

Compound heatwave and wildfire risks in the United States: A state-level assessment based on FEMA's national risk index

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Abstract. Climate change is intensifying both the frequency and severity of extreme climate hazards, with heatwaves and wildfires emerging as two of the most consequential threats in the United States. While these hazards are often assessed independently, their spatial concurrence and interaction can generate compound risks with amplified socio-economic impacts. This study evaluates heatwave and wildfire risks across the fifty U.S. states using the Federal Emergency Management Agency (FEMA)'s National Risk Index (NRI), with particular emphasis on Heat Wave Risk Index (HWRI), Wildfire Risk Scores, and Expected Annual Losses (EAL). Heatwave risk is quantified based on National Weather Service alerts, exposure, event frequency, historical loss ratios, and community vulnerability factors, while wildfire risk reflects climatological conditions and asset exposure. Results reveal distinct regional patterns: heatwave risk is highest in the southern United States, wildfire risk is concentrated in the western states, and combined multi-hazard risk peaks in coastal California, the Southeast, and parts of the Northeast. State-level EALs demonstrate that economically and demographically significant states, including Texas, California, and New York, incur the greatest expected annual losses, often exceeding USD 200 million, driven primarily by high exposure rather than hazard intensity alone. The findings highlight the growing importance of compound climate risks under ongoing warming, underscoring the need for integrated, multi-hazard adaptation strategies that jointly address heat stress, wildfire impacts, and socio-economic vulnerability.

Keywords: wildfire, heatwave, climate hazards, risk index, United States, climate adaptation

1. Introduction

Anthropogenic climate change has driven a sustained increase in global mean temperatures, fundamentally altering the frequency, intensity, and duration of extreme weather events worldwide [1]. Among these extremes, heatwaves and wildfires have emerged as particularly consequential hazards, exerting profound impacts on human health, ecosystems, infrastructure, and economic systems. Rising temperatures intensify evapotranspiration and reduce soil moisture, creating hotter and drier surface conditions that simultaneously elevate heat stress and enhance landscape flammability. As a result, heatwaves and wildfires are increasingly

understood not as independent phenomena, but as interrelated manifestations of a warming climate system whose combined effects can be especially damaging.

Recent research emphasizes that the most severe climate-related impacts often arise from the interaction of multiple hazards rather than from isolated events. These interactions are commonly described as compound events, defined as the concurrence or interaction of two or more climate extremes whose combined impacts exceed those expected from each hazard individually [2]. Compound events have become a defining feature of contemporary climate risk, as many of the most disruptive environmental disasters exhibit characteristics shaped by interacting extremes. Compared with single-hazard events, compound hazards tend to generate disproportionately large damages, overwhelm response capacity, and complicate risk management and adaptation planning.

Heatwaves are among the most pervasive and deadly climate hazards globally [3]. Characterized by prolonged periods of abnormally high temperatures, heatwaves impose cumulative thermal stress on human populations and strain adaptive capacity, particularly when elevated nighttime temperatures limit physiological recovery. Projections indicate that with each incremental increase in global mean temperature, both the frequency and intensity of heatwaves will continue to rise, with especially pronounced increases in the duration of extreme heat events [1]. Urban areas are particularly vulnerable due to the urban heat island effect, which amplifies exposure and exacerbates health risks for vulnerable populations. Beyond health impacts, heatwaves place significant pressure on energy systems, water resources, and infrastructure, highlighting their role as both meteorological and socio-technical stressors [4].

Wildfires are similarly sensitive to climatic warming and hydrological change. Elevated temperatures, reduced humidity, and prolonged dry periods increase vegetation desiccation and fuel availability, thereby enhancing the likelihood of wildfire ignition and spread [5]. Climate change has lengthened wildfire seasons and increased the probability of large, high-intensity fire events, particularly in the western United States. Globally, extreme wildfires are projected to increase by approximately 30% by 2050 and up to 50% by 2100, underscoring the accelerating nature of fire risk under continued warming [6]. These trends are further amplified by expanding development in fire-prone regions, which increases exposure of populations and economic assets [7].

The interaction between heatwaves and wildfires is especially concerning because of strong physical feedbacks linking the two hazards. Extreme heat accelerates soil moisture loss and vegetation desiccation, intensifying drought conditions and creating highly flammable landscapes. In turn, dry soils can amplify surface temperatures by altering land-atmosphere energy exchanges, thereby reinforcing heatwave intensity [8]. Once ignited, wildfires release substantial heat and atmospheric pollutants, degrading air quality and compounding health risks during periods of extreme heat [9]. These coupled processes form a self-reinforcing cycle in which heat intensifies drought, drought elevates wildfire risk, and wildfire activity exacerbates both thermal and air-quality extremes, producing compound risks that differ fundamentally from those associated with isolated hazards.

