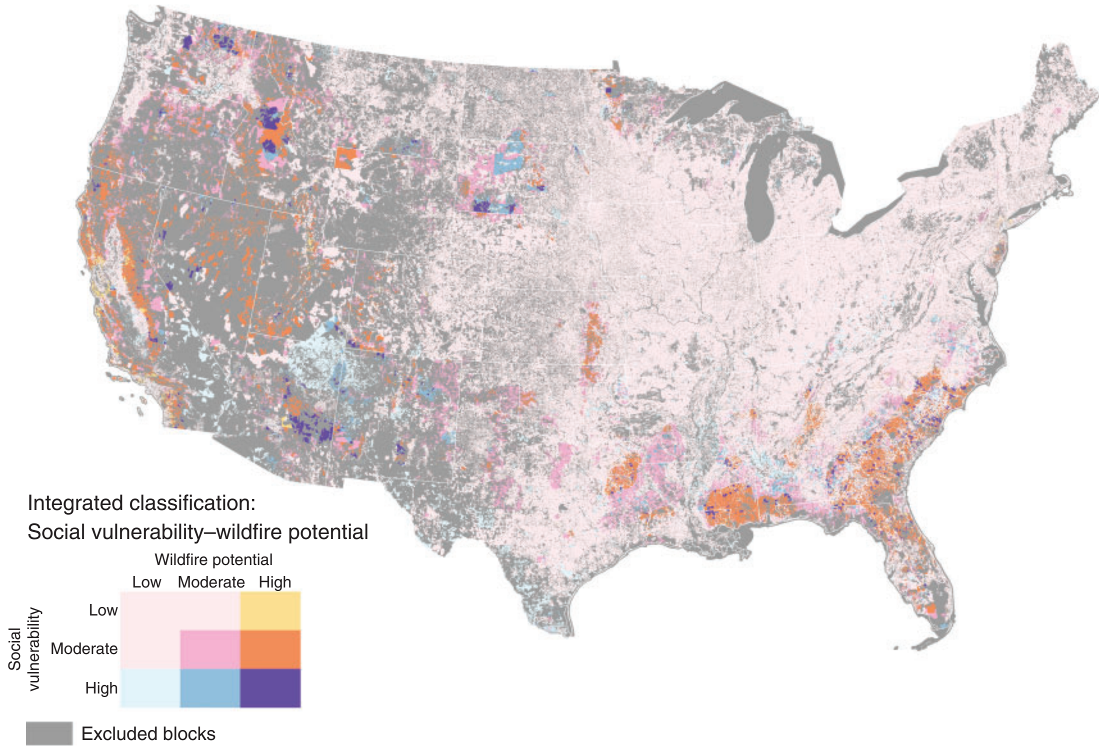

Fig. 4. Intersection of social vulnerability and wildfire potential.

Table 3. Housing unit counts for the 18 vulnerability typologies

For each typology, rows display actual housing unit counts, expected housing unit counts (calculated as if social vulnerability and wildfire potential (WP) were independent, controlling for wildland–urban interface (WUI) designation), and difference (actual – expected)

Social vulnerability		Non-WUI Low WP	Non-WUI Moderate WP	Non-WUI High WP	WUI Low WP	WUI Moderate WP	WUI High WP
Low	Actual	10 899 289	393 632	230 605	6 112 280	563 102	401 976
	Expected	10 981 856	375 342	166 328	6 066 141	579 681	431 536
	Actual – Expected	−82 567	18 290	64 277	46 139	−16 579	−29 560
Moderate	Actual	56 305 944	1 932 709	820 797	30 886 660	2 947 704	2 285 812
	Expected	56 283 325	1 923 674	852 452	30 959 304	2 958 474	2 202 398
	Actual – Expected	22 619	9035	−31 655	−72 644	−10 770	83 414
High	Actual	11 981 140	380 122	147 933	3 932 243	400 582	223 994
	Expected	11 921 193	407 447	180 555	3 905 738	373 233	277 848
	Actual – Expected	59 947	−27 325	−32 622	26 505	27 349	−53 854

