Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira, Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria
 Published by Research Publishing, Singapore.
doi: 10.3850/ESREL2026061419_esrel26-p26531-cd

Assessing how household capabilities and well-being are disrupted in the aftermath of wildfires: A human-centered mixed methods approach

Poulomee Roy
Industrial and Systems Engineering, University at Buffalo, United States. E-mail: poulomee@buffalo.edu

Sayanti Mukherjee
Industrial and Systems Engineering, University at Buffalo, United States. E-mail: sayantim@buffalo.edu

Susan Spierre Clark
Department of Environment & Sustainability, University at Buffalo, United States.
E-mail: sclark1@buffalo.edu

Wildfires present a growing threat to critical infrastructure systems (CIS) and the wildland-urban interface (WUI) communities. With the ever-increasing urbanization and availability of cheaper lands, more population moves towards the forest lands, expanding the WUI regions. As a result, more CIS (e.g., power grid, transportation systems, water distribution) are getting exposed and damaged from wildfires. When CIS are damaged and resulting service disruptions occur, they burden WUI communities by disrupting household capabilities (e.g., cooking, lighting, washing) which are important for maintaining well-being (e.g., maintaining good physical and mental health). Traditional community resilience measuring approaches often fail to account for these social implications of CIS disruptions, focusing mainly on financial costs or CIS outages durations. We address this gap in this research by evaluating how household capabilities are affected by various CIS disruptions (e.g., power outages, water outages, transportation disruptions) and the subsequent severity of these impacts in terms of time and financial costs needed to cope. We collected data through a representative survey of households in the Southwest US that were affected by wildfires since 2016. Leveraging the Capabilities Approach Theory and the Bayes Mallows Ranking Method, we identify the household capabilities most affected in the aftermath of a wildfire and present our results for the state of California, which has witnessed some of the most devastating wildfires to date. Our results show that the ability to cook food and access clean air were the most disrupted capabilities during wildfire-induced CIS disruptions. Other capabilities, such as accessing drinking water and lighting homes, were affected under specific conditions. The most severe impacts occurred when households lost their ability to cook food, access clean air and drinking water, and the ability to refrigerate food and medicine. The outcomes of this research informs more efficient, human-centered resilience planning for the CIS managemnt.

Keywords: Wildfire impacts, Critical infrastructure disruptions, Household capability, Bayes Mallows Ranking Method, Human-centered resilience planning.

1. Introduction

Wildfires have increased in frequency and intensity over the last few years, disrupting communities' lives and posing a threat to critical infrastructure systems (CIS) (Masoudvaziri et al., 2020, 2021; Ganguly and Mukherjee, 2021; Ganguly et al., 2025; Roy et al., 2025). For instance, during the Camp Fire in California (2018) and the Marshall Fire (2021) in Colorado, many communities did not lose their homes (Burke et al., 2021; Maranghides et al., 2021). However, households experienced several disruptions in their daily lives. Families struggled to cook due to prolonged gas shut-offs, elderly individuals found it hard to maintain hygiene due to water shut-offs, and the cooling, heating, and refrigeration capabilities were severely constrained by power outages (Juliano et al., 2023). Traditionally, the impact of wildfires or other natural disasters has been assessed by the adverse effects on the CIS, including power, gas, transit, water, and communication (Fraser et al., 2022; Kalapodis et al., 2025; Ermagun et al., 2025). The economic impact of wildfire-induced CIS failure and restoration costs is often quantified and termed a wildfire-related burden on communities (Wang et al., 2021). Despite being highly relevant to emergency management and helpful for guiding restoration planning, these metrics cannot capture households' suffering at a granular level; they can only provide a high-level overview of wildfire's adverse effects on infrastructure and communities. In fact, infrastructure failures are often considered synonymous with societal or household burdens from wildfires, which fails to recognize that service disruptions across different CIS have different impacts on households' ability to maintain their health and well-being (Cutter et al., 2025).

