

GIS-based wildfire risk and social vulnerability mapping for smart grid resilience in Riverside County



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ABSTRACT

Wildfire poses a growing risk to California's electric grid. In Riverside County, fires ignited near overhead distribution lines and substations lead to power outages and public safety shutoffs, which place a disproportionate burden on disadvantaged communities. This study develops an energy-aware decision-support framework to identify census tracts where wildfire hazard severity overlaps with social and infrastructure vulnerability. Data were obtained from the Riverside County GIS portal, CalEnviroScreen 4.0, and U.S. Census and American Community Survey variables, including income, age, disability, housing conditions, and transportation access. An Infrastructure Risk Index (IRI) was constructed by normalizing and aggregating indicators of sensitivity, adaptive capacity, and exposure, and then integrating wildfire hazard severity to prioritize at-risk assets. Results from a two-sample t-test show that IRI values are significantly higher in areas classified as high and very high wildfire hazard zones, confirming a strong association between fire risk and social vulnerability. The resulting spatial outputs provide actionable guidance for utilities and emergency managers, including vegetation management near power lines, targeted inspections of transformers and switches, equitable placement of emergency resources, and informed funding decisions. The framework can incorporate near-real-time data, such as weather conditions or sensor inputs, and user-defined alert thresholds to support proactive maintenance. By prioritizing under-resourced communities, this approach contributes to improved grid resilience, enhanced public safety, and more equitable wildfire risk mitigation in Riverside County.

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1. Introduction

Wildfire threats are escalating in California, disrupting both communities and the electric grid. In Riverside County, ignitions near power lines and substations have led to outages and safety shutoffs that disproportionately affect vulnerable populations, including low-income households, elderly residents, and those with limited mobility (Xie and Meng, 2025). Strengthening grid resilience while promoting equity is therefore essential to wildfire planning. This study develops a GIS-based Infrastructure Risk Index (IRI) that combines wildfire hazard severity with socioeconomic vulnerability indicators. Using ArcGIS Pro with data

from the Riverside County GIS Portal, CalEnviroScreen 4.0, and the U.S. Census, the framework highlights communities where wildfire and infrastructure risk overlap. This decision-support tool can help utilities and emergency managers prioritize vegetation management, inspections, and resource allocation, advancing both resilience and equity in Riverside County.

2. Literature review

The reviewed literature spans the most recent peer-reviewed studies that analyze social vulnerability to wildfires. It synthesizes six scholarly sources that explore how socioeconomic disparities interact with environmental hazards, specifically wildfires, while also comparing these findings with our Riverside County project. Our reviews emphasize the need to move beyond traditional fire-risk models that focus solely on biophysical elements and instead adopt integrative frameworks that consider social-vulnerability metrics like income,

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access to transportation, disability status, and healthcare disparities. This emphasis is consistent with the project's goal to use spatial analysis to guide equitable allocation of fire-prevention resources in Riverside County.

Several key studies provide both theoretical facts and methodological aspirations for the future. For instance, Lambrou et al. (2023) reviewed social drivers of vulnerability to wildfires, including several social vulnerability indices (SoVIs). While our project does not incorporate longitudinal data, it mirrors some of the approaches used in the studies reviewed by Lambrou et al. (2023). Reilley et al. (2024) highlighted socially vulnerable communities' greater likelihood of suffering from severe wildfires, reinforcing the need to integrate social data into fire-risk assessments. This directly supports our project's argument that addressing wildfire risk without accounting for social inequities will lead to inadequate and unjust resource distribution.

The integration of social vulnerability is very new in wildfire analysis, so we must include some more recent and less rigorously reviewed works in our literature review. Focusing on innovation and implementation practicality, Han et al. (2025) mapped inconsistency in fire-shelter access, proposing evacuation plans to reduce anguish. In parallel, Li et al. (2025) used satellite data and dasymetric population mapping to estimate 2025's economic wildfire losses in Los Angeles. Their use of real-time data magnifies the case for integrating diverse data sources; we echo this recommendation to add critical infrastructure layers and develop interactive GIS dashboards for better decision-making in our Riverside analysis.

