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RESEARCH ARTICLE

Informing proactive wildfire management that benefits vulnerable communities and ecological values

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Abstract

1. In response to mounting wildfire risks, land managers across the country will need to dramatically increase proactive wildfire management (e.g. fuel and forest health treatments). While human communities vary widely in their vulnerability to the impacts of fire, these discrepancies have rarely informed prioritizations for wildfire mitigation treatments. The ecological values and ecosystem services provided by forests have also typically been secondary considerations.
2. To identify locations across the conterminous US where proactive wildfire management is likely to be effective at reducing wildfire severity and to yield co-benefits for vulnerable communities and ecological values, we developed a set of spatial models that estimated wildfire mitigation potential (based on wildfire hazard and biophysical forest conditions) and either included or excluded information on vulnerable human communities, ecological values and ecosystem services. We then compared areas with high wildfire mitigation potential alone to refined 'focal areas' that overlaid social and ecological considerations to quantify the potential benefits of targeted wildfire mitigation treatments.
3. Inclusion of social and ecological considerations substantially increased representation of vulnerable communities and ecological values in focal areas relative to the model that considered wildfire alone. For instance, restoration in these refined focal areas would cover 28% greater imperilled species richness, 45% greater water importance and 26% more families falling below the poverty line.
4. By examining overlap between our refined focal areas and U.S. Forest Service top ranked firesheds (a prominent existing wildfire prioritization scheme), we show that our analysis can help to target wildfire mitigation efforts within firesheds to areas with particularly high social vulnerability and/or ecological value, providing an important compliment to a prioritization scheme based largely on risk to structures.
5. Our results highlight the importance of considering ecological and social factors when implementing wildfire mitigation treatments and provide actionable guidance for integrating these considerations into existing prioritizations.

KEYWORDS
ecosystem services, fire ecology, fuel treatments, landscape planning, restoration, social vulnerability, spatial prioritization, wildfire

1 | BACKGROUND

Forest fire activity has been on the rise due to fire suppression, changing climatic conditions, exclusion of indigenous burning, human-caused ignitions and tree mortality caused by the compounding stressors of climate change, pests and disease (Balch et al., 2017; Hessburg et al., 2021; Parks & Abatzoglou, 2020). Simultaneously, conversion of forested areas to development has expanded the wildland-urban interface (WUI), enhancing the threat of fire to human infrastructure, lives and livelihoods (Balch et al., 2017; Mietkiewicz et al., 2020; Radeloff et al., 2018).

Increased wildfire activity has the potential to impact not only human communities, but also critical ecological values and ecosystem services. While fire is indeed a natural component of a healthy landscape, an increasing number of wildfires are growing to atypical sizes with larger areas burning at high severity (Parks & Abatzoglou, 2020). These 'megafires' can alter or impede post-fire recruitment and ecosystem recovery, even in systems well-adapted to natural fire regimes (Brown & Johnstone, 2012; Davis et al., 2018). A reduction in fire severity could better enable ecosystem recovery, especially as warmer and drier conditions complicate tree regeneration (Davis et al., 2023).

Fuel treatments, including prescribed fire and mechanical thinning, can reduce fire severity with the potential to support biodiversity, habitat quality and vegetation diversity (Hessburg et al., 2021; Jones et al., 2022; Stephens et al., 2024). They have also been shown to decrease the overall cost of future wildfire response, reduce the likelihood of structure loss or risk to firefighters, and maintain beneficial ecosystem services (Bayham et al., 2022). As a result, fuel treatments have been the dominant method of mitigating wildfire risk. For instance, the Biden Administration has committed $1.5 billion to reducing wildfire risk, including safeguarding communities, via proactive wildfire management such as fuel treatments on both federal and non-federal lands (The White House, 2022a, 2022b; U.S. Department of the Interior, 2022). Likewise, the U.S. Forest Service (USFS) 'Confronting the Wildfire Crisis' strategy commits to an 'all-lands' approach to treating up to 8.1-million ha (20-million acres) of national forest (NF) lands and 12.1-million ha (30-million acres) of other federal, state, tribal and private lands over the next 10 years with the goal of protecting human communities and improving forest health and resilience (U.S. Department of Agriculture, 2022; USFS, 2023).

Our goal with this analysis was to identify places where the proactive application of fuel and forest health treatments (hereafter 'restoration', but see Stephens et al., 2020) is likely to be effective in reducing wildfire risk while also directing restoration efforts towards socially vulnerable communities and areas of particularly high ecological value. Typically, restoration is directed towards areas biophysically prone to wildfire and where risk to structures is relatively high (i.e. the WUI); however, research has shown that this approach does not always distribute resources to the communities with the greatest need. In some instances, these resources have even disproportionately gone to more affluent communities at a direct cost to more vulnerable communities (Evans et al., 2007; Morton, 2003; Poudyal et al., 2012; Program for Watershed and Community Health, 2003).

Indeed, communities considered 'socially vulnerable' are less likely to receive or engage in restoration efforts, even when they are at a high wildfire risk (Gaither et al., 2011; Ojerio, 2008; Ojerio et al., 2011; Poudyal et al., 2012). Social vulnerability describes "the ability of individuals and communities to plan for, respond to, and recover from natural disasters" (Ojerio et al., 2011, p.29). The concept centres on a lack of (or limited) access to political power, representation, physical and intellectual resources, social capital, physical health or ability, and infrastructure and is often measured as an integration of contributing factors (Cutter et al., 2003; Cutter & Finch, 2000). For example, in the context of wildfire, prevalence of respiratory conditions including chronic obstructive pulmonary disease (COPD) and asthma are highly relevant due to potential smoke exposure. Likewise, income level reflects the ability to pay for restoration efforts (e.g. brush removal) or to recover from loss of property or livelihood. Discrepancies in social vulnerability necessitate the development of more equitable risk mitigation measures.

The ecological value of forest ecosystems and the services they provide to human communities are also frequently left out of restoration prioritizations. For example, the capacity of forests to support habitat and connectivity (Thompson et al., 2021) as well as provide clean drinking water and carbon storage (Thom & Seidl, 2016; Vukomanovic & Steelman, 2019) can be threatened by wildfire and should be considered in restoration prioritizations (Chamberlain & Jones, 2023). Moving forward, it will be necessary to focus restoration efforts on locations with the greatest restoration efficacy and broader social and ecological co-benefits (Gaither et al., 2011; Poudyal et al., 2012; Wigtil et al., 2016).

To date, restoration prioritizations, such as the USFS Fireshed Registry (Ager et al., 2021), have largely centred on risk to infrastructure, particularly in the WUI. Our research was thus motivated by the need for an intentional shift towards more equitable restoration priorities. Specifically, our research objective was to identify places where restoration is likely to be effective in both reducing subsequent fire severity and in safeguarding socially vulnerable communities as well as important ecological values and services. We developed a tool that highlights the potential co-benefits of restoration for vulnerable communities and ecosystems and that can be used to further refine existing prioritizations (e.g. firesheds) following an 'all-lands' approach across the conterminous U.S. (CONUS). We then compared a spatial prioritization that included only 'wildfire mitigation potential' (i.e. the potential for restoration to effectively mitigate future wildfire behaviour) with a model that integrated wildfire mitigation potential with social and ecological considerations. This allowed us to quantify the potential benefits of targeted restoration efforts for vulnerable communities and ecosystems. Rather than attempting to highlight exact locations where fire management activities should occur, our intent was to identify landscapes that can serve as starting points for consideration when the USFS or other land management agencies are determining which areas to target for restoration. Once landscapes have been identified, collaboration with local communities, tribes, and stakeholders will be necessary to guide the design and implementation of these projects on the ground.