The burdens that households experience during wildfire-induced CIS outages are influenced by disruptions to household capabilities, such as access to food, clean air, and timely information about the event, as well as the ability to maintain hygiene. The inability to meet these critical household needs as usual can have serious consequences, especially if the outages are prolonged and affect a wide area. Often, households adapt to these disruptions by meeting their needs in less convenient, more costly, or more time-consuming ways. For example, if a household is unable to cook, it may rely on restaurant takeout, which is more expensive. These nuances are not captured in previous studies that quantify the impact of wildfire-induced infrastructure failures on households and their communities. To summarize, although CIS service disruptions have severe implications for the well-being of populations during disasters (Shear et al., 2011; Norris et al., 2002; Michel, 2018), there is a lack of human-centric measure of CIS resilience that allows us to evaluate the societal impacts (in terms of capability disruptions instead of only financial or economic loss) of CIS service disruptions during disasters (Clark et al., 2022, 2023).

Our current study addresses this gap by assessing household-level capability disruptions caused by wildfire-induced CIS service outages, leveraging the Capabilities Approach (CA) theory. The CA Theory (CA) is a widely recognized framework for understanding human development and well-being (Sen, 2001; Nussbaum, 2000). It is used by multiple agencies (e.g., the United Nations Development Program (UNDP)) as a theoretical framework for measuring human development outcomes across nations (United Nations Development Programme, 2014). The CA emerged as an alternative to standard economic frameworks for thinking about poverty, inequity, and human development, as it emphasizes outcomes rather than incomes to measure" well-being. The focus is not on resources (i.e., financial resources) but on what an individual can accomplish with them (Alkire, 2013). The CA considers resources (e.g., entitlements, rights, commodities) and conversion factors (e.g., social, environmental, individual characteristics) that individuals have access to and are needed to support the capabilities (e.g., the portfolio of possibilities available to an individual that enables them to achieve a life they consider valuable).

To obtain household-level capability disruption caused by the wildfire-induced CIS service outages, we conducted a household-level survey across California to gather experiences from households affected by wildfires from 2016 to 2024. By analyzing self-reported data using the probabilistic Bayes-Mallow Ranking method, the most critical capabilities for households affected by wildfire-induced CIS service outages are identified and ranked by household preference. Thereafter, we examined the additional costs and time spent in coping with such capability disruptions.

The key contribution of this study is that it foregrounds capabilities, not infrastructure, to provide critical insights into how wildfires impact households. This insight could advance the human-centric measure of infrastructure resilience and inform more equitable wildfire preparedness and effective post-wildfire emergency management within WUI communities.

2. Methodology

In this study, we began by defining the research question, designing a household-level survey grounded in CA theory, and then collecting data through the survey and analyzing the responses to answer the research questions.

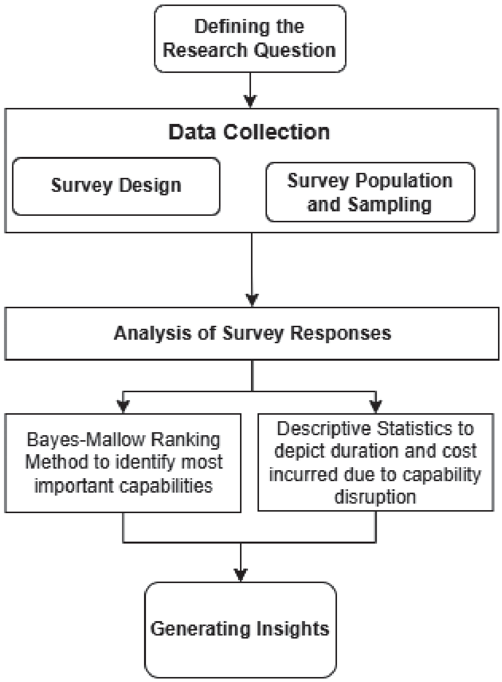

Fig. 1. Research Framework

2.1. *Defining the Research Question*

As the objective of our study is to capture the household burden of wildfire-induced infrastructure disruptions, we primarily focused on the following research question:

- which capabilities, if disrupted, are most impactful for households in during wildfire-driven CIS disruptions?
- to what extent do households spend more time and incur additional costs when coping with capability disruptions?

