Progress in Disaster Science 23 (2024) 100358

Contents lists available at ScienceDirect

Progress in Disaster Science

journal homepage: www.elsevier.com/locate/pdisas

Compound risk of wildfire and inaccessible shelters is disproportionately impacting disadvantaged communities

Alireza Ermagun *, Fatemeh Janatabadi

Department of Geography and Geoinformation Science, George Mason University, 4400 University Dr., Fairfax, VA 22030, USA

A R T I C L E I N F O

Keywords:
Risk assessment
Equity
Accessibility
Wildfire
California
Risk management
Social vulnerability
National risk index

A B S T R A C T

This study proposes measuring access to shelters and wildfire risks in tandem rather than in isolation to prevent wildfires from turning into human disasters. By leveraging a human-centered design approach in California, which has an active wildfire history and experience with some of the deadliest wildfires, three key findings are discerned. First, California experiences undesirable resource allocation where regions with a high risk of wildfire are surrounded by regions with a low level of access to emergency shelters, and regions with a low risk of wildfire are surrounded by regions with a high level of access to emergency shelters. Second, neither access to shelters nor wildfire risk is evenly distributed across space. This uneven distribution, however, discriminates against exurban areas. As one moves away from core cities, higher wildfire risk and comparatively limited access to emergency shelters are noticed, underscoring the heightened susceptibility of exurban areas to wildfires. Third, in contrast with existing research solely focusing on wildfire risk, it is revealed that the elderly, people with disabilities, and Hispanics are at a higher risk of experiencing high wildfire risk and low access to shelters. The findings suggest instilling equity into wildfire preparedness strategies while minimizing the gap in access to resources between disadvantaged and advantaged communities, given the trichotomy of exposure to the hazard (risk of wildfire), proximity to aid (access to shelters), and vulnerability to threat (community characteristics).

1. Introduction

Wildfires are becoming more frequent and intense, scorching the western part of the U.S., particularly where California is experiencing more blazes [46]. This is due to California bearing extreme heat waves and longer wildfire seasons. Once four-month wildfire season now lasts up to eight months [42]. The 2022 outlook in California was dire as the number of wildfires and acres burned were higher compared to the 10-year average. A total of 7490 raging wildfires burned 362,455 acres of land and damaged or destroyed 876 structures, with 9 confirmed losses of life [4]. Over 11,000 people across Placer and El Dorado counties in California were ordered to evacuate due to the Mosquito Fire in September 2022 [7], when Northern California experienced the worst September heat wave on record with the all-time highest temperature of 116 degrees Fahrenheit.

The adverse effects of wildfires can be mitigated only if a community understands its existing vulnerabilities and adopts strategic and equitable preparedness plans, which prior to a disaster, can build resilience. The need for equitable preparedness strategies is painfully clear. First, according to 10-year average statistics, California experiences approximately 8120 wildfires per year, burning over 1.3 million acres of land, destroying more than 7000 structures, and tragically resulting in the loss of 20 lives [6]. Second, more than 29 million Americans live in areas with a significant potential for extreme wildfires, 12 million considered "socially vulnerable" [53]. Third, only 22% of Californians living in hazardous regions can access publicly available evacuation routes and shelters.

For residents who do not have access to transport and resources, "simple" tasks like locating and driving to shelters are not feasible. As wildfires might turn into human disasters when residents fail to evacuate and reach shelters, a critical component helping hinder it is offering "*access.*" Access to shelters is the ease of seeking refuge and is the product of both transport infrastructure and the location of shelters. In its practical application, access counts the number of shelters reachable by a mode of travel (e.g., automobile) in a travel-time threshold (e.g., 30 min) when evacuation is declared. It measures people's ability to reach shelters by not just the ability of physical movement but the location of shelters and land use patterns. Access offers neither what people will do

* Corresponding author.
E-mail addresses: aermagun@gmu.edu (A. Ermagun), fjanatab@gmu.edu (F. Janatabadi).

https://doi.org/10.1016/j.pdisas.2024.100358
Received 20 December 2023; Received in revised form 30 June 2024; Accepted 22 July 2024
Available online 26 July 2024

nor want to do, but rather what people could do. What matters is how many shelters they can reach when seeking refuge. However, wildfire-prone communities in California are inclined to suffer from the lack of access to shelters, exacerbated by limited knowledge of evacuation plans and shelter locations. The sufferance has not been felt equally; following the disastrous events, vulnerable communities are more likely to suffer from the lack of assistance and aid, leaving these individuals to battle the burden of surviving alone. An example of this is the 2018 Paradise fire in California that killed 86 people, the majority of whom were "poor, elderly, and too frail" to reach shelters [23].

There is a pressing need for further research that employs methods to comprehensively assess wildfire risk and access to shelters while taking into account the social vulnerability of communities. Factors contributing to the communities' vulnerability during natural hazards have been laid bare by literature as social marginalization (e.g., race, ethnicity), mobility restrictions due to physical disability to quickly respond (e.g., elderly, people with disabilities), lack of a personal vehicle for timely evacuation, and low community resilience to absorb and recover financial losses (e.g., low-income households) [38]. The contribution of these factors to the extent of negative consequences is now as germane as they were over two decades ago [14]. Despite the efforts, the situation for vulnerable communities has remained fairly stagnant, if not worsened, and the states of the art and practice currently lack a systematic framework that determines access during wildfire events while incorporating equity considerations.

Given the trichotomy of exposure to the hazard (risk of wildfire), proximity to aid (access to shelters), and vulnerability to threat (community characteristics), the overarching goal of this research is to instill equity into wildfire preparedness strategies while minimizing the equity of access gap to resources between disadvantaged and advantaged communities. At this juncture, it is appropriate to raise two fundamental questions: (i) how can we integrate varying levels of access to emergency shelters into different levels of wildfire risk and identify at-risk regions reflecting dual effects? (ii) how does access-incorporated-risk affect the spatial identification of vulnerable communities in high-risk areas? By seeking answers, the contribution of the current research to the existing science of wildfire risk management is twofold. First, we introduce the Wildfire Access-Infused Risk (WAIR) index, which uses spatial analysis to classify areas based on the correlation between wildfire risk and access to shelters. The four categories are: (i) high wildfire risk with high shelter access, (ii) high wildfire risk with low shelter access, (iii) low wildfire risk with high shelter access, and (iv) low wildfire risk with low shelter access. The proposed framework for measuring WAIR provides both state-level and local-level emergency managers with the required tool for identifying areas most vulnerable to wildfire that lack enough accessible emergency shelters. Second, it enables the practitioner to instill equity into their preparedness strategies by identifying those most vulnerable communities and planning according to their emergency needs. Our findings nurture the development and implementation of a science-informed equitable solution for disadvantaged residents and local decision-makers to augment equity discrepancies and community resilience to the devasting impacts of the ongoing challenge for residents of wildfire-prone areas.