Despite growing recognition of these interactions, hazard assessment and policy frameworks have traditionally treated heatwaves and wildfires as discrete phenomena. This single-hazard perspective limits the ability to capture the cumulative and interacting nature of climate risks, particularly at regional and national scales. In response, integrated risk assessment approaches have increasingly emphasized the need to account for hazard frequency, exposure, vulnerability, and potential losses within a unified framework. In the United States, the Federal Emergency Management Agency (FEMA)'s National Risk Index (NRI) provides a standardized approach to multi-hazard risk assessment by combining hazard occurrence, exposure of people and assets, historical loss ratios, and community susceptibility into comparable risk metrics [10, 11].

Building on this framework, the present study examines spatial patterns of heatwave and wildfire risk across the United States from a risk-based perspective. Rather than identifying individual compound events at the event scale, this analysis focuses on the convergence of multiple hazards and their associated economic impacts, as measured by hazard-specific risk scores and Expected Annual Loss (EAL). By evaluating how heatwave and wildfire risks overlap spatially and how exposure and vulnerability shape economic losses, this study aims to identify regions most susceptible to compound climate risks. In doing so, it provides an integrated assessment that aligns with emerging evidence that effective climate adaptation must address the interconnected and cumulative nature of climate hazards in a warming world.

2. Materials and methods

The Heatwave data were obtained from the FEMA National Risk Index (NRI) database [10, 11], accessible at <https://hazards.fema.gov/nri/heat-wave>. The corresponding technical documentation is available at https://www.fema.gov/sites/default/files/documents/fema_national-risk-index_technical-documentation.pdf.

The Heat Wave Risk Index (HWRI) is a composite metric developed by FEMA to quantify the relative risk of heat waves to communities. According to FEMA [10], heat waves are identified using local National Weather Service (NWS) alerts indicating "abnormally and uncomfortably hot and unusually humid weather" conditions. The HWRI is calculated at the Census block level using the following steps:

Expected Annual Loss (EAL): EAL is calculated for each block as the product of three components (see Equation (1)):

Exposure: The value of buildings, population, and agricultural assets within the block.

Annualized Frequency (AF): The frequency of heat wave event-days, derived from a 16.9-year record of NWS-reported heat wave days.

Historic Loss Ratio (HLR): The ratio of historical losses due to heat waves relative to exposure.

$$EAL = Exposure \times AF \times HIR \quad (1)$$

Aggregation to County Level: EAL values for all consequence types are summed to obtain the county-level EAL.

EAL Score: The county-level EAL is converted into a national percentile ranking (EAL Score).

Community Risk Factor Adjustment: The final HWRI score is obtained by multiplying the EAL Score by a Community Risk Factor (CRF), which reflects the susceptibility of the community to heat-related hazards (see Equation (2)):

$$HWRI = EAL\ Score \times CRF \quad (2)$$

3. Results

3.1. State-level population and GDP profiles

The state-level population and density map, presented on a logarithmic scale (see Figure 1), reveals a pronounced coastal clustering pattern across the United States, contrasting sharply with the sparsely populated interior regions. Population density is highest along the Northeast and Mid-Atlantic corridor (e.g., Massachusetts, New Jersey, Maryland), reflecting the long history of urbanization in these areas. Significant

population concentrations are also evident along the Pacific Coast, particularly in California, and in large peninsular states such as Florida. These regions serve as major economic and population hubs, typically situated along coastal plains and accessible waterways.

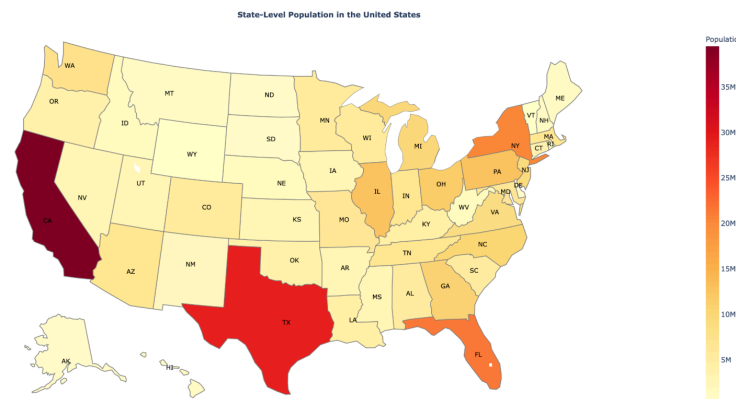


Figure 1. Population map in fifty states

Note: The population map of the fifty U.S. states shows dense concentrations along the East and West coasts, with sparse distribution across the central and western interior regions.