To address the research questions, we collected data through a household survey, which is described in the next section.

2.2. *Survey Design*

A digital survey was designed using the Qualtrics platform to collect responses from affected households. The survey consisted of four sections: a screening section, a demographics and household characteristics section, an infrastructure outage section, and a wildfire-induced capability-disruption section. The screening section ensures that the respondent is an adult and that their household experienced a wildfire between 2016 and 2024 in Arizona, California, Colorado, Nevada, New Mexico, or Utah. In this paper, we focus only on households in California. Variables informing household characteristics include the number of residents, the number of elderly residents, the family's mean income, and the highest educational attainment. Information on capability disruption was obtained by first asking which capabilities were disrupted, then which of those were most impactful for the household. Furthermore, the survey asks about the time burden and the costs incurred to adapt to or cope with household capability disruptions.

2.3. *Survey Population and Sampling*

The study area has been determined by the frequency and intensity of wildfires (Radeloff et al., 2018). Given California's experience with the most devastating wildfires and its diverse household composition (Verisk Analytics, 2024), we selected California as the area of study. For survey recruitment, we have followed the Institutional Review Board regulations at the University at Buffalo. Also, survey participants were recruited by the market research company IPSOS Insights, LLC.

2.4. *Data Collection and Quality Checks*

After collecting the data from the survey responses, we performed several quality checks. To ensure data quality, we removed any respondents who completed the survey too quickly (i.e., survey time was less than the average survey time minus two times the standard deviation of the survey time distribution), did not answer the open-ended questions meaningfully, or had any contradictory responses.

2.5. *Analyzing the Survey Responses*

Data collection is followed by the analysis of the survey responses. To address our research question, we ranked the most impactful household capabilities using the probabilistic Bayes-

Mallows method. We also analyzed how additional costs and time burdens were associated with the wildfire-induced disruption of household capabilities.

2.6. *Bayes Mallows Ranking Method*

To assess the importance of household capabilities, rather than using descriptive statistics or calculating the mean of the ranking questions, we employed the Bayes-Mallows Ranking method. This method is probabilistic and heterogeneous, accounting for uncertainty in the dataset (Vitelli et al., 2018). Each household that reported a capability disruption was asked to rank its capabilities based on perceived importance. Since households' priorities for capabilities may vary, the mean ranking may aggregate diverse perspectives and thus dilute the insights. In Bayes-Mallows ranking, the assumption is that the observed ranking is derived from the latent consensus ranking (i.e., the most agreed-upon ranking among households that reported this capability disruption), and fluctuations from this consensus ranking are quantified as a distance metric in the permutation space (i.e., the interval shown in the graph). The survey only allows the respondent to rank the impact of the capabilities if they have reported disruption of that particular capability in the previous question. This method develops the most agreeable ranking where n-size plays a crucial role. For example if a capability is ranked high by a handful of households and another capability is ranked moderate by more number of households the later may be ranked higher based on its overall relevance to the wildfire situation. Also, the Kendall distance is used to quantify deviation (pairwise disagreement), and a Markov Chain Monte Carlo simulation is implemented to yield the consensus ranking and uncertainty intervals (Kendall, 1938). By implementing the Bayes-Mallows Ranking method, we derived a statistical ranking of the importance of household capabilities, along with a measure uncertainty.

3. Result

We present key insights from our data analysis across two major dimensions: first, the consensus ranking of all household capabilities after implementing the Bayes-Mallows ranking method; and second, the additional cost and time burden of the households in managing capability disruptions. These results show that the household burden cannot be expressed by infrastructure outages and losses alone, but by how they hinder residents' daily lives by imposing economic strains and increasing time costs.