ratios skewed towards males respectively. Blocks with high wildfire potential had the highest average vulnerability score for the Age component ($P < 0.01$), possibly reflecting relatively older populations compared to other blocks. Blocks with high or moderate wildfire potential had the highest average vulnerability scores for the Native American component, but this effect was not significant ($P > 0.05$). These blocks likely have higher proportions of Native American populations. Considering the main effect of WUI designation, WUI blocks had lower vulnerability scores, on average, than non-WUI blocks for the Hispanic/Education and Female components and higher vulnerability scores, on average, for the Material Resources, Age, Housing and Native American components ($P < 0.01$). There was no significant difference between WUI and non-WUI blocks for the Socioeconomic Status component ($P > 0.05$).

Areas with both high social vulnerability and high wildfire potential (collapsed across WUI designation) contained nearly 372 000 housing units (Fig. 4). Non-WUI blocks contained ~148 000 of these housing units whereas WUI blocks contained 224 000 units (Table 3). We separately tested the partial contingency tables (non-WUI/WUI) for independence between social vulnerability and wildfire potential. For both tables, social vulnerability and wildfire potential were related (non-WUI: χ^2 (4, $n = 83\,092\,171$) = 36 000, $P < 0.001$; WUI: χ^2 (4, $n = 47\,754\,353$) = 19 000, $P < 0.001$). For both WUI and non-WUI areas, there were more housing units in the

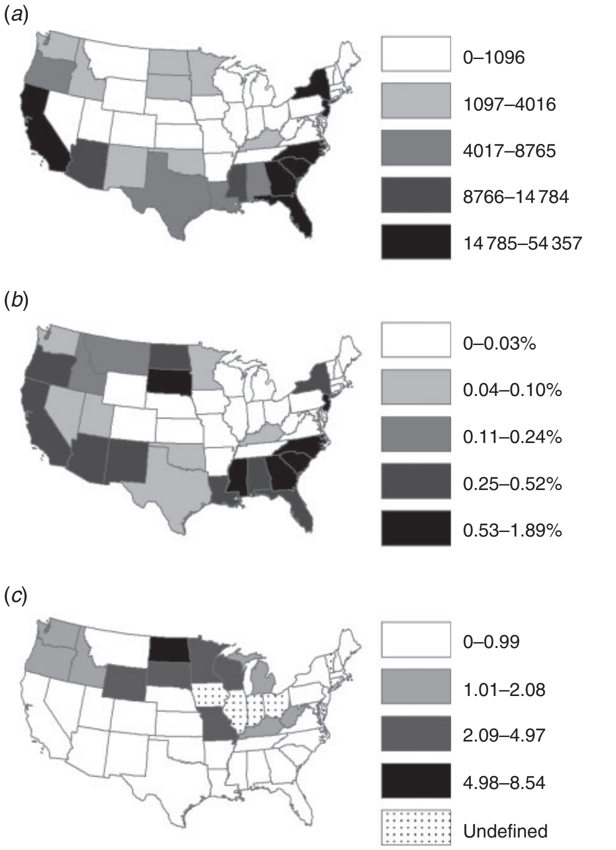

Fig. 5. Housing with high vulnerability. (*a*) Housing unit counts in the high-social-vulnerability, high-wildfire-potential typology; (*b*) proportion of state's housing units that are in the high-social-vulnerability, high-wildfire-potential typology; and (*c*) ratio of actual to expected housing unit count in the high-social-vulnerability, high-wildfire-potential typology (states marked 'Undefined' had an expected count of zero).

high-wildfire-potential–low-social-vulnerability type than the high-wildfire-potential–high-social-vulnerability type. Considering the high-wildfire-potential–high-social-vulnerability type, there were fewer housing units in both WUI and non-WUI areas than we expected. But in the high-wildfire-potential–low-social-vulnerability type, we observed fewer than expected housing units in WUI blocks and more than expected housing units in non-WUI blocks. Again, we concluded that wildfire potential and social vulnerability are negatively related.