In contrast, interior states of the West and the Great Plains exhibit the lowest population densities (e.g., Wyoming, Montana, North and South Dakota, Nevada). Contributing factors include rugged terrain, arid climates unsuitable for large-scale agriculture, and historical limitations in coastal port access. Alaska, due to its vast size and harsh environment, also ranks among the lowest in population density. Overall, population distribution is highly localized and strongly favors coastal regions over the continental interior (see Figure 2 for density patterns).

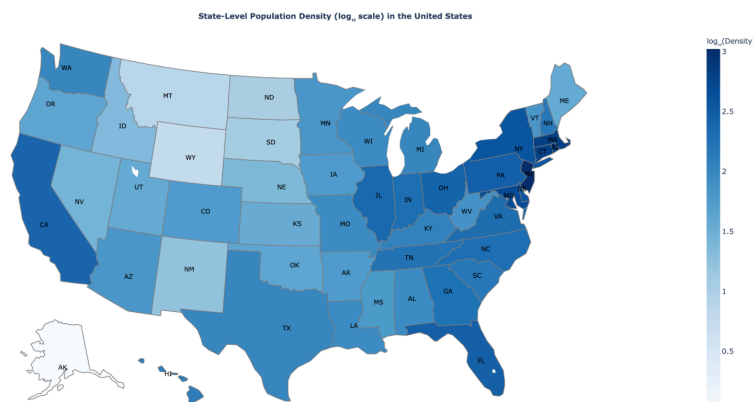


Figure 2. Population density map in fifty states

Note: The population density map of the fifty U.S. states highlights high densities along the East and West coasts, with much lower densities in the central and western interior.

The bar chart of average annual state-level GDP further underscores the concentration of economic activity in the United States (see Figure 3). California stands out as the nation's largest economic engine, generating substantially more output than any other state. Other major contributors include New York and Texas, which, together with California, dominate the economic landscape due to diverse industrial bases, large populations,

and major financial centers. Conversely, most other states register GDP levels below \$500 billion, highlighting a marked disparity in economic output across the country (see Figure 4).

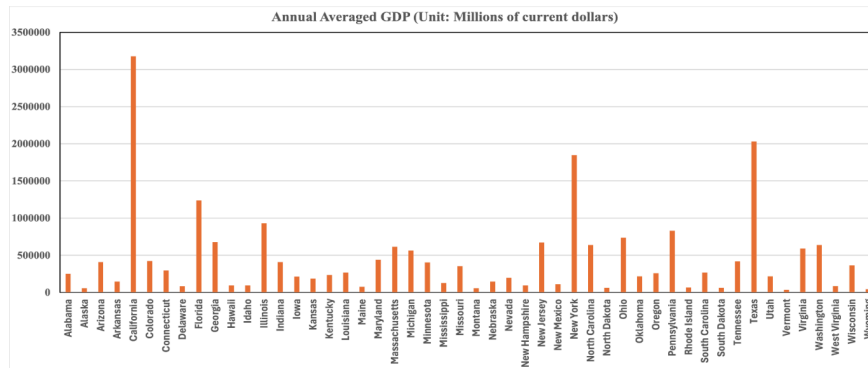


Figure 3. Annual averaged GDP during 2015-2024

Note: The map shows the average annual GDP of U.S. states from 2015 to 2024, highlighting the concentration of economic output in a few major states.