3.1. *Extent of Capabilities Disrupted from Households' Perception*

Figure 2 shows the consensus ranking of household capabilities disruptions obtained by leveraging the Bayes-Mallows method. The Bayes–Mallows model identifies a latent consensus ranking that represents the ordering most consistent with observed rankings while explicitly accounting for uncertainty and heterogeneity among respondents. Thus, the posterior rank distributions obtained from this methods reveal strong agreement for top-ranked capabilities, while mid-ranked and low-ranked items exhibit substantial uncertainty, suggesting context-dependent prioritization. Lower the consensus rank of a capability **does not** indicate that those capabilities are less impactful, but it indicates that it is context-specific and more sample size is needed for inferencing. Thus, we will focus discussing mostly the top ranked capability disruptions. The horizontal interval shows the standard deviation or uncertainty in the consensus ranking.

From Figure 2, we observe that disruptions to cooking, access to clean air, and access to food are the most impactful capabilities that were disrupted across households based on the consensus ranking. That pattern isn't random. It reflects how wildfires simultaneously stress household infrastructure, indoor environmental quality, and local supply chains. Cooking, for example, is a capability that depends on multiple "hidden" supports such as energy service continuity (i.e., electricity for electric stoves/microwaves, gas supply and safe ventilation for gas cooking, and refrigeration which get disrupted by the wildfires) or just basic safety constraints such as advice to avoid activities that generate indoor particles during smoke episodes (U.S. Environmental Protection Agency,

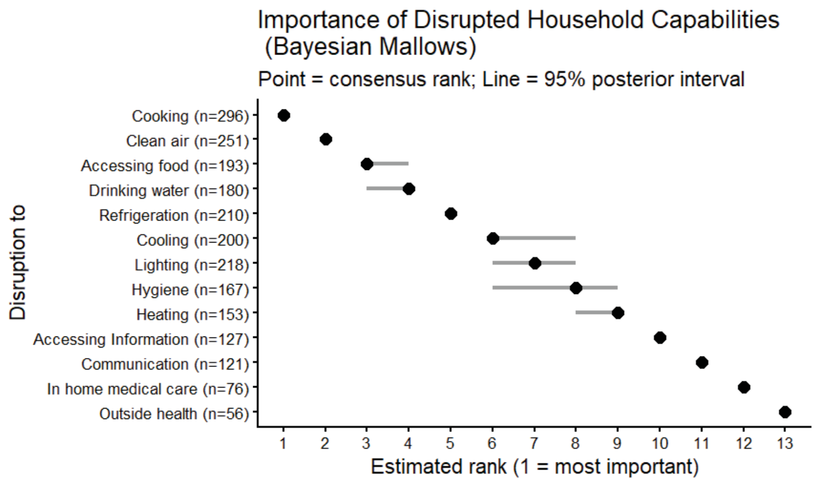

Fig. 2. Mean Importance of the Disrupted Capabilities by Bayes-Mallows Probabilistic Ranking method

2025). Besides the fact that wildfire smoke carries high concentrations of fine particulate matter and pollutants that penetrate indoors even when windows are closed, households have to keep their windows and doors closed to keep smoke out which again hampers natural ventilation and access to indoor clean air. To minimize this effect and substantially reduce indoor smoke particles, HVAC filtration and portable filtration can play an instrumental role and thus can be used as a coping strategy for the households (Davison et al., 2021). Similarly, food access to after wildfires is often constrained through multiple pathways including the physical access problems such as evacuations, road closures, fuel constraints, disrupted transportation, and retailer closures, availability problems (Wei and Mukherjee, 2024a,b) such as damaged distribution nodes, delayed deliveries, and supply-chain interruptions and household utilization problems including not being able to cook safely and effectively, limited refrigeration, and food safety concerns. In these situations, socially vulnerable households are even more impacted (Wei and Mukherjee, 2023).