Nearly 78% of all housing units in the high-social-vulnerability–high-wildfire-potential type were located in seven states: California, North Carolina, Florida, South Carolina, Georgia, New Jersey and New York (Fig. 5*a*). New Jersey and New York were notable among these, as they are not commonly associated with recent large destructive wildfires. This result likely reflects attempts to balance large and small wildfire concerns within the wildfire potential dataset. South Carolina, North Carolina, Mississippi, South Dakota, New Jersey and Georgia were ranked highest in the proportion of housing units falling in the high-social-vulnerability–high-wildfire-potential type (Fig. 5*b*). Computing the ratios of observed housing unit counts to the expected housing unit counts (Fig. 5*c*), we found that states with ratios less than 1 had fewer than expected housing units, whereas greater than 1 had more than expected housing units. North Dakota, South Dakota, Wyoming, Wisconsin, Missouri, Minnesota and Washington were the highest-ranked states in this regard. The rankings demonstrate how vulnerability data can be used to identify socially vulnerable locations or regions for policy intervention, with hazard managers able to choose the summary geography appropriate to their intervention goal.

Discussion

We found that areas of high wildfire potential exhibited, on average, lower social vulnerability. However, high social vulnerability and high wildfire potential do intersect, and affect ~372 000 (0.3%) of the housing units in the coterminous US. Overlap between social vulnerability and wildfire potential suggests a need to evaluate wildfire management policies with regard to social conditions. Although 372 000 housing units represent only a small fraction of all housing in the coterminous US, it is more than two orders of magnitude greater than the average number of residences (1372) burned by wildfires annually between 1999 and 2011 (National Interagency Fire Center 2014). Nine per cent of housing units in high-wildfire-potential areas also had high social vulnerability. Given that communities with higher social vulnerability participate less often in wildfire mitigation programs (Gaither *et al.* 2011; Ojerio *et al.* 2011), our study can help to identify those communities that could benefit from additional wildfire management assistance. Because so few communities exhibit both high social vulnerability and high wildfire potential, mitigation programs may not need to target social vulnerability as a special concern.

We found that ~40% of housing units in areas of both high social vulnerability and wildfire potential were in non-WUI blocks. Radeloff *et al.* (2005) WUI delineations are based on federal WUI definitions that do not 'assess wildland fire risk specifically' (Radeloff *et al.* 2005, p. 803). Although communities developing Community Wildfire Protection Plans under the Healthy Forests Restoration Act are able to define their WUI using flexible criteria (Grayzeck-Souter *et al.* 2009), plans often fail to identify adjacent areas that contribute to wildfire potential (Ager *et al.* 2015). Thus, reliance on federal or locally generated WUI definitions alone may lead to the underestimation of wildfire vulnerability in some communities. This is noteworthy because a portion of fuel reduction funding is allocated based on WUI delineations (Jakes *et al.* 2011).

We found that wildfire potential was negatively related to social vulnerability. Case studies may help explain this divergence between biophysical and social vulnerability. In some parts of California, political and economic processes have incentivised residential development in high-wildfire-potential areas (Fu 2013; Simon and Dooling 2013). For example, Fu (2013) suggested that some architectural restrictions meant to reduce home ignitability are only feasible for the advantaged and hence less vulnerable. Fu (2013) argued that by providing the impression of safety, these processes have encouraged human settlement in high-wildfire-potential areas that may otherwise have remained uninhabited. In the political ecology tradition, marginalisation produces vulnerability. However, Collins (2008*a*) suggested that facilitation, the antithesis of marginalisation, may be the more relevant concept for wildfire hazards in the US. Facilitation means that those who are less vulnerable are typically able to take advantage of political and economic incentives. Further study may reveal additional processes that differentially promote either the facilitation or marginalisation of wildfire vulnerability.