2 | METHODS

To achieve our research objective, we developed two composite indices (Burgass et al., 2017; Greco et al., 2019; Wiréhn et al., 2015; see Appendix S1) describing (i) the potential to reduce future wildfire severity (hereafter, the 'wildfire mitigation potential index' or WMPI) and (ii) social vulnerability of communities and ecological values and services that are potentially at risk from wildfire (hereafter, the 'social-eco index' or SEI). The WMPI was derived from existing spatial indicators describing forest condition and wildfire hazard potential. To derive the SEI, we developed and combined three sub-indices, each describing a distinct category of factors potentially at risk from wildfire (social vulnerability, ecological value, ecosystem services; Figure 1) and each composed of a unique set of social or ecological indicators. We then overlaid the WMPI and SEI to identify areas for restoration that achieve multiple objectives (Figure 1). Spatial data used to derive each of these indicators are described below.

The method of combining indicators to derive a particular index (or sub-index) varied between models, drawing on the most appropriate approach for a particular index type. Most of the indices described below were derived as the weighted linear sum of the underlying indicator values such that

$$y_i = \sum_{j=1}^{J} x_{ij} w_j \qquad (1)$$

where y_i is the value of the index at location i, x_{ij} is the (standardized) value of indicator j at location i, and w_j is the weight applied to indicator j. We utilized a recently developed method for deriving indicator weights, w_j, such that each indicator had a predefined influence on the resulting index value, y_i while accounting for correlations among indicators (Becker et al., 2017; Paruolo et al., 2013; Suraci, Farwell, et al., 2023; see also Appendix). Analyses were conducted in R (v4.2.1), ArcGIS Pro (v3.0.0) and Google Earth Engine (GEE; Gorelick et al., 2017) via the Earth Engine Python application programming interface. Final model layers (indices and sub-indices) were resampled to 90-m resolution in GEE.

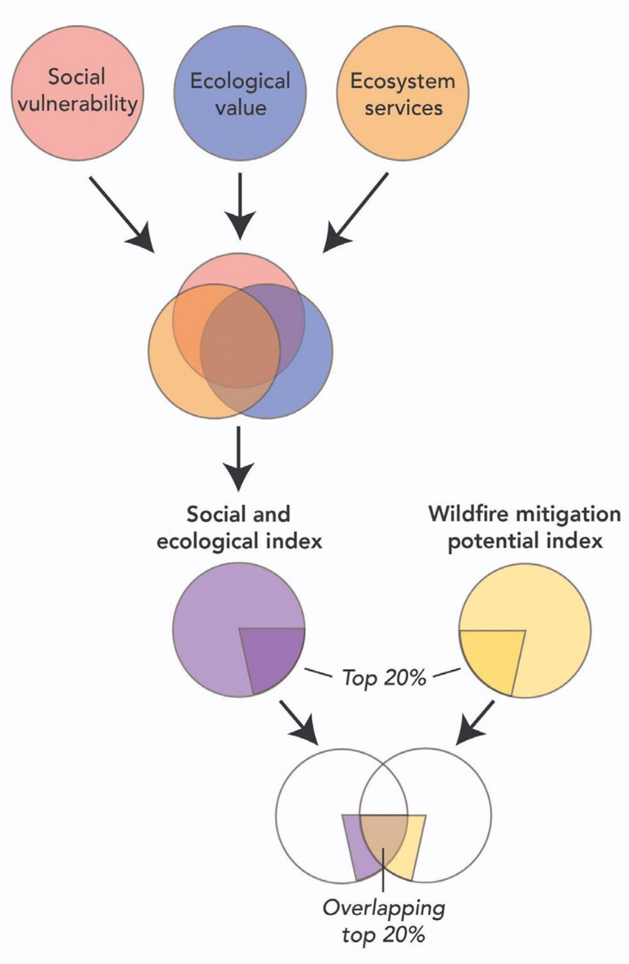


FIGURE 1 Workflow for identifying areas where restoration has the potential to both reduce subsequent fire severity and to safeguard vulnerable communities and important ecological values and services. Spatial sub-indices defining social vulnerability, ecological value and ecosystem services were combined into a 'social and ecological index'. Pixels of this index and a separately derived 'wildfire mitigation potential index' were thresholded to identify areas falling in the top 20% for each index within each U.S. Forest Service administrative region (USFS regions shown in Figure 2). Locations where the top 20% of both indices overlapped were identified as targets, or 'focal areas', for restoration.

2.1 | Wildfire mitigation potential index

The WMPI integrates forest conditions and wildfire hazard potential to suggest where restoration may be most effective from a biophysical perspective and may therefore moderate future wildfire behaviour. Specifically, we included the following datasets in this index (see also Appendix S1):

- *Wildfire hazard potential* (*WHP*) quantifies the relative potential that a wildfire will occur at a given location and that the fire will be difficult to control through standard suppression techniques (Dillon et al., 2015; Scott et al., 2020).
- *Percent low-severity fire* (*PLS*) estimates the historical proportion of low-severity fire relative to mixed- and high-severity fires prior to European settlement (LANDFIRE, 2020).
- *Vegetation departure* (*VDep*) depicts the degree to which present-day vegetation is different from historical conditions prior to European settlement (LANDFIRE, 2020).

We included WHP to ensure that our model focused on areas most likely to experience difficult-to-control wildfire. We included VDep to capture locations where human actions have drawn forests far from the conditions historically maintained by natural dynamics. For example, widespread fire suppression has led to substantial changes in forest composition, structure and fuel accumulation in many contexts (Hagmann et al., 2021). Lastly, we included PLS because high VDep cannot independently discern where restoration may be most beneficial. High VDep may occur in locations such as tree plantations in moist climates (e.g. the southeastern U.S.) where vegetation departures are substantial but where restoration is not known to reduce fire severity. Accordingly, areas that historically experienced high degrees of low-severity fire (high PLS) are elevated in our index. These locations tend to experience arid conditions conducive to frequent burning and have historically not had high accumulations of fuel, but fire suppression has interrupted that dynamic (e.g. ponderosa pine or oak woodlands in the western U.S.). Ample evidence points to the efficacy of restoration in moderating fire behaviour in such contexts (e.g. Jones et al., 2022), whereas there is limited evidence that restoration is effective in forest types that historically experienced less low-severity fire and more mixed or high-severity fire (Halofsky et al., 2018; Schoennagel et al., 2004).

We derived the WMPI as the weighted linear sum (see above) of WHP, VDep and PLS, with each layer rescaled to 0–100. We used the optimization procedure described in Appendix S1 to identify the set of weights that lead to relative influence of 2:1:1 for WHP, VDep and PLS, respectively, on the final index values (i.e. WHP was twice as influential as VDep and PLS in determining the index result for a given pixel). We chose this set of relative influence values to ensure that our index highlighted areas with relatively high probability of actually experiencing a wildfire.