Building foundational literature strengthens our project's principle. Schoennagel et al. (2017) supported the adaptation of fire management strategies that prioritize risk-based allocation rather than reactive suppression. Our project aligns with this point of view by illustrating a proactive, data-informed GIS model that allows agencies to identify and support communities at greater risk before disasters arise. Finally, Davies et al. (2018) emphasized how low-income and minority communities' less versatile abilities lead to excessive wildfire impacts. This aligns closely with our project analysis, which focuses on mapping and addressing such disparities within the county's most vulnerable census tracts.

Altogether, this literature review demonstrates that integrating social vulnerabilities can reveal connections among wildfire hazard zones. Using tools such as ArcGIS Pro and CalEnviroScreen offers a better viewpoint and an effective approach to risk mitigation. The review also highlights how this project stands out by providing a localized, geospatial framework that can directly inform public agencies, policymakers, and communities. By translating complex data into actionable maps and priorities, our project not only contributes to academic discourse but also offers a practical tool for equitable wildfire preparedness and response.

3. Methods

3.1. Study area and data sources

Our study focused on Riverside County, California, a geographically diverse region with extensive wildland-urban interface zones that expose both communities and electric infrastructure to wildfire hazards. The county's population growth and reliance on overhead power distribution make it a representative case for resilience planning.

We compiled spatial and tabular data from multiple sources (Table 1). Wildfire-hazard severity zones were obtained from the Riverside County GIS Portal. Socioeconomic indicators, including income, age, disability status, and vehicle access, were drawn from CalEnviroScreen 4.0 (CES) and the American Community Survey (ACS). Infrastructure-related layers, including utility corridors and proximity to transmission lines, were also incorporated to reflect grid exposure.

Table 1: Spatial and tabular data sources for wildfire risk and vulnerability modeling

Dataset	Source	Purpose
Fire hazard severity zones	RCIT (2022)	Identify fire risk zones
CalEnviroScreen 4.0	OEHHA (2021)	Provide vulnerability indicators
American community survey	Census (2021)	Provide demographics at tract level
National risk index	FEMA (2021)	Validate local hazard conditions

3.2. Data integration into ArcGIS Pro

The study area was defined using the county boundary shapefile, which was applied to clip census tract polygons so that the analysis was restricted to Riverside County. Vulnerability data from CES and ACS were then joined to the census tracts using the GEOID field. The selected indicators were organized into three main categories: sensitivity (such as the percentage of elderly, disabled individuals, and people living in poverty), adaptive capacity (including the percentage of individuals with limited English proficiency and those without vehicles), and exposure (such as the percentage of mobile homes, uninsured individuals, and proximity to transmission lines). For the IRI calculation, each variable was normalized using z-scores to ensure equal weighting. Specifically, each tract's value was adjusted by subtracting the mean of the variable and then dividing by the standard deviation,

$$z = \frac{x - \mu}{\sigma},$$

where, x is the tract's raw data value, μ is that variable's mean over the entire data set, and σ is the variable's standard deviation. No other factor analysis or weighting was applied.

The IRI was calculated by summing each tract's z-scores in ArcGIS Pro, producing a composite measure of infrastructure and community vulnerability to wildfire. Thresholds in IRI scores can

serve as triggers for maintenance alerts or inspection prioritization.

This workflow established a flexible framework that can be expanded with such near-real-time data as IoT-based vegetation sensors or live weather feeds to support proactive grid management.