Our study is based on only one point in time, a shortcoming that must be taken into account (Adger *et al.* 2004). Social conditions and wildfire potential inevitably change over time, as people migrate into fire-prone areas and land-use practices and climates change (Theobald and Romme 2007; Hammer *et al.* 2009; Syphard *et al.* 2013), potentially effecting changes in the spatial distribution of social vulnerability in the future. Unit of aggregation, spatial relationships and geographic context also influence vulnerability assessments. Our summaries of biophysical data at the census block level and of vulnerability data at the state level raise concerns about modifiable areal units (Fotheringham and Wong 1991; Dark and Bram 2007). Although census blocks are the smallest aggregate census unit, their sizes and populations vary. Although our analysis excluded large areas of uninhabited public lands, rural blocks may still be sparsely populated. Further research may be necessary to determine the true intersection of biophysical and social vulnerabilities within these blocks. Schmidtlein *et al.* (2008) found that scalar changes impact the numeric properties of social vulnerability indices, but do not have a significant impact on identifying vulnerability components.

Coupled with the various spatial scales at which wildfire impacts other than direct physical property damage occur (e.g. smoke, viewshed impacts, economic losses from resource degradation), we are confident that our vulnerability analysis provides useful and relevant information. However, we did not explicitly consider spatial relationships. Given that wildfire potential and social vulnerability are both likely dependent on the characteristics of nearby places, finding clusters or vulnerability hotspots would be an appropriate next step (e.g. Gaither *et al.* 2011; Poudyal *et al.* 2012). State and region-specific vulnerability evaluations have produced results different from those we found for the coterminous US (Gaither *et al.* 2011; Ojerio *et al.* 2011; Poudyal *et al.* 2012). Wildfire managers should be aware of these differences and select risk evaluation methods appropriate to the spatial characteristics of their application.

Our social vulnerability index may have some limitations. Social vulnerability metrics provide only a limited representation of reality. We cannot be sure we have identified all of the processes that determine vulnerability, or if all the processes that determine vulnerability can even be quantified (e.g. Kelly and Adger 2000). Although social vulnerability indices can efficiently describe broad-scale vulnerability, they also can fail to capture more localised information related to exposure, sensitivity and adaptive capacity that is often better collected using qualitative methods (Fischer *et al.* 2013). Validation is possible if post-hazard outcomes are compared with pre-hazard vulnerabilities (Cutter *et al.* 2008). For example, flood events in Texas, Hurricane Katrina and the 1995 Chicago extreme heat event have been used to validate social vulnerability indicators and indices (Zahran *et al.* 2008; Finch *et al.* 2010; Johnson *et al.* 2012). However, the success of social vulnerability indices arguably is highly context-dependent. Although regional wildfire vulnerability indices have been validated using the presence or absence of wildfire prevention and mitigation programs (Gaither *et al.* 2011; Ojerio *et al.* 2011), more direct post-hazard measures of responses, such as economic loss (e.g. Ash *et al.* 2013), health impacts, fire extent, or structure loss and rebuilding (e.g. Alexandre *et al.* 2014), remain untested. For example, although post-fire rebuilding rates vary, they do not appear to follow easily identifiable geographic or ecological patterns (Alexandre *et al.* 2014), and 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 vulnerability indices themselves and our broader understanding of social vulnerability to wildfire.

Still, we feel that indices such as ours can be useful now for broad-scale planning with limited resources. Our resulting map would allow managers to quickly distinguish between areas that may require additional support or evaluation and areas that may not require additional resources. Our research supports the concept that the WUI is not uniform in biophysical or social conditions, but rather includes a mosaic of community types, and that policy flexibility and adaptability will be necessary to address wildfire hazards affecting these communities (Paveglio *et al.* 2009). Our 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 wildfire managers' ability to meet the diverse challenges involving wildfire. Difficult policy decisions must be made as federal spending on wildfire management and protection continues to increase and wildfire managers search for ways to minimise loss of life and property damage (Bracmort 2014). In the short term, managers might prioritise programs and funding for those places that face the greatest wildfire potential and lack the capacity to prevent or mitigate that risk. In the longer term, however, land-use policies and political and economic incentives ultimately must be evaluated to assess the degree to which they contribute to wildfire vulnerability by incentivising settlement in fire-prone landscapes.

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