2. Previous studies

Risk assessment methods for wildfires have traditionally focused on quantifying expected losses. Common methodologies involve developing prediction models that quantify the likelihood, intensity, and susceptibility to wildfire effects [3,33]. These models have predominantly centered on the physical characteristics of wildfires and their potential economic impacts, often neglecting the vulnerabilities of affected communities [20]. As our understanding of natural hazards has progressed, risk assessment methods have also advanced. Risk assessments have gradually incorporated the concept of population vulnerability, recognizing that the impact of a hazard is not solely determined by its physical characteristics but also by the social and environmental contexts in which it occurs. The devastation of wildfires in Victoria, Australia, in 2009 [45] and Southern California, United States, in 2003 and 2007 [26], demonstrated the need for a better understanding of why traditional mitigation plans failed to protect the community in these events and to improve community resilience. Researchers began to integrate both biophysical and social vulnerability to provide a more comprehensive understanding of the risk of natural hazards [14].

The recent increase in the frequency and severity of wildfires has led to significant loss of life and property, particularly in California [3]. This increase is due in part to the warming climate. However, changes in land use patterns have also exacerbated wildfire risk for communities, particularly in sprawling areas [2,10,41]. Urban sprawl has led to the rapid expansion of human settlements into wilderness regions and has placed more individuals at the interface of natural vegetation and heightened wildfire risk [40]. Responses to these threats fall into two categories: evacuation and shelter-in-place [12]. Yet, living far from urban density eliminates people's access to safe locations in the face of natural hazards. With fires often blocking roads, evacuation may not always be a viable option. The 2003 Cedar Fire, the 2007 Witch Creek Fire, and the 2008 Tea Fire [12] are examples where sheltering in safe nearby facilities was preferred over evacuation [12]. The distance from urban density was a factor; all three fires occurred in suburban and sprawling areas, demonstrating the vulnerability of these regions.

Recent advancements in wildfire risk assessment have shifted focus from mere proximity to fire-prone areas to a nuanced understanding of vulnerability, influenced by a combination of risk factors, spatial dynamics, and social conditions [9]. This evolution has prompted researchers to examine the impacts of changing land use patterns and the expansion of urban sprawl into wilderness regions, which significantly increase wildfire risk [2,41]. Studies on the association between shelters and wildfire risk have predominantly centered on logistical and infrastructural considerations. These include assessing the spatial proximity of shelters to high-risk zones, evaluating local adaptation strategies, and reinforcing critical infrastructure [12,31,37]. They also include estimating evacuation times and the capacity of shelters to accommodate affected populations during emergencies [21], as well as identifying optimal shelter locations [16]. The presence of shelters in wildfire-prone areas is recognized as a strategic factor in mitigating wildfire fatalities [16]. The Federal Emergency Management Agency (FEMA) has adopted a similar approach by integrating considerations of population and shelter availability into its wildfire risk index. The FEMA National Risk Index combines components such as expected annual loss, social vulnerability (including socioeconomic status, household composition, transportation access, and health status), and community resilience (encompassing economic development, social capital, community planning, information and communication, adaptive capacity, and built environment) to assess wildfire risk across counties and census tracts in the United States [52]. Within the built environment factor, FEMA includes the number of shelters available in an area.

It is important to distinguish between the availability and accessibility of shelters. Availability refers to the presence of shelters, while accessibility considers the ease with which individuals can reach these shelters, influenced by factors such as transport infrastructure and spatial distribution of shelters. This distinction underscores the critical need for a community-centered approach in wildfire risk assessment, ensuring that vulnerable populations have adequate access to lifesaving shelter resources during wildfire events. Practically, shelter accessibility assesses the number of shelters reachable within a specific travel time (e.g., 30 min by car) when an evacuation order is issued. It evaluates not only physical mobility but also considers the spatial distribution of shelters and local land use patterns. Access determines what actions individuals can take during emergencies, emphasizing the importance of how many shelters are reachable. The concept of "access to shelters" addresses the critical element of people's capabilities to seek refuge, highlighting the need for a community-centered approach in natural hazard risk assessment.

3. Materials and method

3.1. Study area

Our study region includes the Los Angeles, Riverside, San Diego, and Sacramento metropolitan areas, which have an active wildfire history and have experienced some of the deadliest wildfires. These areas are particularly susceptible to wildfires due to their arid climate, strong winds, abundant flammable vegetation, and proximity to wildland areas [29]. Fig. 1 illustrates the characteristics of the study area. On average, San Diego has the highest number of shelters per block group at 0.91, whereas Los Angeles has the lowest at 0.40 shelters per block group. Riverside and Sacramento have 0.78 and 0.71 shelters per block group, respectively. Los Angeles exhibits the highest share of block groups lacking any shelters, with 73% having none. In comparison, 51% of block groups in Sacramento, 46% in Riverside, and 37% in San Diego have no shelters. Examining the risk of wildfire, according to FEMA [54], 35% of block groups in Los Angeles are at relatively high or very high risk of wildfire. In contrast, Riverside has 20% of its block groups at high risk, Sacramento has 13%, and San Diego has 10%. In addition, FEMA measures and reports the social vulnerability index to assess the susceptibility of social groups to adverse impacts from natural hazards.