3.3. Spatial and statistical analysis

Wildfire hazard exposure was assessed using ArcGIS Pro’s Intersect tool, which overlaid census tracts with Very High and High wildfire hazard zones obtained from the Riverside County GIS Portal. This process enabled the classification of tracts based on their exposure level and helped identify areas with the highest risk, particularly those near grid infrastructure. To examine whether wildfire-prone areas also have higher levels of infrastructure and social vulnerability, a two-sample t-test was conducted to compare IRI scores between tracts located within High and Very High hazard zones and those outside these areas. The results indicated a statistically significant difference ($p < 0.01$), with higher average IRI values observed in fire-prone zones. Furthermore, IRI scores within High and Very High hazard zones were mapped and divided into quartiles to support severity-based prioritization. Tracts in the highest quartile were identified as areas with combined energy and social risks and are therefore strong candidates for targeted actions such as vegetation management, transformer inspection, and outage mitigation planning.

4. Results and discussion

4.1. Key indicators of wildfire vulnerability

Overlaying wildfire hazard zones with social-vulnerability data revealed strong spatial overlaps between high fire risk and limited adaptive capacity (Table 2). Tracts with elevated IRI scores were concentrated in areas with high percentages of elderly residents, households in poverty, limited vehicle access, and mobile homes. These conditions increase evacuation difficulty and exacerbate recovery timelines during extended outages. The distribution of these tracts by hazard zone is summarized in Table 3. Fig. 1 further illustrates these intersecting risk factors, highlighting specific areas where socially vulnerable populations are collocated with elevated wildfire exposure.

4.2. IRI indicator correlation with wildfire severity

The IRI was significantly higher in census tracts located within very high and high wildfire hazard zones (Fig. 2). A two-sample t-test confirmed that the mean IRI in fire-prone areas is significantly greater than in lower-risk zones ($p < 0.01$). This reiterates that wildfire-exposed areas are also the most socially and infrastructurally vulnerable,

posing heightened threats to grid reliability and public safety (Fig. 3).

Table 2: Social vulnerability indicators are categorized by sensitivity, adaptive capacity, and exposure

Category	Field name	Reason
Sensitivity	Pct_Elderly	More vulnerable during evacuation
	Disability_Pct	Physical/cognitive barriers in emergencies
	Poverty_Pct	Less access to protective resources
Adaptive capacity	Pct_LimitedEnglish	Challenges understanding emergency info
	E_NOAUTO_pct	Evacuation difficulty
Exposure	Pct_MobileHomes	Weaker, fire-prone housing
	Pct_Uninsured	Fewer financial resources for recovery

Table 3: Average Infrastructure Risk Index scores across wildfire hazard zones in Riverside County

Zone type	Avg. vulnerability score	Count of tracts
Very high hazard	27.3	45
High hazard	24.6	82
Moderate/low/none	19.2	210

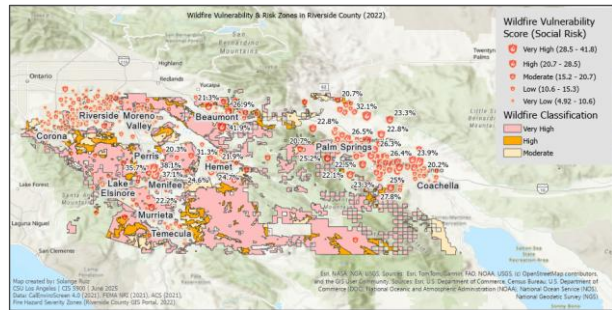


Fig. 1: Overlay of wildfire hazard zones and social vulnerability scores; High overlap zones indicate communities with elevated exposure and reduced capacity to recover

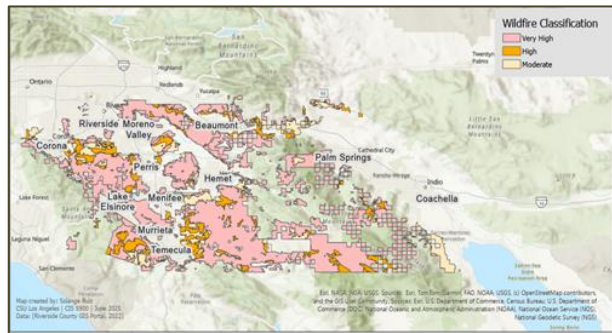


Fig. 2: Wildfire hazard severity zones across Riverside County; Zones are categorized as very high, high, and moderate based on vegetation, slope, and historic ignition patterns