2.2 | Social and ecological index

The SEI was derived by combining three separate sub-indices, each describing a set of characteristics or values that may be threatened *if an uncharacteristic wildfire were to occur* and was designed to be agnostic to the actual likelihood of wildfire in a given location. It is important to note that these sub-indices do not necessarily quantify the expected loss of a given value *to* wildfire (e.g. amount of forest carbon or degree of connectivity potentially lost to fire), but rather are meant to highlight locations where these values are high and where restoration may jointly protect these values and yield substantial co-benefits as a result.

2.2.1 | Social vulnerability sub-index

The social vulnerability sub-index identifies places where communities may be particularly impacted by, or least able to recover from, wildfire due to factors such as income, prevalence of health issues, or other demographic characteristics. We focused on census tracts as the spatial unit of analysis given data availability and the common usage of census tract-level data in deriving similar indices (e.g. Davies et al., 2018). We reviewed indicators across 14 existing indices of social vulnerability and selected indicators most salient to wildfire (see Appendix S1). The final set of indicators encompassed nine themes (Table 1). All indicators, with the exception of median household income, were provided as a percentage of the census tract population or an otherwise regionally adjusted value to reduce potential bias associated with regional variation.

These 22 indicators were combined in a principal components analysis (PCA) using the 'factoextra' package in R to reduce the dimensionality of the indicator set and account for correlation among them. Any missing indicator values at individual census tracts (3% of the total dataset) were imputed using a regularized iterative PCA algorithm in the R package 'missMDA' (see Appendix S1). PCA scores for all census tracts with imputed values were then predicted from the original PCA run only on complete records.

We used the inverse of the first principal component (PC1) as our metric of social vulnerability (i.e. social vulnerability $= -1 \times$ PC1). Our intent with the PCA was not to explain as much variance as possible (PC1 explained 27.6% of variance across all indicators), but rather to reduce the dimensionality of a large set of indicators. In our view, the inverse of PC1 serves this purpose well in that all social indicators vary with our social vulnerability metric in an intuitive direction. For instance poverty, unemployment and minority status all increase with our vulnerability index while income level, broadband access and voter turnout all decrease (see Figure S1.1). Incorporating PC2 into the index would indeed have explained more of the overall variation in the set of social indicators, but the PC2 axis did not map clearly onto social vulnerability (see Appendix S1). We acknowledge the limitations associated with PCA, namely its assumption that linearity can be established between variables. However, given our primary goals of reducing data dimensionality and deriving a continuous metric of social vulnerability, PCA remained the most readily interpretable approach in this context and is consistent with similar analyses (e.g. Wigtil et al., 2016). We calculated social vulnerability values for each census tract, and tracts were then rasterized at a 90-m resolution for subsequent analysis.

TABLE 1 The 22 indicators of social vulnerability in the context of wildfire used to represent the social vulnerability sub-index, organized by theme.

Theme	Dataset
Education level	% of the total population (25+ years old) without a high school diploma[a]
Employment status	% of the civilian labour force (16+ years old) currently unemployed[a]
Health status and access to care	Prevalence (%) of COPD[b]
	Prevalence (%) of asthma[b]
	% of the total population with a disability[b]
	% of the total population without health insurance[b]
	Number of ICU beds available per 100k people[c]
Living situation	% of housing units that are mobile homes[a]
	% of crowded housing (i.e. housing units with more than one occupant per room)[a]
	% of households with children under 18 that are headed by a single parent[a]
	% of the total population living within institutionalized group quarters[a]
	% of the total population living in nursing and skilled nursing facilities[d]
Income	% of families whose income is below the poverty line[a]
	Median household income[a]
Cost of living	Median gross rent as a percentage of income[a]
Demographics	% of the total population (5+ years old) that speaks limited English[a]
	% of the total population with minority status[a]
Community engagement	Voter turnout in the 2020 presidential election (as a percentage of the total population over 18)[e]
Quality of life	% of households with a broadband subscription[a]
	% of households with phone service[a]
	% of households without complete plumbing[a]
	% of housing units without a vehicle[a]

[a] Manson et al. (2022).

[b] Centers for Disease Control and Prevention (2021).

[c] Schulte et al. (2020).

[d] Department of Homeland Security (2022).

[e] Atlas of U.S. Presidential Elections (2022).

2.2.2 | Ecological value sub-index

The ecological value sub-index estimates the potential for a location to contribute to important ecological processes such as supporting biodiversity, connectivity and climate adaptation. The set of indicators included the following (see also Appendix S1):

- *Climate accessibility* estimates the degree to which the local climate conditions currently experienced by a species will be accessible in the future (by the year 2055; higher climate accessibility = greater ability of species to adapt to climate change via movement). This metric is effectively the inverse of climate velocity (Hamann et al., 2015).
- *Imperilled species richness* estimates the number of species of conservation concern likely to occur in a given area (NatureServe, 2020).
- *Vertebrate species richness* estimates the number of terrestrial, non-volant species likely to occur in a given area (Conservation Science Partners, 2021).
- *Ecological intactness* estimates the degree to which a given location remains in a natural state (i.e. little to no influence from contemporary human land use changes; Parrish et al., 2003; Suraci, Farwell, et al., 2023).
- *Ecological connectivity* estimates the ability of a given location to support the natural movement of organisms through processes such as dispersal, migration and gene flow and to provide linkages between areas of high quality habitat (Dickson et al., 2017; Suraci, Littlefield, et al., 2023).
- *Vegetation diversity* describes the diversity of plant communities, defined here as groups of 'plant community types (associations) that tend to co-occur within landscapes with similar ecological processes, substrates, and/or environmental gradients' (Comer et al., 2003).

The above indicators were standardized (*z*-score transformation), resampled to a common resolution (90-m) and combined using the weighted linear sum method described above. We applied the set of weights such that each indicator had equal influence in the resulting sub-index (see Appendix S1).

2.2.3 | Ecosystem services sub-index

The ecosystem services sub-index captured two key ecosystem services that forests provide – (1) the provisioning of clean drinking water and (2) carbon storage. This sub-index identifies areas where wildfire may negatively impact the capacity of forests to provide these services. While recognizing that forests provide many ecosystem services beyond those discussed here (e.g. recreational value), we focused on water supply and carbon sequestration because they are (i) readily quantifiable at the national scale and (ii) largely non-redundant with the values in the ecological value sub-index. As noted above, these indicators are not intended to capture the actual loss of carbon or drinking water to fire, but rather to focus attention on locations where these values are relatively high (see also Appendix S1):

- *Total forest carbon* estimates current (circa 2018) carbon storage as tons of carbon per pixel across forests in CONUS (USFS Forest Inventory & Analysis, 2022; Wilson et al., 2018).

- *Relative importance to surface drinking water* quantifies a watershed's ability to provide clean drinking water to human communities (National Forests to Faucets v2.0—Mack et al., 2022).