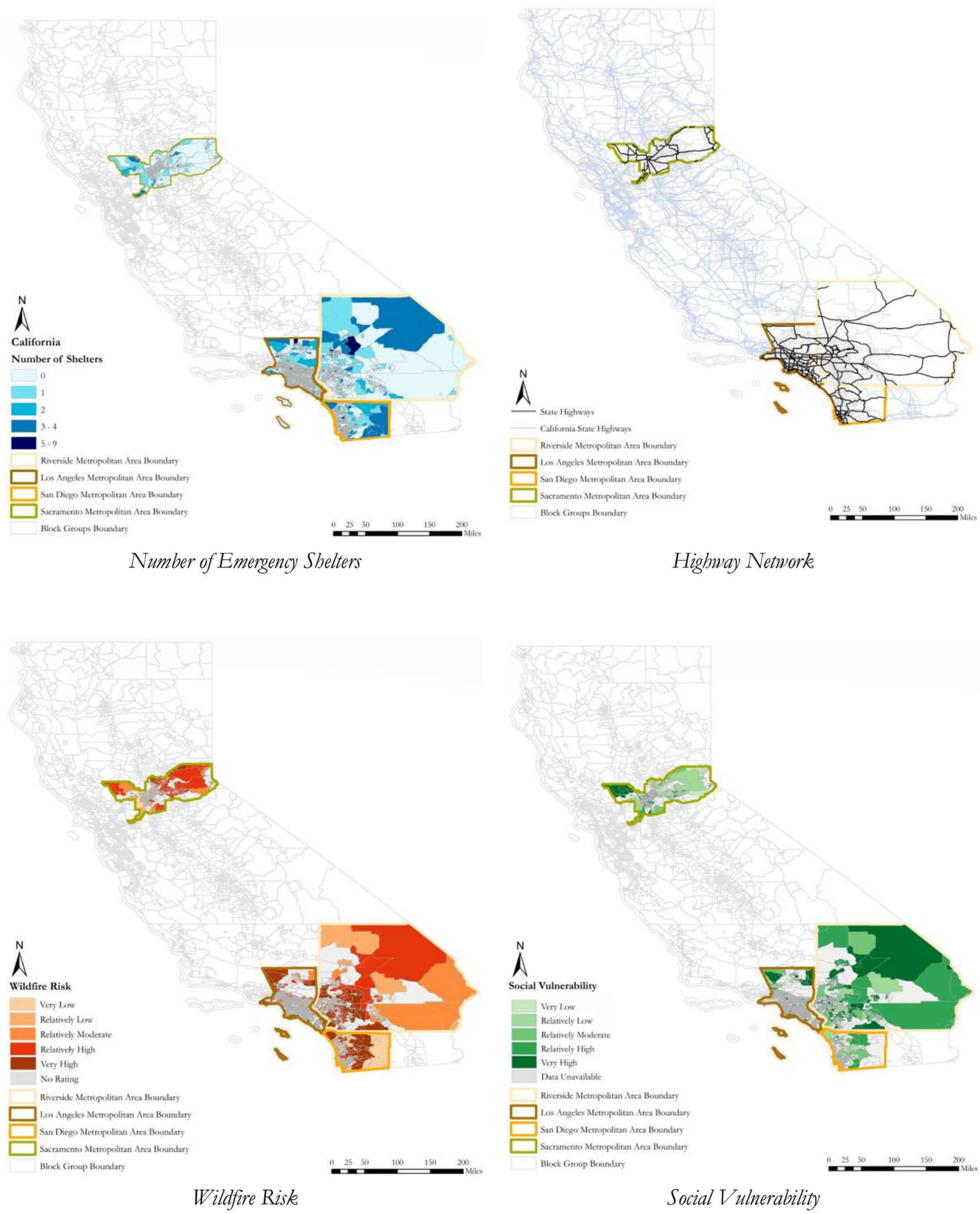

Fig. 1. Spatial distribution of emergency shelters, state highways, wildfire risk index, and social vulnerability index across the study area.

Mapping the social vulnerability of the study area reveals that Sacramento stands out with very high and relatively high social vulnerability, while the other metropolitan areas exhibit less concerning vulnerability levels, ranging from very low to relatively moderate.

3.2. Data description

Our proposed multi-faceted framework utilizes four datasets: (i) wildfire risk data, (ii) emergency shelter locations, (iii) roadway network data, and (iv) demographic and socioeconomic data. First, we extracted wildfire risk scores and levels at the census tract geographical level from the FEMA National Risk Index [54]. A limitation of the FEMA dataset is that it employs a uniform approach to measuring and reporting risk across different regions. While this ensures consistency for nationwide comparisons, it can downplay the perceived severity of hazard exposure in specific regions if the risk appears less severe when viewed in a national context. Consequently, this approach may not fully capture disparities within smaller regions or specific communities, leading to potential overestimation or underestimation of actual wildfire risk. As our access calculations are conducted at a finer geographical level (i.e., census block groups), we allocated the wildfire risk of each census tract to its corresponding block groups. This approach is more conservative, ensuring that the risk assessment does not underestimate potential hazards at the finer geographical scale. Second, we extracted the spatial locations of emergency shelters from the Homeland Infrastructure Foundation-Level Data [25], which includes educational, community, health, civic, and religious centers. While this dataset provides a comprehensive overview of shelter locations, a limitation is that it does not offer real-time updates on the availability or condition of these shelters. It may not encompass all potential shelters or accurately reflect their current capacity and readiness during an emergency. We associated the latitude and longitude coordinates of these shelters with the corresponding census block groups. Third, we extracted the roadway network from OpenStreetMap North America in the osm.pbf format. OSM data is characterized by its broad coverage and detailed attribute information. However, its quality and accuracy can vary depending on the region and the level of community engagement, as it relies on crowdsourcing. Despite these potential limitations, OSM data is widely regarded as a reliable source [34]. Fourth, we extracted the demographic and socioeconomic characteristics of populations at the block group geographical level from the 2019 American Community Survey (ACS) five-year estimates. This ongoing survey collects population statistics that were previously only available through the long form of the U.S. Decennial Census. As the U.S. Decennial Census is conducted every ten years, the ACS estimate offers a higher temporal resolution, making it more favorable for estimating the current population exposed to wildfire risk.

3.3. Measuring access to shelters

Access is defined as the number of emergency shelters that can be reached from the population weighted centroid of block groups by automobile at a 30- and 60-min travel-time thresholds. We use cumulative opportunities measure for analysis [55]. Cumulative metrics implicitly assume that the demand for available opportunities is uniformly distributed in space and do not account for the capacity limitations of those opportunities. While this approach does not accurately capture the situation for emergency shelters, it remains the best approach for this study as: (i) there is no public information available for shelter capacity, and (ii) for providing a framework for policy and decision-making, cumulative access measure provides the most comprehensible and easy to use outcome [27]. Access is formulated in Eqs. (1 and 2) where A_i is the access of census block group i to shelter O located in census block group j. The cost of travel between i and j follows a binary function, $f(C_{ij})$, where t represents the travel time threshold.

$$A_i = \sum_{j=1}^{n} O_j f(C_{ij}) \tag{1}$$

$$f(C_{ij}) = \begin{cases} 1, & \text{if } C_{ij} \le t \\ 0, & \text{if } C_{ij} > t \end{cases} \tag{2}$$

3.4. Measuring wildfire access infused risk (WAIR) index

The Wildfire Access Infused Risk (WAIR) Index is measured by examining the statistical significance of the association between the wildfire risk index at location i (i.e., x_i) and the average of neighboring values for access to shelters (i.e., its spatial lag $\sum_j w_{ij} y_j$). We employ a Bivariate Local Indicator of Spatial Autocorrelation (BiLISA) [56,57], also known as bivariate Local Moran's I, to form the spatial clusters of the WAIR Index per Eq. (3). In this equation w_{ij} is the spatial weight matrix established using first-order queen contiguity. This is legitimate as both wildfire risk and access to shelters are spatially correlated by nature and over our study region.

$$I_i^B = c x_i \sum_j w_{ij} y_j \tag{3}$$

By conducting 1000 randomization permutations with a pseudo p-value of 0.10, we assess the pseudo-significance of the BiLISA statistic. This approach spatially correlates wildfire risk index in a core area and automobile access to shelters in neighboring areas and classifies the block groups into four clusters: (i) areas with high wildfire risk and high access to shelters (HH), (ii) areas with high wildfire risk and low access to shelters (HL), (iii) areas with low wildfire risk and high access to shelters (LH), and (iv) areas with low wildfire risk and low access to shelters (LL). For example, the HL category represents areas with high wildfire risk spatially surrounded by regions with low automobile access to shelters. Areas with no significant spatial correlation are labeled "Not Significant" (NS). Here, the WAIR Index is developed by spatially correlating the National Wildfire Risk Index extracted from the FEMA and automobile access to shelters for 30-min and 60-min travel time thresholds at the block group geographical level. The WAIR Index, however, can be measured using any wildfire risk index, any method of computing access to shelters, and at any geographical scale.