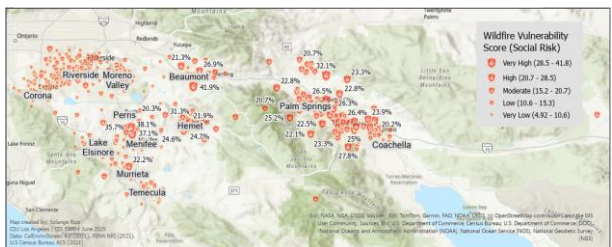


Fig. 3: Social vulnerability scores by census tract across Riverside County; Scores reflect age, poverty, disability, and transportation access using CES 4.0 and ACS data

These values show that vulnerability increases with wildfire hazard severity.

4.3. T-test analysis

Quartile classification of IRI values identified tracts with the highest compound risk (Fig. 4). These areas include parts of Temecula, Anza, San Jacinto Valley, and eastern Coachella regions where grid infrastructure intersects with vulnerable populations. As shown in Fig. 5, these tracts were mapped as priority zones for fire mitigation, based on their elevated IRI scores and overlapping vulnerability. These zones can guide utilities in prioritizing vegetation trimming, transformer inspections, and sensor deployment for real-time monitoring. Threshold-based alerts can help automate maintenance and preempt service disruptions. This analysis supports our hypothesis that vulnerable populations are disproportionately located in areas of elevated wildfire risk.

This composite map identifies where high wildfire hazard zones overlap with high social vulnerability tracts. These overlapping zones indicate communities with increased exposure to wildfire risk and reduced capacity to prepare for, respond to, and recover from wildfire events. Highlighting these critical areas supports targeted planning efforts for wildfire mitigation and resource allocation to enhance community resilience.

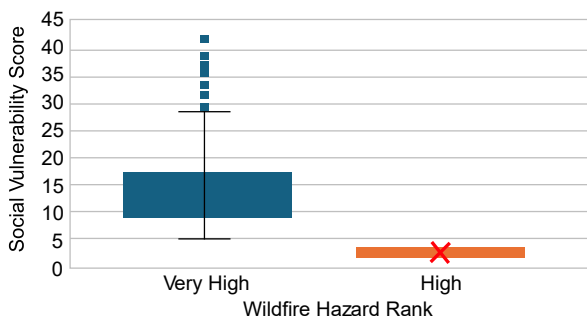


Fig. 4: Boxplot comparing social vulnerability scores across wildfire hazard levels

Higher risk zones show significantly elevated social and infrastructure vulnerability.

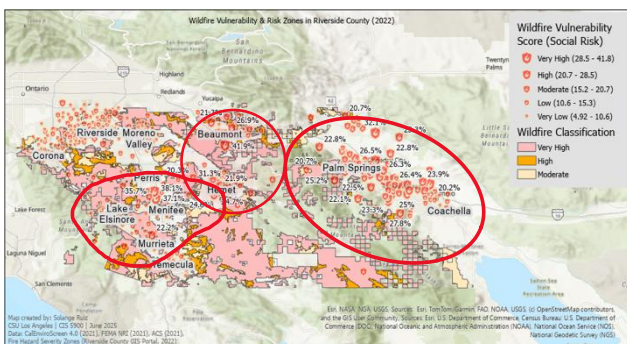


Fig. 5: Identified priority zones for fire mitigation in Riverside County; These areas, Hemet, Beaumont, and the eastern Coachella Valley, exhibit both high wildfire risk and high social vulnerability

These zones represent census tracts with both elevated IRI scores and high social vulnerability. By combining wildfire hazard severity with socioeconomic factors, we identify these priority areas as crucial targets for vegetation management, infrastructure inspections, sensor deployments, and other mitigation strategies. Focusing efforts here can improve safety, reduce service disruptions, and support equitable resilience across vulnerable populations.