The ecosystem services sub-index was derived by standardizing (*z*-score transformation) the indicator layers, resampling them to 90 m and calculating a weighted linear sum using the set of weights that yielded equal influence of the two indicators.

2.2.4 | Deriving the social-eco index

Finally, we combined each of the three sub-indices (social vulnerability, ecological value and ecosystem services) into the SEI using the same weighted linear sum approach described above. We acknowledge that our approach of applying the social vulnerability metric across entire census tracts will result in some uninhabited areas being considered socially vulnerable. However, there is a trade-off between generalizing social vulnerability to uninhabited areas and focusing instead on mapped developed areas, which risks inadvertently overlooking some of the most socially vulnerable rural and isolated communities. Given this, we maintained our census tract-wide social vulnerability values when combining these three sub-indices. We recognize this would lead to some areas (specifically those with higher ecological values and ecosystem services) being elevated in the SEI, despite a relatively limited number of people affected. However, the communities that could be affected in or near those areas are among the most underserved in risk reduction investments (Morgan et al., 2024; Ojerio et al., 2011), and thus we deem this trade-off warranted.

We standardized the three sub-indices (*z*-score transformation) and derived weights such that each sub-index had equal influence on the resulting index values. While our goal here was to ensure equal influence of each sub-index, there is inherent subjectivity in selecting any particular weighting scheme for combining metrics into a composite index. Accordingly, we emphasize the exploratory nature of this analysis and the potential for similar analyses to produce varying results depending on researcher or practitioner priorities and variable weights assigned, which we find to be a valuable opportunity for future research.

2.3 | Combining the wildfire mitigation potential and social-eco indices

To identify target landscapes for management considerations across CONUS, we smoothed each index by taking the mean within a 405 ha (1000 acre) moving window. This smoothing process retained the original data resolution but removed spatial artefacts or anomalies (e.g. single high-value pixels surrounded by those of lower value), thus identifying contiguous areas of similarly high value for a given index. We chose 405 ha to ensure that our smoothing would be done at a scale substantially smaller than what typically constitutes a project planning area (on the order of 10,000 ha; Ager et al., 2021). To avoid targeting areas where active management is administratively constrained, we masked out of the smoothed rasters designated Wilderness and Wild and Scenic Rivers (both categories of GAP 1 protected area within which natural disturbances are allowed to occur; USGS, 2020).

For each smoothed index (WMPI and SEI), we then identified areas with pixel values in the top 20% of index values within each USFS region (Figure 1). Finally, we identified contiguous groups of pixels falling within the top 20% of both the WMPI and SEI within a given USFS region and drew polygons around these areas (Figure 2). These polygons containing the overlapping top 20% of WMPI and SEI values (hereafter, 'focal areas') were considered as potential targets for restoration given the co-benefits they represent. We chose the 20% cut-off as a conservative decision rule meant to focus attention on the lands with greatest potential for co-benefits. To remove potential artefacts and polygons too small to be of relevance to management, we filtered the focal areas to only those greater than 405 ha.

2.4 | Identifying coincidence and complementarity between focal areas and alternative management targets

To assess the complementarity between prioritizations focused solely on biophysical wildfire risk or structural impacts and our alternative that *also* integrates social and ecological considerations, we then compared our focal areas to (1) areas within the top 20% of the WMPI (identified based on biophysical wildfire risk) and (2) the USFS' top 10 firesheds within each USFS region (identified based on wildfire ignitions on NF land, restoration feasibility, and risk to structures; Ager et al., 2021). Given that our indices followed an 'all-lands' approach and were scaled relative to values within each USFS region, we selected the 'all-lands' top 10 firesheds ranked relative to all firesheds within each region for use in our comparisons.

The CONUS-wide mean value for each indicator that contributed to the three sub-indices of the SEI (e.g. prevalence of COPD, ecological connectivity) was extracted within the following domains: (1) areas within the top 20% of the WMPI, (2) all focal areas (i.e. where the top 20% of both the WMPI and SEI overlap), (3) USFS top 10 firesheds in each region, and (4) all areas in which focal areas and the USFS top 10 firesheds overlap. These values were then used to compute the percent change in each indicator value when (1) refining targets from the top 20% of the WMPI down to focal areas alone and (2) refining targets from all USFS top 10 firesheds per region down to only locations in which those firesheds overlap with our focal areas.

3 | RESULTS

The top 20% of values within the WMPI for each USFS region encompassed 106.2 million ha. Retaining areas within the top 20% of