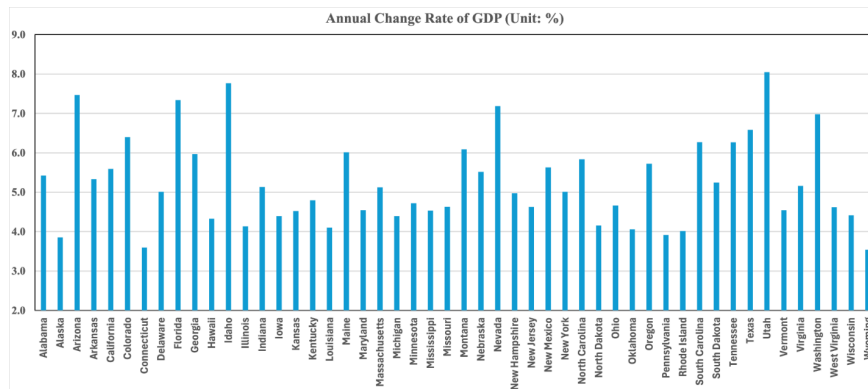


Figure 4. Annual change rate of GDP during 2015-2024

Note: The map illustrates the annual GDP growth rate of U.S. states from 2015 to 2024, highlighting regional differences in economic expansion.

3.2. State-level risk scores for heatwave, wildfire, and combined events

The map of state-level wildfire risk demonstrates that the highest danger is concentrated in the Western United States (see Figure 5). States along the Pacific Coast, including California and Washington, and inland Rocky Mountain states such as Idaho, Wyoming, and Utah, exhibit the highest risk scores (above 80). These elevated risks are largely attributable to hot, dry climates, vegetation types, and rugged terrain. In contrast, most states in the Midwest and Northeast show low risk scores, though pockets of moderate to high risk appear in parts of the Southeast, including Florida and Texas, due to localized dry conditions.

Heatwave risk displays a distinct geographic pattern, with the highest scores concentrated in the South, from the inland Southeast westward into the Southern Great Plains, including Texas (see Figure 6). High heatwave risk is driven by the combination of extreme temperatures and high humidity, producing elevated heat index values. In contrast, the Northeast, Mid-Atlantic, and Upper Midwest exhibit moderate to low risk, while mountainous Western states show variable heatwave risk; high temperatures are often mitigated by

lower humidity, resulting in relatively lower danger scores. These patterns highlight that heatwave impact is strongly modulated by both temperature and humidity.

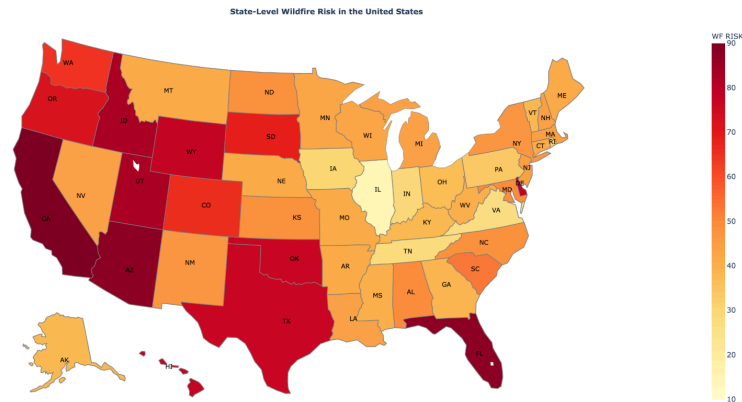


Figure 5. Wildfire risk score for fifty states

Note: State-level Wildfire Risk Scores indicate elevated danger in the Western U.S., especially in California, Oregon, and Washington, while the Midwest and Eastern states generally exhibit low risk.

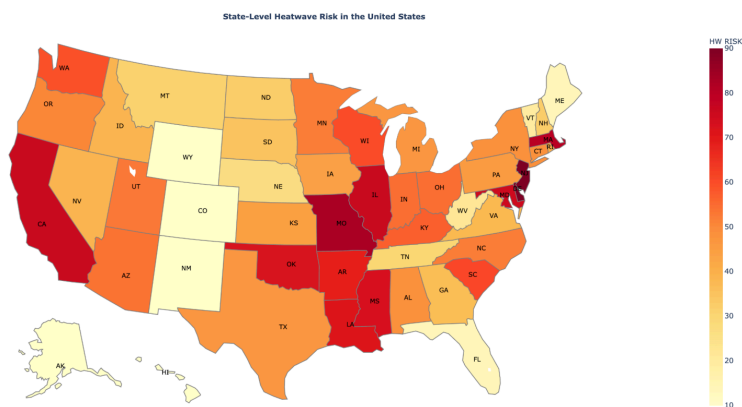


Figure 6. Heatwave risk score for fifty states

Note: The map shows the Heatwave Risk Score across the fifty U.S. states, highlighting higher risk in the South and lower risk in the Northeast and Midwest.