Cooling, refrigeration, lighting, heating, and hygiene are ranked moderately rather than as top priorities after a wildfire, mostly because these services are partially substitutable, temporally flexible, or less immediately life-preserving than clean air, cooking, and food access during the acute post-fire phase. We also observe that communication, in-home and outside medical care, are ranked low. However, this does not indicate they are less important but it means that it is context specific and since not all the households' require these capabilities or did not experience disruptions in these facilities, these rankings have less statistical confidence. Overall, we see a consistent pattern in the consensus ranking of the capabilities based on number of people being experiencing such disruption, immediacy, capabilities that cannot be substituted by others, and health risk. For example, cooling, refrigeration, lighting, heating, and hygiene are undeniably important, but they are more adaptable in the short term (e.g., using small coolers, flashlights, batteries, bottled water), more context-dependent (e.g., long term electricity outage versus short term power cuts affecting space conditions, lighting, having additional medicines, or moving to a temporary shelter), and less directly tied to acute mortality risk than smoke exposure and food access.

3.2. *Cost and Time Burden of Capability Disruptions to the Households*

The analysis of cost burden associated with cooking and accessing food is observed to be the highest ($60 -$80 additional out of pocket cost per

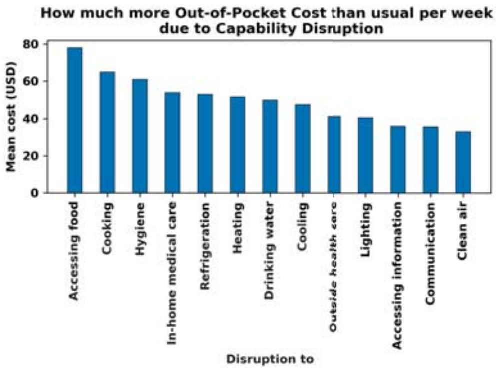

Fig. 3. How much more Out-of-Pocket Cost than usual per week due to Capability Disruption

household on average per week) in the aftermath of the wildfire (see (Figure 3). This is expected as these capabilities are significantly influenced by the disaster induced supply-side price shocks and demand surges (Bellemare, 2015), infrastructure disruption (Ganguly and Mukherjee, 2021; Wei and Mukherjee, 2024a), and constrained household coping options (U.S. Environmental Protection Agency, 2025)). Thus, in contrast to services like lighting or short-term thermal comfort, food-related costs escalate immediately and compound across multiple channels. Although less important than cooking and access to food, hygiene, in-home medical care, and refrigeration also pose a substantial financial burden on households after wildfires because they require out-of-pocket expenditures, replacement of spoiled or damaged goods, and costly coping strategies that are rarely offset by immediate assistance. For example, post-disaster studies document increased household spending on water, sanitation, and hygiene supplies, with costs escalating during prolonged disruptions (Watson et al., 2007). Also, wildfire smoke has been linked to increased medication use and healthcare expenditures, much of which is borne directly by households, since these are indirect and long-term consequences that are difficult to attribute to specific wildfire events (Reid et al., 2016).

An analysis of the time burden, on the other hand, reveals a different trend. We observe that heating, hygiene, and in-home medical care demand are the capabilities that require the highest additional time investment from households, i.e., more than three hours per week per household. All other disrupted capabilities require less additional time, averaging around 2.8 to 3 hours per week per household. This pattern reflects that not only these capabilities are disrupted in the short-term by the wildfires but they also demand time-sensitive coping, coordination and recovery efforts that extend well beyond the immediate response phase. This is expected as all these capabilities require sustained daily attention and depend on slow-to-recover infrastructure systems such as electric grid, water and sanitation and healthcare systems. Overall, the findings from this study reveal that the overall impact of capability disruption on a household does not necessarily align with the most costly or time consuming disruptions. This further reinforces the importance of assessing wildfire impacts across multiple dimensions.