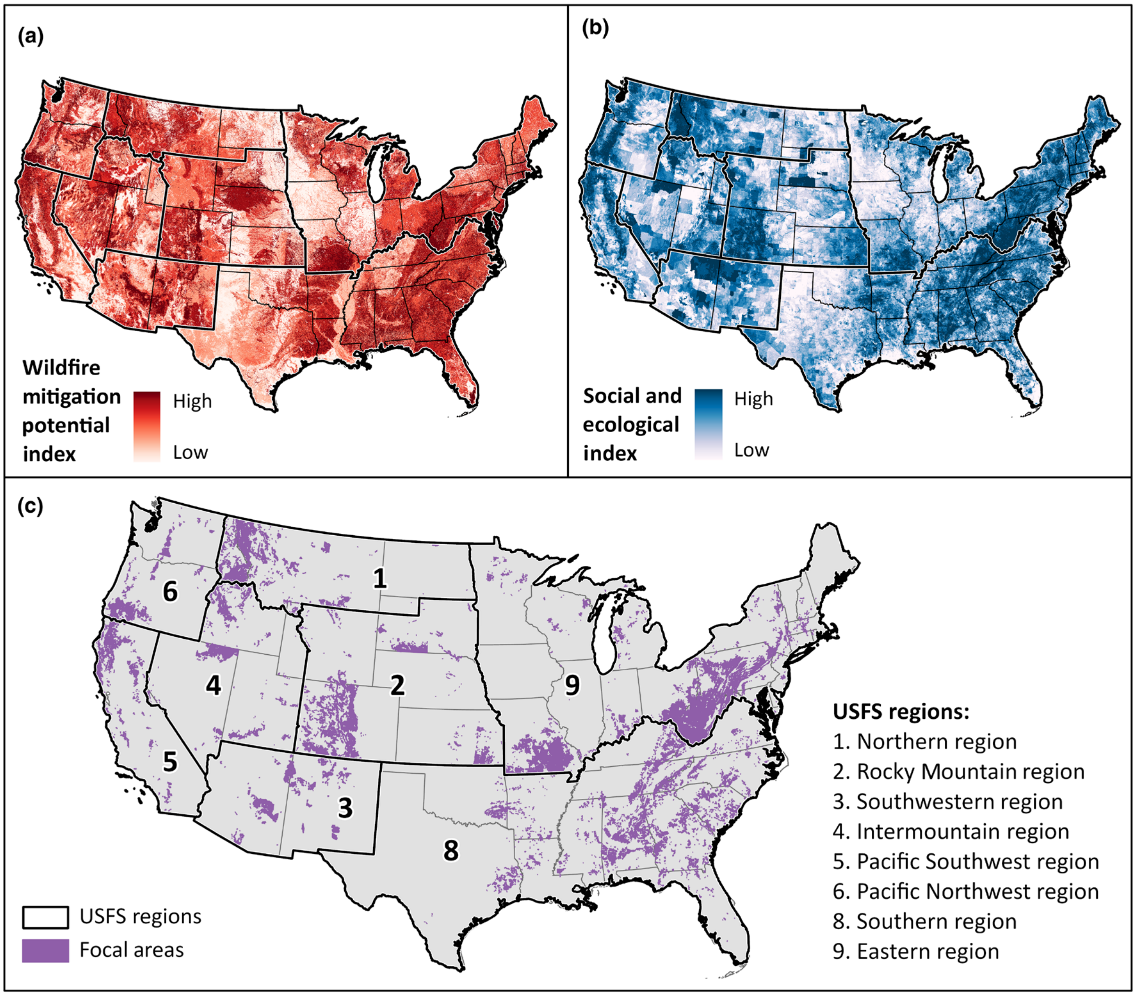


FIGURE 2 CONUS-wide distribution of (a) the WMPI, (b) the SEI, and (c) focal areas (areas of overlap between the top 20% of WMPI values and top 20% of SEI values). Both indices were scaled relative to values within each USFS region (regions indicated by bold black lines and listed according to region ID).

both the WMPI and SEI (i.e. focal areas) reduced this land area by more than half, to 41.9 million ha. These focal areas are locations where restoration is likely to be effective in both reducing the severity of future wildfires and safeguarding vulnerable communities and important ecological values and were generally concentrated along the Appalachian Mountains, Ozarks, Rocky Mountains and the Pacific Coastal Ranges (Figure 2). The Eastern Region contained the largest amount of land within focal areas (14.2-million ha; 8.3% of total region area), and the smallest amount was found in the Pacific Northwest Region (2.0-million ha; 4.7% of total region area; Table 2).

The addition of the SEI in identifying focal areas substantially increased representation of ecological values, ecosystem services and social vulnerability. Relative to conducting restoration within areas defined only by high values (top 20% per region) of the WMPI, prioritizing focal areas would target restoration to locations with, on average, 28% greater imperilled species richness and 45% greater drinking water importance and would increase the representation of families falling below the poverty line and populations with COPD by 26% and 14%, respectively (Figure 3a).

There is a high degree of complementarity between our focal areas and the top 10 firesheds within each USFS region, with 33.6% (2.9-million ha) of the top 10 firesheds overlapping focal areas (Figure 4). If the USFS were to target restoration on the 2.9-million ha in which firesheds and focal areas coincide, they would capture more climate resilient and intact landscapes that provide greater connectivity for wildlife and that also support greater overall species richness than firesheds do on average (Figure 3b). Likewise, these areas of overlap present opportunities to preserve 14% more clean drinking water and 39% greater forest carbon as well as reach nearly 50% more families below the poverty line and 42% more individuals with COPD. The region around Boise, Idaho, provides a localized example of the complementarity between areas prioritized by USFS firesheds and the focal areas developed here, refining the overall footprint of firesheds to focus on locations that are particularly high for both wildfire mitigation potential and social and ecological considerations (Figure 5, see Section 4 for more details). Additional case studies for Denver, Colorado and Charleston, West Virginia are presented in Appendix S2.

TABLE 2 Total area of identified focal areas (in millions of hectares) within each USFS region across CONUS. Focal area is also expressed as a percentage of total region area.

Region name[a]	Region area	Focal area
Northern	64.7	4.3 (6.6%)
Rocky Mountain	105.3	6.1 (5.8%)
Southwestern	61.0	2.5 (4.1%)
Intermountain	72.6	2.9 (4.0%)
Pacific Southwest	42.3	2.5 (5.9%)
Pacific Northwest	42.5	2.0 (4.7%)
Southern	220.7	7.4 (3.4%)
Eastern	171.5	14.2 (8.3%)

[a]Regions correspond to those shown in Figure 2c.

4 | DISCUSSION

The mounting threat of uncharacteristic wildfire and its inequitable impacts necessitate swift and strategic action from land managers as they identify restoration priorities. Here we have integrated critical social and ecological considerations and developed an index that is complementary to existing prioritizations based on potential structural loss, a combination that is essential to better understand where and when communities and resources are likely to be impacted by wildfire. Our results suggest that focusing on biophysical components of wildfire risk alone may not account for some of the important ecological values and services and vulnerable human communities that would be compromised if a wildfire were to occur. By integrating our focal areas with existing prioritizations, managers