4. Results and discussions

4.1. Reporting wildfire-access infused risk

Here, we visually illustrate the WAIR index and compare it with FEMA's wildfire risk index. The WAIR index is an infusion of FEMA's wildfire risk and automobile access to shelters. Fig. 2 depicts the results. Three observations are discerned.

First, there is a spatial mismatch between shelter locations and wildfire risk. This mismatch results in areas with an imbalance between wildfire risk and access to shelters. This pattern is visually indicated by the bundles of HL and LH clusters on the maps. HL areas have high wildfire risk yet suffer from low access to shelters, while LH areas have low wildfire risk and high access to shelters. Neither scenario is desirable. HL indicates a potential under-allocation of resources, while LH suggests possible over-allocation. Although both HL and LH areas exhibit spatial mismatches, the underlying causes differ. We speculate that this mismatch is attributed to two factors. The first factor is the multi-objective nature of these shelters. Many emergency shelters are not solely designated as emergency centers but serve multiple public functions. In our study region, out of 1743 shelters, roughly 1% are designated emergency centers, while the rest mostly are educational (47%), religious (14%), and community (11%) centers. These locations are repurposed as shelters during emergencies based on availability. Consequently, their locations are not specifically chosen to address high-

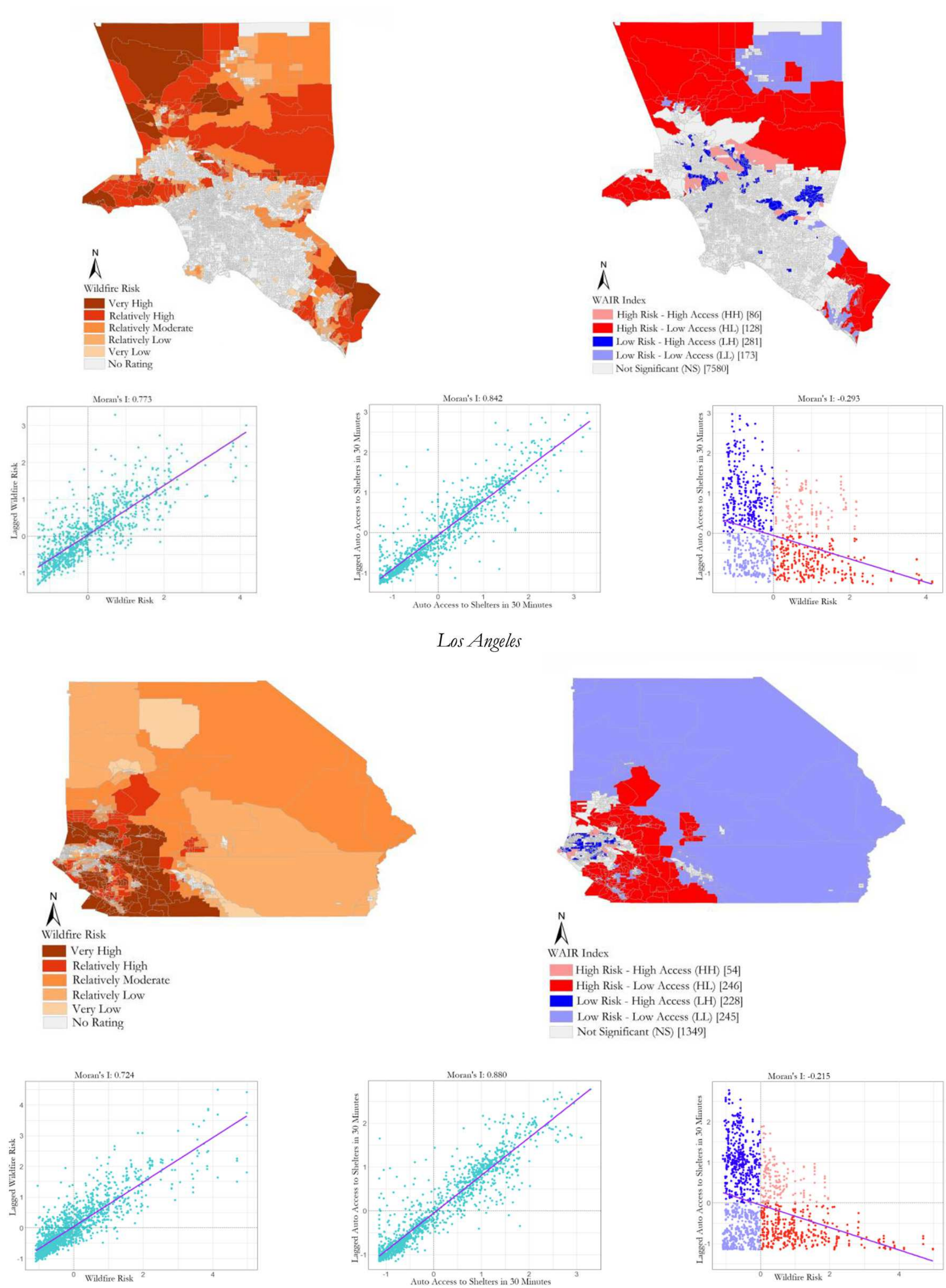

Fig. 2. Depiction of wildfire risk map and BiLISA cluster maps pertaining to automobile access disparity to emergency shelters during wildfire events for a 30-min travel-time threshold at a 0.10 significance level across Los Angeles, Riverside, Sacramento, and San Diego. The numbers within the brackets indicate the number of block groups located in each cluster. Maps are accompanied by three scatter plots: (i) a univariate cluster map of wildfire risk, (ii) a univariate cluster map of automobile access to shelters, and (iii) a bivariate cluster map of wildfire risk and automobile access to shelters.

risk areas but to meet broader community needs. The placement of these shelters is influenced by socioeconomic and demographic conditions, population density, geographic and environmental considerations, and land use development patterns, potentially exacerbating the urban-exurban divide. The second factor is the interaction between power dynamics and resource allocation, which may supersede need-based