The combined risk score, integrating multiple natural hazards, identifies three primary high-risk zones. The Western zone, including California, Arizona, and Nevada, experiences elevated risk due to wildfires, earthquakes, and drought. The Southeastern zone, particularly along the coast and in Florida, faces combined risks from hurricanes, severe storms, and heatwaves. The Eastern zone, including parts of the Northeast such as New York, is primarily affected by coastal storms, hurricanes, and urban heat island effects. By contrast, central states in the Great Plains and Midwest generally exhibit the lowest overall risk, indicating reduced exposure to a combination of major natural hazards.

3.3. Expected Annual Loss (EAL)

State-level EAL maps quantify the expected annual economic losses from heatwaves and wildfires (see Figures 7 and 8, respectively). For heatwaves, the highest financial losses are concentrated in populous,

economically significant states such as Texas, Illinois, and New York, with expected losses exceeding \$200 million per year. These elevated losses are driven not necessarily by extreme heat intensity but by high population density and economic activity, which amplify the disruption and associated costs. States with frequent heatwaves but smaller economies, such as Arizona, exhibit lower expected losses due to fewer exposed assets.

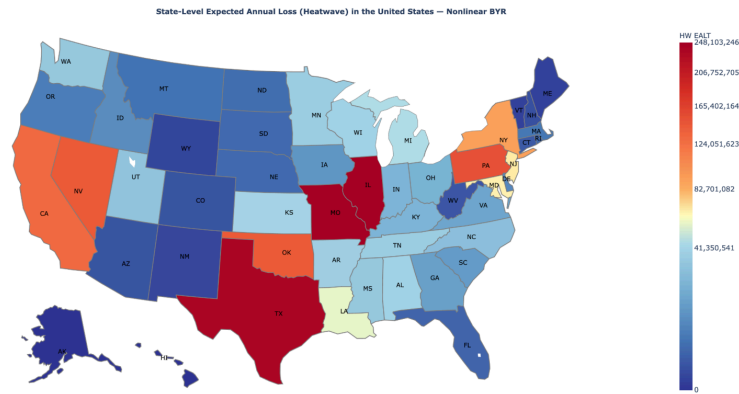


Figure 7. State-level Expected Annual Loss (heatwave) in the United States

Note: This map depicts the state-level Expected Annual Loss (EAL) from heatwaves in the United States, representing the average annual economic loss (in dollars) due to heatwave impacts, with higher values in populous, economically significant states.

In contrast, EAL from wildfires is predominantly concentrated in the Western United States (see Figure 8), particularly California, Oregon, and Washington, where frequent and severe fire events coincide with substantial economic activity and dense development near wildland areas. High wildfire risk combined with extensive exposure results in annual expected losses that often exceed \$200 million, reflecting the considerable economic impact of wildfire events in these states.

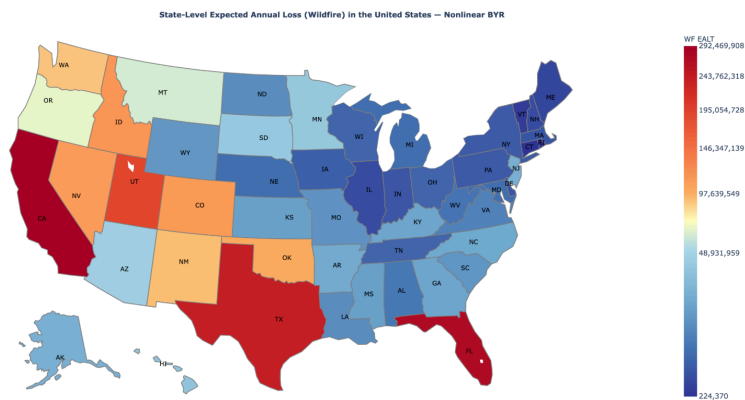


Figure 8. State-level Expected Annual Loss (wildfires) in the United States

Note: This map depicts the state-level Expected Annual Loss (EAL) from wildfires in the United States, representing the average annual economic loss (in dollars) due to wildfire impacts, with the highest losses concentrated in Western states that combine high wildfire risk and significant exposure of population and assets.