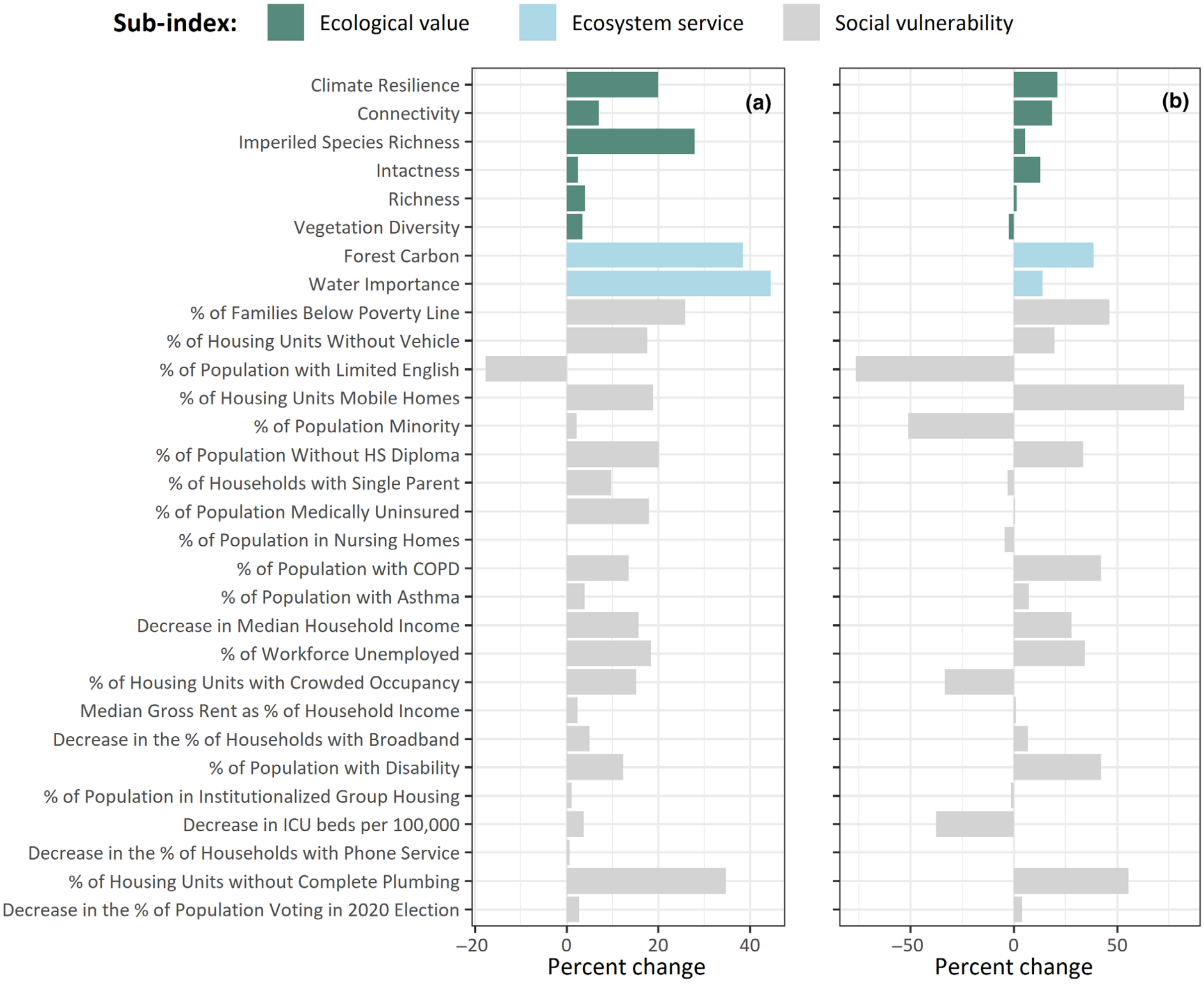


FIGURE 3 The percent change in all ecological value (green), ecosystem service (blue) and social vulnerability (grey) indicators that contributed to the SEI within target areas when (a) refining the target areas from the top 20% of the WMPI down to focal areas alone (i.e. where the top 20% of both the WMPI and SEI overlap) and (b) refining the target areas from USFS top ten firesheds per region to only areas of overlap between those firesheds and focal areas. Five indicators were quantified such that a decrease in their value indicates greater representation of social vulnerability: Median household income (USD), % of households with broadband, % of households with phone service, % of population participating in voting and the number of ICU beds per 100,000 people. These indicators have been represented as the percent change in the *decrease* of their values. See Appendix S2 for tables of values.