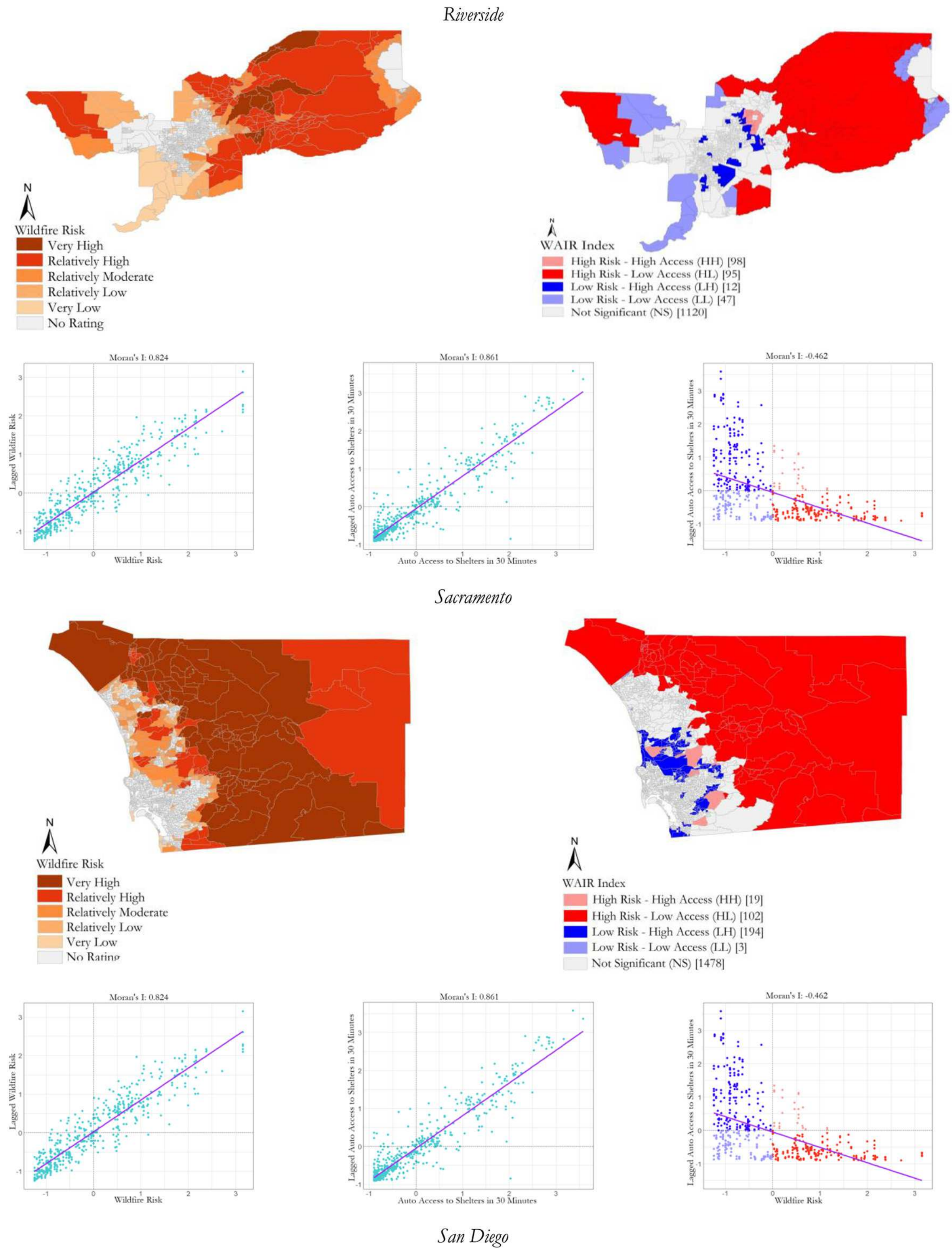

Fig. 2. (*continued*).

allocation. As Perry and Lindell [39] stated, "emergency planning involves the allocation of power and resources." This process is influenced by how effectively communities advocate for their needs, thereby attracting more investments and services. Understanding this dynamic is critical for recognizing the imbalance between needs and services, which is essential for both the people affected and the decision-makers responsible for resource distribution. The observed patterns of mismatch are also empirically confirmed through the negative correlation between wildfire risk and the spatial lag of automobile access to emergency shelters reported in the scatter plots. The scatter plots identify spatial patterns and correlations between wildfire risk and access to shelters using Moran's I index. All metropolitan areas have positive univariate Moran's I for wildfire risk and access to shelters, meaning high and low values of these variables tend to be spatially clustered. Bivariate Moran's I for wildfire risk and access to shelters, relating the non-lagged dependent variable (wildfire risk) with the lagged dependent variable (access to shelters), is negative for all areas, indicating high and low values of two variables tend to be spatially clustered. We presented the cluster maps for the 60-min travel-time threshold for comparison in Supplementary Data I.

Second, there is an urban-exurban divide in spatial access to emergency shelters in risky areas. Exurban areas, located beyond the immediate suburban periphery of metropolitan regions, exhibit a higher susceptibility to wildfire risk compounded by low access to shelters. As noted earlier, shelters are not necessarily emergency centers and often serve other community needs. Access to shelters decreases as one moves away from the central core of metropolitan areas, resulting in clusters of HL and LL in exurban and outer skirts of metropolitan areas. FEMA's risk maps indicate that exurban areas have higher wildfire risk, partly due to the presence of wildlands and dense vegetation, which serve as fuel for