4. Discussion

The trajectory of global climate change indicates a marked intensification of natural hazards. The Intergovernmental Panel on Climate Change (IPCC) reports that each incremental rise in global temperature is directly associated with increased intensity and frequency of extreme temperature events [1]. This trend fosters conditions in which single-hazard events evolve into complex, compound risks, posing significant challenges to both human and ecological resilience. In many regions, projected increases in both daytime highs and nighttime lows by mid- to late-century are expected to push more days beyond critical heat thresholds. Research further indicates that the longest and most intense heatwaves are lengthening at rates that exceed the pace of global warming itself [12]. As these prolonged heat events expand, the natural cooling that typically occurs at night weakens, exacerbating heat stress on human health, infrastructure, and agriculture. Urban areas face additional pressures from the urban heat island effect, which amplifies risks for vulnerable populations. This underscores a crucial point: the greatest hazard lies not solely in isolated days of extreme temperature, but in the cumulative strain imposed by sustained heat on human physiology and the inability of essential infrastructure to recover overnight [13].

Future wildfire risk is intrinsically linked to rising temperatures and shifts in the hydrological cycle. Climate change is driving conditions that are hotter, drier, and windier, generating highly flammable landscapes. In regions such as the Western United States, earlier snowmelt reduces water availability in late summer, thereby prolonging fire seasons and increasing their severity. The United Nations Environment Programme projects that extreme wildfires will increase globally by 30% by 2050 and by 50% by 2100 [6]. Fire-prone areas are also expected to expand into regions historically considered low-risk, including the Arctic and Central Europe. These future fires are likely to burn larger areas at greater intensity, causing substantial ecological disruption and elevating public-health risks from smoke that can travel thousands of miles.

A primary concern under future climate scenarios is the increasing prevalence of compound events, particularly those combining extreme heat and drought. The concurrence of prolonged heatwaves and drought constitutes a critical precondition that sharply elevates wildfire risk [14]. Compound events are projected to become more frequent [15], with one illustrative example being the heatwave–drought–wildfire sequence. In this sequence, drought-driven reductions in soil moisture are exacerbated by extreme heat, creating exceptionally flammable conditions that increase the likelihood of severe wildfires. These fires can trigger cascading impacts, including vegetation loss, accelerated soil erosion, and heightened susceptibility to flash flooding when intense rainfall subsequently occurs. Another emerging compound risk is the heat–air quality interaction, wherein extreme heat accelerates the formation of ground-level ozone while simultaneously promoting wildfires that emit substantial smoke. The resulting combination of elevated ozone and dense particulate matter generates hazardous air-quality episodes, posing significant respiratory risks to populations in major urban centers.

5. Conclusion

Climate change has long been a focal point in public discourse, often framed through the lens of individual extreme events, such as isolated wildfires. Traditional meteorological research has treated such hazards as "discrete phenomena", studied independently of one another [2]. However, the increasing recognition of compound events has revealed that Earth's climate system is far more interconnected than previously understood. While these events embody the true complexity of our climate, they have only emerged as a research priority within the past decade. By analyzing historical data from 2000 onward and projecting trends

through 2100, our findings indicate that the frequency, severity, and geographic extent of coupled hazards are rising at an accelerating pace.

The analysis also underscores a pronounced regional divide. The Western United States, particularly California and the Pacific Northwest, emerges as a primary hotspot for compound events [16]. Here, feedbacks between desiccated soils and atmospheric heating generate a "tinderbox effect", wherein heatwaves not only elevate fire probability but also intensify fire behavior. Concurrently, the Southern and Eastern United States face escalating heatwave risks that, when compounded by high population densities and aging energy infrastructure, result in substantial Expected Annual Losses (EAL), exceeding \$200 million annually in states such as Texas and New York.

Under high-emission scenarios (RCP8.5 and SSP5-8.5), the concept of a defined "fire season" is becoming increasingly obsolete, as extreme fire risk persists throughout much of the year in numerous states. Equally concerning is the shifting geographic distribution of these hazards: regions such as the Rocky Mountains and the Southeast are experiencing risk levels historically confined to the arid West. These patterns indicate that climate adaptation strategies can no longer operate in isolation; a heatwave response plan that fails to account for concurrent wildfire smoke exposure or electricity grid strain is inherently insufficient.

In conclusion, this study provides a framework for integrated, multi-hazard risk assessment. Protecting ecosystems, infrastructure, and public health in the United States will require policies that address the compound nature of climate hazards. Key measures include enhancing power-grid resilience to accommodate peak cooling demand during smoke-diminished solar output and implementing forest management strategies [17] that disrupt feedback loops intensifying regional warming. As mid-century approaches, the capacity to anticipate and adapt to compound climate events will be a defining determinant of U.S. climate resilience.

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