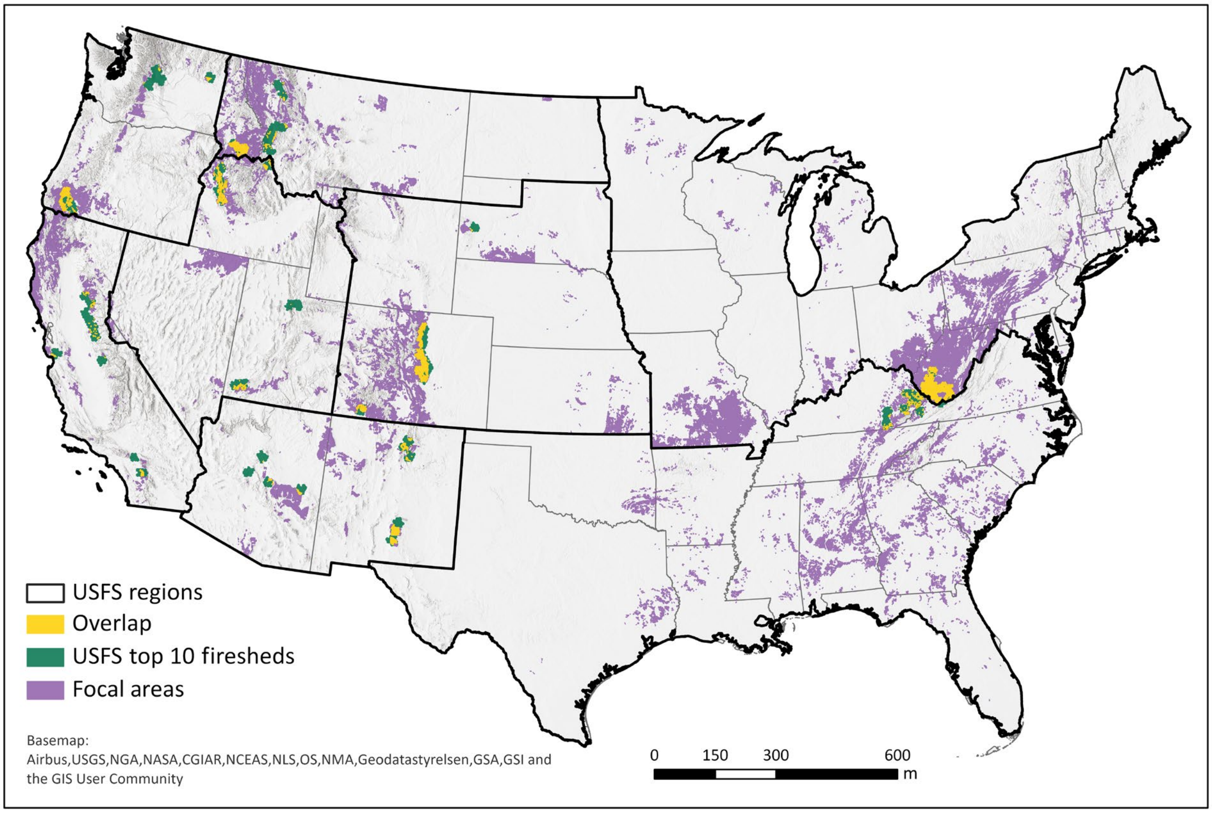


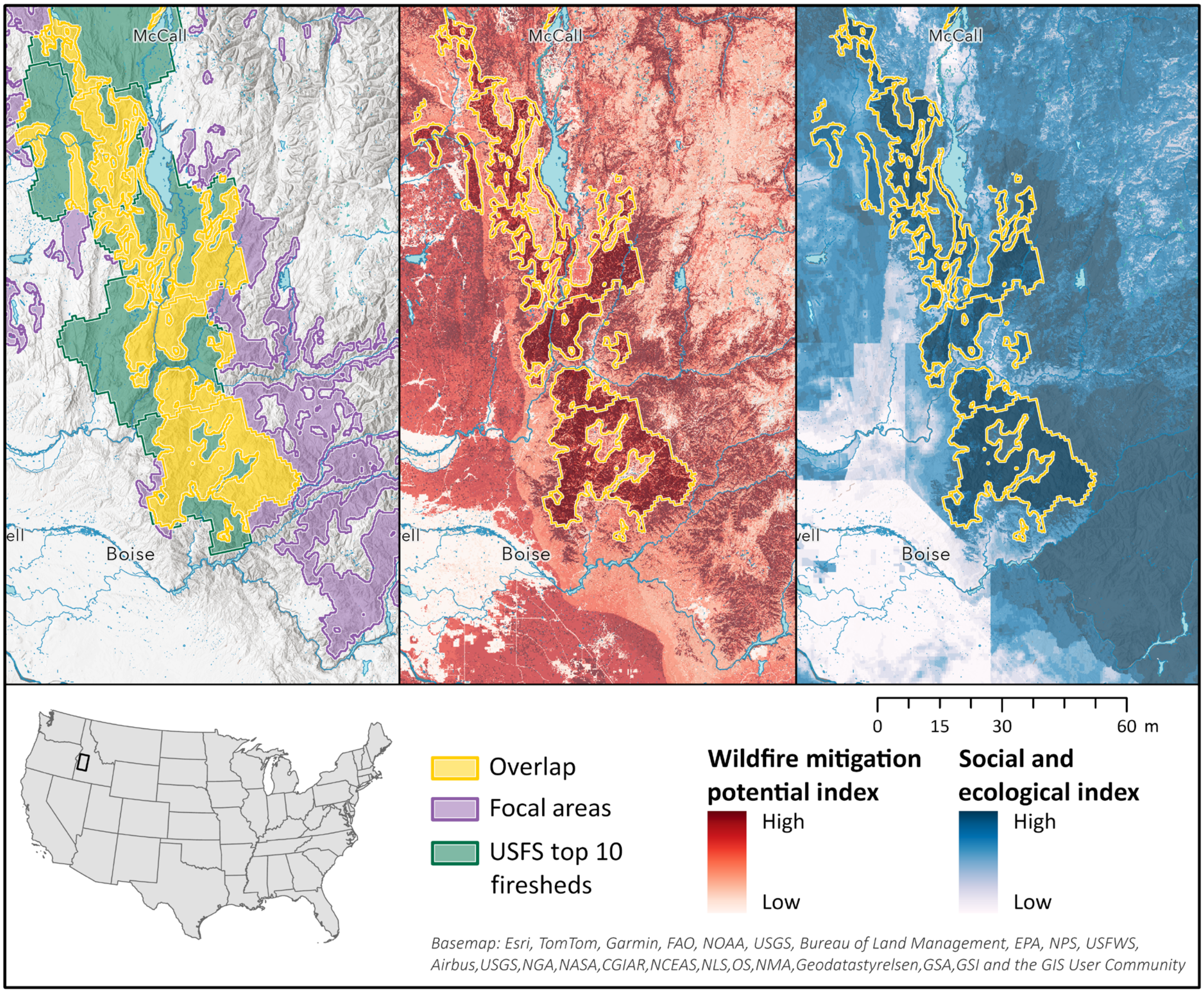
FIGURE 4 USFS top 10 firesheds (green) for each USFS region overlaid with all focal areas (purple), which were identified as the locations in which the top 20% of the WMPI coincided with the top 20% of the SEI. Areas of overlap between firesheds and focal areas are indicated in yellow.

can strategically focus their efforts in areas with the greatest co-benefits across all of these factors.

The region around Boise, Idaho, demonstrates some of the distinct opportunities to capture greater overall social and ecological values through a strategic refinement of USFS management targets. Wildfires in this region have the potential to threaten human communities as well as nearby highly intact, connected and climate resilient landscapes, including Boise NF. Boise NF also contains some of the most important watersheds in all of Idaho for the provisioning of clean drinking water, making it essential to many of the human and ecological communities found here. The areas of overlap between the top ranked firesheds and our focal areas in this region (a total of 236,900 ha) capture some of the highest values within both indices and could help focus restoration that would maximize combined benefits to human communities and ecological systems (Figure 5). This strategic management will be necessary given the wide range of costs associated with fuel treatments and land managers' limitations in restoration funding (Hunter & Taylor, 2022).

In a time of increasingly frequent, large and destructive wildfires and mounting ecological crises, understanding which locations are at the nexus of these diverse priorities will be essential to efficiently deploy a finite amount of funding and resources for restoration. This is particularly salient given that wildfire is a nationwide issue, with the greatest number of wildfires occurring in the southeastern U.S. and the largest in terms of burn area occurring in the west (Mitchell et al., 2014; Schoennagel et al., 2017; U.S. Environmental Protection Agency, 2022). This issue also extends beyond the U.S. (e.g. Australia's bushfires (Deb et al., 2020), Canada's Northwest Territory fires and record-breaking 2023 season (Kochtubajda et al., 2019; Kolden et al., 2024), and a dramatic increase in wildfire across the Amazon in Brazil (Kolden et al., 2024)), thus this analysis can inform a more integrated approach to prioritizing wildfire restoration efforts worldwide as governments work to fight a global increase in extreme wildfire (United Nations Environment Programme, 2022). The all-lands approach employed here paired with the balanced consideration of social, ecological, and wildfire-based metrics will ensure a more even distribution of priority landscapes identified across the whole of CONUS, rather than emphasizing any single region and could serve as a transferable model for similar analyses elsewhere.

Although previous research has integrated a variety of social, ecological and/or wildfire-relevant biophysical metrics in identifying priority areas for restoration (e.g. Ager et al., 2015; Baskent et al., 2020; Davies et al., 2018; D'Evelyn et al., 2022; Peeler et al., 2023; Wigtil et al., 2016), none integrated all three at once as we have done here. Giving these important ecological values and services and vulnerable communities ample consideration is necessary given their dependence on healthy, functioning forests. For example, forest conversion in fire-prone landscapes could alter biodiversity and habitat connectivity (Sitters & Di Stefano, 2020; Thompson et al., 2021) and affect vegetation diversity (Forrestel



Basemap: Esri, TomTom, Garmin, FAO, NOAA, USGS, Bureau of Land Management, EPA, NPS, USFWS, Airbus,USGS,NGA,NASA,CGIAR,NCEAS,NLS,OS,NMA,Geodatastyrelsen,GSA,GSI and the GIS User Community

FIGURE 5 The overlapping area (236,900 ha) between a portion of the USFS top 10 firesheds and our focal areas (left) near Boise, Idaho, and the WMPI (centre) and SEI values (right) that are contained within those overlapping polygons.

et al., 2011; Keeley et al., 2003). By integrating social and ecological values and ecosystem services into our prioritization, we were able to increase the representation of families below the poverty line by 26%, imperilled species richness by 28%, climate resilient landscapes by 20%, and clean water provisioning by 45% when compared to areas identified by the WMPI alone. We also increased the representation of populations with COPD and asthma by 14% and 4%, respectively, which is critical given a positive association between exposure to wildfire smoke and aggravation of these respiratory conditions (Cascio, 2018; D'Evelyn et al., 2022).

The overall representation of social vulnerability, ecological values and ecosystem services increased, on average, by 10%, 11%, and 42%, respectively, compared to prioritizations based on wildfire mitigation potential alone. The focal areas identified here could therefore serve as a complement to similar analyses, including that of Peeler et al. (2023) examining hotspots of wildfire-caused carbon loss and risk to human communities across USFS firesheds, to ensure even greater gains for human and ecological communities alike. An examination of our results alongside those of Peeler et al. (2023), Wigtil et al. (2016), and other similar studies underscores how the spatial distribution of landscape priorities can shift based on researcher or practitioner priorities and that these priorities must be thoughtfully identified and results interpreted with caution.

We used the best available CONUS-scale datasets, drawing on USFS and other federally derived datasets where available (e.g. WHP, PLS, VDep, Census Bureau data) and employed established methods for combining these datasets into a set of composite indices (Suraci, Farwell, et al., 2023). However, all spatial datasets are subject to uncertainties, which are inherently propagated into our indices. These datasets serve as approximations that should be interpreted with caution at finer scales. We also note that the datasets used here had variable native resolutions (90-m to 2-km), or in the case of social vulnerability, were based on data summarized at the level of census tracts. We therefore anticipate that our results will be most relevant for landscape-level prioritizations, rather than localized decision-making. We have accounted for this consideration in part by smoothing and filtering our focal areas to 405 ha. Given this, we suggest that the focal areas identified here can best serve as starting points to direct attention to landscapes that may provide substantial co-benefits if managed to reduce wildfire risk.