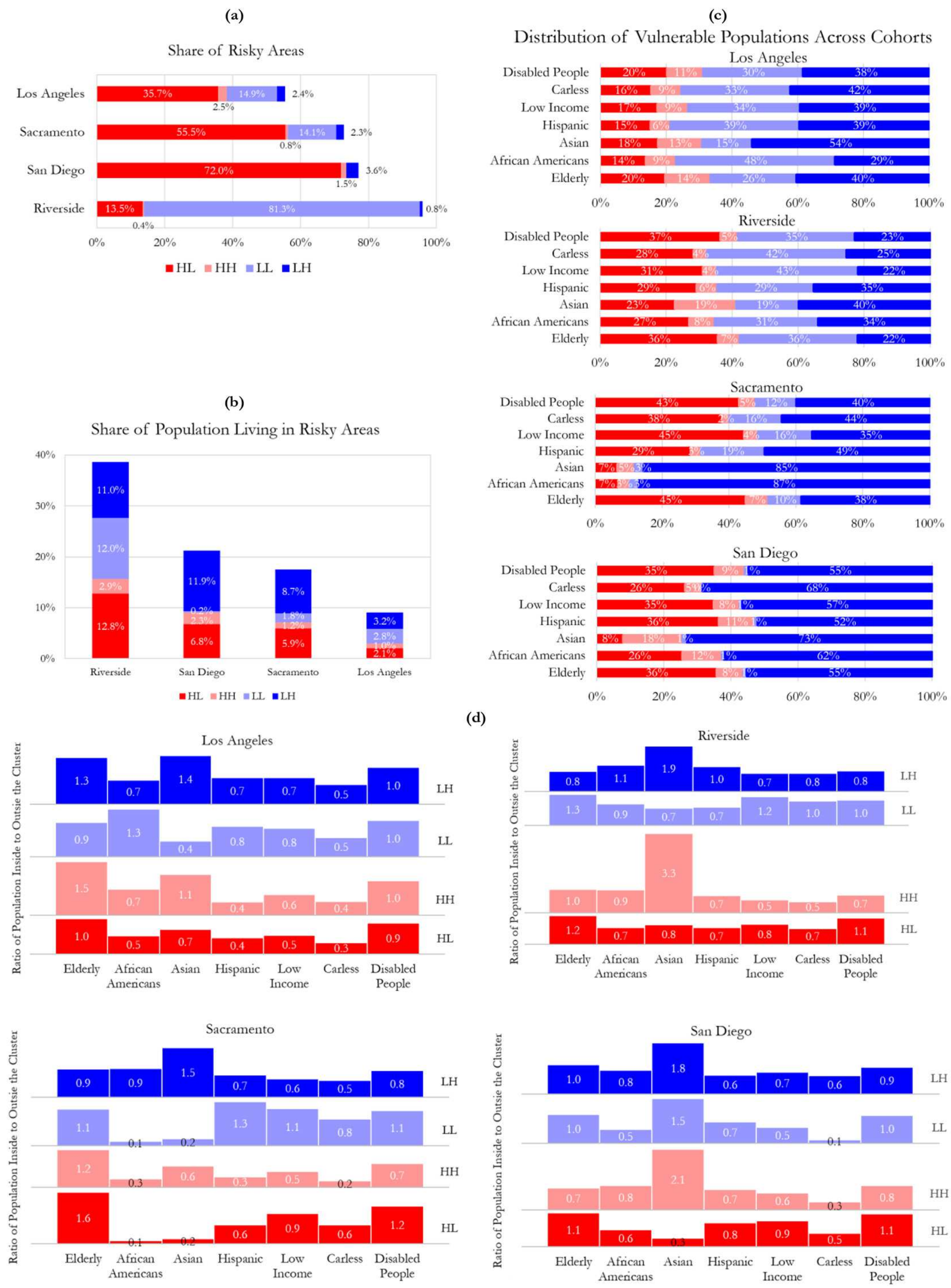

Fig. 3. Proportion of land exposed to wildfire risk, disaggregated by metropolitan and vulnerable cohorts. **(a)** Illustrates the proportion of land in areas classified as risky (i.e., HH, HL, LL, LH) compared to those outside these areas. **(b)** Displays the share of the population living in risky and non-risky areas per metropolitan area, alongside the percentage of areas classified into each cluster per city. **(c)** Provides a granular depiction of the distribution of vulnerable populations across each cluster (i.e., HH, HL, LL, LH) per metropolitan area. **(d)** Depicts the ratio of the percentage of vulnerable populations residing in each cluster compared to those living outside of the cluster, within the same vulnerable group. The percentage of the risky lands and population living inside and outside of risky areas and the distribution of vulnerable populations across each cluster are reported in Supplementary Data II.

wildfires. Communities living in these exurban areas, therefore, face a higher risk of wildfires while having relatively lower access to shelters compared to urban residents, indicating the “environmental perils of sprawl” [22]. The urban-exurban divide significantly impacts social dynamics and community resilience. Exurban areas often house low-income and marginalized communities that suffer from lower access to services and facilities [24] while urban and even suburban populations benefit from relatively better access to amenities and services [13]. This disparity in access to resources between urban and exurban communities is reflected in their access to emergency shelters. This observation indicates the need for more equitable resource allocation and targeted emergency planning strategies in exurban areas. This calls for prioritizing the specific needs and vulnerabilities of exurban communities to foster more resilient and equitable wildfire preparedness efforts.

4.2. Examining social and spatial disparities by wildfire-access infused risk

While identifying the proportion of block groups associated with each cluster is undoubtedly a valuable step in understanding the spatial distribution of the WAIR index, examining the population exposed to each cluster carries greater significance. Two reasons support this assertion. First, pre-existing social and physical vulnerabilities in risk-prone communities exacerbate disaster impacts and hinder recovery efforts [51]. Identifying the characteristics of the population within each cluster and understanding their vulnerabilities ensures that emergency measures are effectively targeted. Second, disaster response and recovery efforts are resource-intensive undertakings. The allocation of resources, including emergency personnel, supplies, and funding, should, therefore, be proportionate to community needs and the potential scale of the impact. This approach not only enhances the effectiveness of disaster response but also ensures that aid reaches those who need it most, thereby optimizing the overall resilience of the affected regions [19].

Here, the spatial distribution of seven socially vulnerable populations (i.e., people with disabilities, the elderly, carless individuals, low-income households, Hispanics, Asians, African Americans) is examined across four clusters (i.e., HH, HL, LH, LL). Our assessment for each metropolitan area, depicted in Fig. 3, illustrates (i) the land distribution of at-risk areas (i.e., HH, HL, LH, LL), (ii) the population distribution of at-risk areas, (iii) a detailed breakdown of the demographic and socioeconomic characteristics of individuals residing in each cluster, and (iv) an equity index depicting the share of vulnerable populations in each cluster relative to its corresponding share of the overall population. Three observations can be discerned from this figure.

First, there is a discrepancy between the population residing in risky clusters and the extent of land exposed to those clusters. A significant portion of land characterized by high wildfire risk and low access to shelters exists across the Los Angeles, San Diego, and Sacramento metropolitan areas. In San Diego, 72% of the land falls into this category, compared to 35.7% in Los Angeles and 55.5% in Sacramento. Riverside has the lowest share, with only 13.5% of the land exposed to high wildfire risk. Despite this, Riverside has the highest proportion of its population living in high-risk, low-access areas (HL areas), with 12.8%, compared to 6.8% in San Diego, 5.9% in Sacramento, and 2.1% in Los Angeles. These disparities, depicted in Fig. 3(a) and Fig. 3(b), underline the need to distinguish between land-based and population-based mitigation and emergency efforts. Land-based efforts are essential for preventing the destruction of land, which can lead to cascading hazards [49]. For instance, wildfires that devastate large tracts of land can result in soil erosion, loss of vegetation, and increased vulnerability to landslides and flooding. Population-based efforts, on the other hand, prioritize eliminating human risk by ensuring that individuals and communities are adequately protected and can evacuate safely during emergencies. Population-based efforts aim to reduce casualties, prevent injuries, and safeguard livelihoods. Effective planning and policy must integrate both land-based and population-based strategies to address the multifaceted challenges posed by wildfires. This dual approach ensures that while we work to protect and rehabilitate natural landscapes, we also prioritize the safety and well-being of at-risk populations.

Second, there is an unequal distribution of vulnerable populations in wildfire-prone and low-access areas across metropolitan regions. Examining the share of vulnerable populations in each cohort between metropolitan areas, results indicate that metropolitan areas do not discriminate based on socioeconomic status, age, or disability characteristics. However, there is discrimination observed based on racial categories, as shown in Fig. 3(c). We observe a lower proportion of Asians residing in HL areas in Sacramento and San Diego, while the same group exhibits a relatively higher share in Los Angeles and Riverside. A similar trend is observed for African Americans, and to a lesser extent for Hispanics. These racial cohorts may represent the highest proportions in one metropolitan area and the lowest in another. However, when examining age, disability, income, and car ownership, we find consistently high proportions of these groups living in HL clusters across all metropolitan areas. This suggests that vulnerability based on these factors is relatively consistent across different regions, highlighting the significance of racial disparities in the distribution of wildfire-risk areas. Previous research revealed that low-income communities are particularly vulnerable to the devastating effects of wildfires, bearing a disproportionate burden of both the direct and indirect impacts of this natural hazard [30,35]. Our findings confirm previous research that suggests the elderly, people with disabilities, and low-income individuals are at a higher risk of experiencing high wildfire risks and low access (HL), regardless of the metropolitan area.