4.4. Policy implications and equity focus

These findings highlight the importance of integrating social vulnerability into energy-resilience planning. High-IRI zones should be prioritized for proactive utility investments and equitable funding allocation. This includes deploying backup power in medically dependent communities, funding tree trimming along key corridors, and aligning hazard-mitigation grants with grid vulnerability maps. Equitable energy adaptation requires not just hazard modeling, but also identification of the people most at risk when systems fail.

5. Smart-grid applications for wildfire resilience

As wildfires increasingly disrupt California’s electric grid, smart-grid technologies offer critical tools to prevent outages, manage infrastructure risk, and ensure equitable energy access.

5.1. Relevance of smart grid in risk mitigation

Communities in wildfire-prone regions face compound threats: Not only are they more likely to experience infrastructure damage, but socially vulnerable populations often lack the resources to recover. Our findings identify census tracts in Riverside County where high wildfire-hazard zones intersect with elevated social vulnerability. These areas face an increased likelihood of service interruptions, delayed emergency response, and safety risks. Such smart-grid solutions as two-way communication, self-healing, and islanding can directly address these exposures by improving monitoring, responsiveness, and localized energy resilience.

5.2. Smart-grid tools for fire-risk mitigation

Smart-grid technologies enable utilities to identify, isolate, and respond to wildfire threats in real time. Key applications include:

- Vegetation and weather sensors: Deployed in high-IRI zones to monitor fuel conditions and trigger early alerts for utility action.
- Remote switches and automated reclosers: Reduce the likelihood of ignition by allowing grid sections to be rapidly deenergized or rerouted.

- Advanced metering infrastructure (AMI): Enables real-time outage reporting and energy use data to prioritize emergency-service deployments.
- Community microgrids and battery storage: Offer backup power for critical services (e.g., hospitals, shelters) in communities that may experience long outages.
- Distribution system sectionalization: Allows greater control over high-risk segments, particularly in foothill and mountain zones flagged by our GIS analysis.

5.3. Targeted deployment in vulnerable zones

By integrating wildfire-hazard data with our IRI, utilities can prioritize deployment in census tracts at risk:

- Tracts in Hemet, Beaumont, and the Coachella Valley with High IRI scores could benefit from targeted vegetation sensors and transformer upgrades.
- Areas with limited vehicle access or mobility constraints may be prioritized for microgrid installation to support isolated populations during outages.
- Our analysis provides a replicable model for data-driven investment, ensuring smart-grid upgrades are not only responsive to physical risk but also equitably distributed.

This data alignment also supports cost efficiency by directing resources toward tracts with the greatest infrastructure vulnerability and the most limited recovery capacity.

6. Conclusion and recommendation

This project highlights the importance of integrating social vulnerability into wildfire risk planning. By using publicly available spatial data and GIS tools, we identified communities in Riverside County with the highest combined wildfire exposure and social vulnerability. This initial version is limited by its use of static data. However, it can be expanded with such near-real-time data as vegetation sensors, live weather feeds, and Smart meters to support proactive grid management. Additionally, the granularity of the work is limited by the scale of census tracts, but the data is limited at the individual household level for privacy reasons. Results confirm that vulnerable populations, such as those with limited mobility, older adults, and residents in poverty, are disproportionately exposed to wildfire hazards. These insights provide a foundation for equity-focused mitigation planning. We recommend future strategies emphasize data-driven resource allocation for fire shelters, vegetation management, and targeted public education, particularly in high-risk zones with limited infrastructure.

As climate change continues to increase wildfire risk, local governments must prepare communities

through proactive adaptation. This includes workforce training for vegetation management, investment in green infrastructure, and partnerships with community-based organizations. Even under resource limitations, scalable strategies such as mobile alert systems and community-led fire-watch programs can improve resilience in high-risk areas.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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