More detailed, on-the-ground investigations of proposed focal areas, as well as collaboration with local communities, tribes and stakeholders, would be necessary in making any final determination about where to apply treatments. These collaborations, especially an integration of Indigenous Knowledge and Western science, could help scientists and practitioners garner valuable historical context for land management practices in a given area while gathering localized details that can inform fine-scale decision-making (Ray et al., 2012).

When incorporating these results into community level decisions, it will be essential to carefully consider the complex and varied relationships between different communities and the role of fire on the landscape, as well as the historical dynamics of power surrounding decision-making regarding dominant land management practices (Bourke et al., 2020; Christianson et al., 2022). Great care and respect should be given to understanding and elevating Indigenous fire stewardship practices that have historically been excluded from post-colonization land management practices (Bourke et al., 2020; Hoffman et al., 2022; Peeler et al., 2023), as well as the social and cultural dynamics within a community (e.g. livelihood, income level, upbringing) that may influence how individuals perceive or respond to wildfire risk (Hamilton et al., 2019; McFarlane et al., 2011). The interplay of these dynamics must be thoughtfully addressed in the process of identifying wildfire treatment areas, particularly through identifying and bridging 'collaboration gaps' to establish more coordinated, collaborative, supportive and incentivized wildfire restoration efforts moving forward through an interweaving of Indigenous Knowledge and Western science (Charnley et al., 2020; Eisenberg et al., 2024; Hamilton et al., 2021).

In practice, these efforts could include participatory mapping initiatives or multi-criteria analyses and planning activities that engage communities and reveal local priorities. Such efforts could also improve researchers' and land managers' understanding of finer-scale interactions between wildfire risk and community-defined social and ecological values (Gamboa et al., 2023; McBride et al., 2017). McBride et al. (2017) highlight how participatory mapping can facilitate more effective communication and integration of Indigenous Knowledge and Western science in forest management by compiling information in a Geographic Information Systems (GIS) interface and thus can provide a roadmap for similar applications. Another approach could centre on establishing collaborative organizations composed of members representing community groups, government agencies and non-profits at local, regional and/or national levels. These collaboratives can then coordinate and scale large-scale analyses and guidance to local-scale needs and existing social and political infrastructure within a community (Edgeley & Paveglio, 2024; Huayhuaca et al., 2023). For example, the USFS Collaborative Forest Landscape Restoration Program (CFLRP) was established in 2009 with the goal of encouraging collaborative, science-based forest ecosystem restoration on USFS lands by integrating local, national and private stakeholders and resources (Schultz et al., 2012). Through the CFLRP, communities can apply for funding and the opportunity to work collaboratively with USFS land managers to implement community-led landscape-scale restoration projects. This program has helped to bridge information gaps between community members and federal agency staff and has served as a valuable incubator and model for a collaborative, multi-scale approach to land management (Schultz et al., 2012; Urgenson et al., 2017). The proposed National Old Growth Amendment is another example of how a national direction for adaptive management can be used to develop local solutions through close collaboration with Tribes and other governmental and non-governmental stakeholders, particularly through the development of an *Adaptive Strategy for Old-Growth Forest Conservation* for each national forest to ensure locally appropriate management and monitoring (U.S. Forest Service, 2024).

Lastly, we acknowledge that while we identify the ecological values, ecosystem services and socially vulnerable communities that could be protected by or benefit from restoration, we cannot say that high-severity fire will diminish any of the indicators contributing to these sub-indices. Further analysis is necessary to deepen our understanding of how much of these indicators may in fact be lost in the absence of restoration if a wildfire were to occur (Peeler et al., 2023). Regardless, the ecological, social, and biophysical aspects of wildfire risk are highly interconnected. For example, wildfire can impact biodiversity, which could result in carbon loss that may affect ecosystem services that can determine human community health. As we increasingly recognize these dynamics, we must begin to reflect them in our restoration prioritizations.

5 | CONCLUSION

The focal areas we have identified can inform a strategic shift or refinement of current management prioritizations, including the USFS' top ranked firesheds approach. Based on an average treatment cost per hectare of just over $3700 ($1500/acre; Hunter & Taylor, 2022), the $1.5 billion pledged by the Biden Administration could support fewer than 405,000 ha (1 million acres) of restoration activities, requiring tough decisions about which areas to prioritize. To begin these decision-making conversations, we have provided the model results, sub-indices comprising the SEI, and a set of focal area polygons summarized to areas within and immediately adjacent to USFS lands in a web application for viewing at https://csp-inc.github.io/pew-usfs-app/. While the analysis described here followed an 'all-lands' approach across CONUS, the results provided in the web application are intended to specifically inform USFS management and thus were limited to the extent of NFs and their intersecting firesheds. Irrespective of analysis extent, we can ensure the USFS and other land managers secure the maximum possible co-benefits while working within budgetary constraints by focusing restoration on areas with the greatest identified wildfire mitigation potential while also considering social and ecological values within and around their existing fireshed framework. Safeguarding these values now will be essential to ensure their resilience in an uncertain future.

AUTHOR CONTRIBUTIONS

Justin P. Suraci, Blake S. Busse and Brett G. Dickson conceived the ideas. Caitlin E. Littlefield, L. Mae Lacey, Justin P. Suraci, Blake S. Busse and Brett G. Dickson designed the methodology. Justin P. Suraci, L. Mae Lacey and Caitlin E. Littlefield collected and analysed the data; L. Mae Lacey led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

None of the authors have a conflict of interest to declare.

DATA AVAILABILITY STATEMENT

All data supporting this analysis are publicly available, and all analysis outputs are available at https://doi.org/10.6084/m9.figshare.c.7430305.v2.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Supplementary methods.

Table S1.1. The fourteen indices of social vulnerability considered here and the indicators selected from each for inclusion in this analysis.

Figure S1.1. PCA biplot for the social vulnerability dataset, highlighting the mapping of demographic and health datasets along Principal Component (PC) 1 and PC2.

Figure S1.2. CONUS-wide distribution of the three sub-indices contributing to the SEI: (a) social vulnerability, (b) ecological values, and (c) ecosystem services.

Appendix S2. Supplementary results.

Table S2.1. Mean values (±SD) for all indicators within high value polygons summarized across CONUS as well as the percent change in those indicator values when refining areas within the top 20% of the WMPI by focusing solely on focal areas.

Table S2.2. Mean values (±SD) for all indicators within the top ten USFS firesheds by region summarized across CONUS, as well as the percent change in those indicator values when focusing solely on areas of overlap between these top firesheds and our focal areas.

Figure S2.1. The overlapping area between the USFS top 10 firesheds and our focal areas (left) around Denver, Colorado and the WMPI (center) and SEI (right) values that are contained within those overlapping polygons.

Figure S2.2. The overlapping area between the USFS top 10 firesheds and our focal areas (left) around Charleston, West Virginia and the WMPI (center) and SEI (right) values that are contained within those overlapping polygons.

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