Third, vulnerable populations experience disproportionate exposure to high wildfire risks and limited access to shelters. We compared the proportion of each vulnerable population within specific clusters to their proportion outside those clusters. A ratio greater than 1 indicates a higher concentration of vulnerable populations within the cluster compared to the broader region. For individuals residing in the HL cluster, characterized by elevated wildfire risks and reduced shelter access, this imbalance could exacerbate the severity of wildfires, potentially leading to humanitarian crises. As depicted in Fig. 3(d), in the Riverside, Sacramento, and San Diego metropolitan areas, the elderly and individuals with disabilities exhibit higher proportions within HL areas compared to outside these clusters. Specifically, in Sacramento, the proportion of the elderly and individuals with disabilities residing in the HL cluster is respectively 1.6 and 1.2 times greater than in non-HL regions. This observation, whether due to self-selection or external factors, is troubling, as both groups are among the least mobile vulnerable populations, facing challenges during evacuation and shelter-seeking processes. Our findings diverge from previous studies that suggest people of color face heightened exposure to natural hazard risks [17,32]. However, our analysis reveals no disproportionate concentration of Asians, African Americans, and Hispanics in HL areas compared to outside these clusters.

4.3. Leveraging WAIR index for wildfire mitigation

Identifying clusters of risk and access along with the characteristics of communities living in each cluster helps formulate community-centric mitigation plans and emergency responses. This knowledge (i) enables proper infrastructure planning, (ii) increases community capacity to face natural hazards, and (iii) builds resilience to prevent human disasters. This can be achieved by considering the WAIR index in short-term and long-term mitigation strategies and establishing science-based risk assessment methods.

Short-term solutions can be classified into three strategies. First, establishing temporary shelters or designating public facilities to enhance access in HL areas. Establishing and designating temporary shelters necessitates a collaborative effort involving local authorities and organizations. Close coordination with local authorities, non-profit organizations (e.g., American Red Cross, Salvation Army), and private companies is essential to identify suitable locations for temporary shelters and mobilize the necessary resources. Improving access also requires effective communication and coordination with emergency services to establish evacuation routes and ensure the swift movement of individuals to designated shelters during wildfire events. Access considerations must ensure that temporary shelters are easily accessible to all members of the community, particularly vulnerable populations. If this requirement is not met, on-demand or out-of-station high-capacity fleets (e.g., public transit, school buses) for vulnerable individuals can be allocated. Second, employing strategic communication for emergency responses, particularly for the residents of HL and HH areas, to assist with evacuation or provide navigation to accessible shelters. Effective communication during wildfire events relies on a multifaceted approach using various channels such as social media, emergency alerts, traditional media outlets, and community engagement platforms to disseminate timely and accurate information to residents. It is important to ensure that emergency communication messages are clear, concise, and accessible to diverse populations, including those with language barriers or disabilities [44]. Proactive outreach and engagement initiatives within vulnerable communities are essential to raise awareness about wildfire risks and empower them for effective self-advocacy and risk management. This involves fostering partnerships with community leaders, organizations, and local stakeholders to amplify messaging and promote community resilience. Third, prioritizing emergency response for disadvantaged communities in all clusters, with a particular focus on the residents of HL areas. Targeted resource allocation is essential to prioritize emergency response efforts for disadvantaged communities disproportionately affected by wildfires. This involves deploying emergency personnel, medical supplies, and support services to areas with higher concentrations of vulnerable populations. Equity in resource distribution must be ensured to address the specific needs of disadvantaged communities, including access to healthcare, transportation, and temporary shelter. Factors such as socioeconomic status, age, disability, and cultural diversity should be considered in resource planning and allocation decisions.

In addition to the immediate solutions, long-term solutions are classified into three strategies. First, creating a network of permanent shelters in HL and LL areas. These shelters should be designed to serve dual purposes, serving as community centers or schools during non-emergency periods [43]. This not only ensures the availability of safe havens during wildfire events but also optimizes the utilization of infrastructure resources, promoting cost-efficiency and sustainability. Second, using an advanced risk-based approach in tandem with improving the resilience of transport infrastructure in HL areas to ensure low-risk evacuation routes. Risk assessment traditionally hinges on gauging the likelihood of potential hazards and their associated consequences. However, a resilience-based approach offers a more comprehensive perspective, emphasizing the system's capacity to effectively navigate unexpected disruptions across various domains. Transitioning from risk to resilience-oriented strategies enhances preparedness for unforeseen disruptive events, particularly the new generation of extreme wildfires. This shift underscores the importance of not only mitigating risks but also fortifying the transport infrastructure's resilience to withstand and recover from wildfire-related challenges [1]. Third, investing in early warning systems, particularly in low-access areas, is crucial for ensuring the safety and resilience of communities facing wildfire threats. Advanced monitoring mechanisms enable timely alerts and notifications, allowing communities with higher wildfire threats and lower access to shelters to take prompt and decisive action. Employing technologies such as wireless sensors and unmanned aerial vehicles provide significant advantages in gathering environmental data and issuing early warnings [28,50]. Comprehensive examinations of fire danger rating and early warning systems highlight the importance of forecasted fire weather and remotely sensed fire activity [15]. Prioritizing HL areas in these early warning systems ensures more intensive monitoring and quicker alerts for these vulnerable zones. Integrating these advancements into long-term solutions establishes robust early warning systems capable of promptly alerting communities to impending wildfire threats. Of course, the accessibility and inclusivity of these warning systems are essential, so all segments of society, regardless of socioeconomic status or geographic location, receive timely information. This proactive approach minimizes wildfire-related casualties and empowers communities to take preemptive measures to protect lives and property from wildfires.

The implementation of the proposed strategies for the scientific community focuses on improving risk assessment methods by establishing community-centric assessment approaches. Future research should prioritize developing and refining predictive models that integrate wildfire risk, population vulnerabilities, and access to shelters. This requires extensive data collection and fine-grained analysis, including geographic, demographic, and environmental data, to enhance model accuracy. At its core, this method advocates for resilience-based approaches rather than mere traditional risk assessments, emphasizing the capacity of communities to withstand and recover from wildfires. Engaging with affected communities to gather insights ensures that scientific solutions are grounded in the realities of those most at risk. By concentrating on these implementations, future research can contribute to more equitable community-centric wildfire preparedness and response strategies, ultimately enhancing community resilience and reducing the adverse impacts of wildfires.

5. Conclusion

In 1994, President Clinton signed Executive Order 12898 to "Address Environmental Justice in Minority Populations and Low-Income Populations." Decades have passed, yet the gravity of natural hazards toward vulnerable populations persists. In 2017, during a Senate hearing on disaster preparedness and response, Paul Timmons, the president of Portlight for Inclusive Disaster Strategies, stated that "people with disabilities and older adults are two to four times more likely to die or be seriously injured in a disaster" [11]. This disproportionate threat is partly due to risk factors, but the extent of susceptibility to natural hazards is multifaceted, involving policy, planning, people, risk, and geography [32,36]. Efforts have been devoted to measuring, managing, and mitigating risk in the realm of natural hazards [8,18]. Relying exclusively on risk assessments to rank and prioritize geographical regions creates a hierarchy that prioritizes individuals residing in high-risk areas over those in low-risk areas, irrespective of their pre-existing vulnerabilities and available resources. Additionally, individuals living in areas with similar risk factors receive comparable attention, regardless of their pre-existing vulnerabilities. People with limited access to shelters are at greater risk of experiencing human disasters when exposed to threats due to the inability to escape, evacuate, and seek shelters promptly. Similarly, individuals residing in regions with lower risks may be overlooked, even though they are still susceptible to harm from a possible but less probable hazard.

In April 2022, the U.S. government allocated $1.5 billion to the Department of the Interior's Wildland Fire Management Program to mitigate wildfire risk for communities "over broad landscapes" and to "reduce the trajectory of wildfire risk to communities and natural resources." These financial resources will be allocated to roughly 7.1 million acres of land identified as having a high and very high risk of wildfires [46]. In January 2023, another program announced expanded efforts to reduce wildfire risk with a $490 million budget allocation to 11 key landscapes in the western U.S., including California. The aim is to mitigate wildfire risk in high-risk areas around 200 communities determined by the Wildfire Crisis Strategy [48]. The Wildfire Crisis Strategy defines high-risk areas as "firesheds," encompassing expansive forested landscapes where the potential for ignition poses significant risks to homes, communities, and infrastructure [47]. Budget allocations in wildfire management are then influenced by the extent of land exposure; tools such as California's Fire Hazard Severity Zones Maps aid in decision-making [5]. These budgeting practices could be less effective if (i) targeted mitigation plans and allocated funds are solely based on risk-driven prevention strategies rather than proactive ones, and (ii) risk reduction decisions are influenced by the share of exposed land to wildfire, disregarding vulnerable communities.

The current research aimed to equip planners and emergency managers with essential knowledge and tools for effective wildfire risk mitigation efforts, benefiting both decision-makers and communities. Enhancing knowledge empowers politicians who influence the fair and effective allocation of public funds and enforcement of regulations. Enhancing knowledge also empowers communities to engage proactively in decision-making. When communities understand their unique needs and challenges, they can actively participate in planning, advocate for customized emergency responses, and collaborate with authorities to bolster overall preparedness and resilience. Effective communication of community-centric solutions for wildfire mitigation, such as WAIR, has two positive outcomes: (i) it builds community resilience and (ii) it finds more effective and equitable solutions.

An example articulated with our analysis further elaborates this point. Let us assume there is a $10 million wildfire reduction budget to be allocated to the San Diego and Riverside metropolitan areas. Under two different scenarios, this budget will be distributed. In the first scenario, similar to government plans, funding is allocated to these areas solely based on the share of their lands exposed to high risks of wildfire. In San Diego, the area exposed to very high and relatively high risk of wildfire is 5.3 times more than in Riverside. San Diego will then receive $8.5 million, and Riverside will receive $1.5 million. In the second scenario, the allocated funding is decided based on the share of affected vulnerable communities. The vulnerable population affected by high-risk and low access to shelters in Riverside is 1.8 times more than in San Diego. Human-centered planning would prioritize Riverside over San Diego for shelter allocation, dedicating $6.5 million for proactive strategies in Riverside and $3.5 million in San Diego. Prioritization significantly differs in these scenarios. The allocation of wildfire funding to counties and jurisdictions is a complex process that should take into account both the share of exposed land and the affected community. The goal is to allocate funding in a way that maximizes the effectiveness of wildfire prevention and preparedness efforts and minimizes the impact of wildfires on communities. Current policies, however, overlook the importance of vulnerable communities and access to shelters. Infusing access to shelters into wildfire risk will induce (i) a more comprehensive understanding of the interests of communities, (ii) a mechanism for mitigating the equity gap between advantaged and disadvantaged communities, and (iii) a catalyst for initiating dialogues among planners, emergency managers, and communities.

Integrating access considerations into national risk assessment methods, such as those used by FEMA, represents an advancement in disaster preparedness and response strategies. Currently, FEMA's Wildfire Risk Index focuses primarily on the number of shelters in its risk assessment approach, overlooking whether these shelters are accessible, which can also vary among different populations. Incorporating access metrics into risk assessment indices empowers both communities and decision-makers. It helps decision-makers make informed choices, optimize resource allocation, and design policies that are responsive to the unique needs and challenges of their communities. It enhances community understanding of the risks they face, encouraging self-advocacy to attract targeted investments. Such an approach serves as an instrument for examining how preparedness strategies can narrow the disparities in access to shelters between disadvantaged and advantaged communities. It not only fosters transparency but also promotes a collaborative approach among stakeholders and communities, enabling them to collectively shape the future of disaster preparedness and response efforts in their regions.

We acknowledge that the proposed approach is not free from limitations. These limitations, however, suggest avenues for future research. First, the access analysis solely considers the physical presence of shelters, failing to account for whether these shelters would be operational during wildfire events, have enough capacity to accept refugees, meet the accessibility needs of specific populations (e.g., persons with disabilities, the elderly), or be at risk of road closures, which might prevent reaching shelters. Such information is not readily available and would necessitate data collection from each potential shelter. If incorporated, this information would affect the number of accessible shelters and increase the precision of the analysis. Future studies can focus on collecting and using such information. Second, while FEMA's Wildfire Risk Index is a valuable tool for assessing wildfire risk, it has several limitations. One key issue is its reliance on historical data, which may not accurately reflect future conditions, especially in the face of rapid climate change. This can result in an underestimation of risk in areas experiencing rapid environmental shifts. The granularity of the data used can lead to inconsistencies in risk assessment at the local level, making it less effective for precise, community-specific planning. The index's methodology may not fully capture the dynamic and complex nature of wildfire behavior, leading to gaps in risk prediction and mitigation strategies. Despite these limitations, this study does not purport to offer a definitive solution; rather, it aims to serve as a theoretical stepping stone toward adopting a more comprehensive, multidisciplinary perspective on disaster preparedness and management. It encourages a rethinking and reimagining of risk assessment and mitigation strategies that account for the distinct challenges faced by diverse communities.

CRediT authorship contribution statement

Alireza Ermagun: Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Fatemeh Janatabadi:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Alireza Ermagun reports financial support and article publishing charges were provided by National Science Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data and codes will be distributed at no cost. All datasets and computational products will be shared with other researchers who would like to replicate or validate the results and perform further analysis, except for commercial use, with proper citations and acknowledgement of the authors.

Acknowledgement

This research was made possible by the National Science Foundation Disaster Resilience Research Grants program, under award number 2242647, titled "Snuff It Out: Extinguishing the Disparity of Access to Shelters for Disadvantaged Communities in Wildfire-Prone Areas."

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pdisas.2024.100358.

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