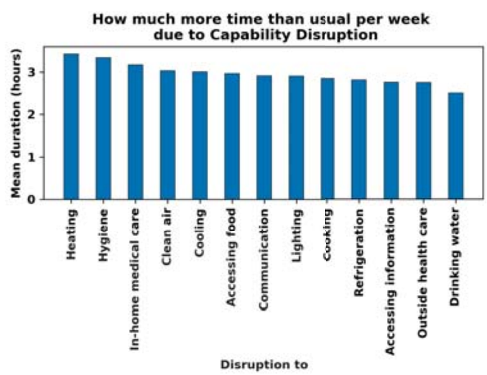

Fig. 4. How much more time than usual per week due to capability disruption

4. Conclusion

In this paper, we analyze how the wildfire induced infrastructure disruption impact the various capabilities of the households and what impact these disruptions have on their cost and time burden. To that end, we conducted a represented survey of households impacted by wildfires. Leveraging Capabilities Approach Theory and Bayes Mallows Ranking method we identified the various critical capabilities that when disrupted can lead to severe health and wellbeing impacts of the households. Our results reveal that capabilities like cooking and accessing food are most impacted and economically costly, whereas capabilities like heating and hygiene pose a greater time burden.

To summarize, this study shows a transition from infrastructure-based wildfire impact assessment to the capability-centric impact evaluation. This is important for more strategic planning that seeks to maintain critical household and community needs during CIS outages. The capabilities that are most impactful to households should be prioritized in emergency management and community resilience planning. For example, alternative methods for cooking, accessing food, and accessing clean air during CIS outages would alleviate some of the top concerns for households during wildfires and mitigate many of the burdens that households experience. This study also underscores the value of capability-centric evaluation of wildfire impact by self-reported survey responses. This will help stakeholders streamline the decision-making process by providing insights from this study, which explores how infrastructure outages hinder daily life by disrupting essential capabilities.

References

Alkire, S. (2013). *Choosing dimensions: The capability approach and multidimensional poverty*. Springer.

Bellemare, M. F. (2015). Rising food prices, food price volatility, and social unrest. *American Journal of agricultural economics 97*(1), 1–21.

Burke, M., A. Driscoll, S. Heft-Neal, J. Xue, J. Burney, and M. Wara (2021). The changing risk and burden of wildfire in the united states. *Proceedings of the National Academy of Sciences 118*(2), e2011048118.

Clark, S., S. Peterson, R. Rivera-Gutiérrez, A. Zambrana-Rosario, and M. Shelly (2022). Impact of Infrastructure Disruptions on Puerto Rican Household Capabilities, Health, and Well-Being. *Natural Hazards Center, University of Colorado Boulder*.

Clark, S. S., S. K. Peterson, M. A. Shelly, and R. F. Jeffers (2023). Developing an equity-focused metric for quantifying the social burden of infrastructure disruptions. *Sustainable and Resilient Infrastructure 8*(sup1), 356–369.

Cutter, S. L., M. Gall, and C. B. Rubin (2025). *US emergency management in the 21st century: from disaster to catastrophe*. Taylor & Francis.

Davison, G., K. K. Barkjohn, G. S. Hagler, A. L. Holder, S. Coefield, C. Noonan, and B. Hassett-Sipple (2021). Creating clean air spaces during wildland fire smoke episodes: Web summit summary. *Frontiers in Public Health 9*, 508971.

Ermagun, A., D. Thompson, F. Vahedifard, and R. C. Silver (2025). Emergency managers' challenges with wildfires and related cascading hazards in california. *Journal of Environmental Management 374*, 124008.

Fraser, A. M., M. V. Chester, and B. S. Underwood (2022). Wildfire risk, post-fire debris flows, and transportation infrastructure vulnerability. *Sustainable and Resilient Infrastructure 7*(3), 188–200.

Ganguly, P. and S. Mukherjee (2021, September). Understanding Wildfire Induced Risk on Interconnected Infrastructure Systems Using a Bow-Tie Model with Bayesian Network and Self Organizing Maps. *31st European Safety and Reliability Conference*. Accessed on February 06, 2026.

Ganguly, P., S. Mukherjee, J. L. Walteros, and L. Herrera (2025). An integrated framework to improve the resiliency of electricity distribution systems exposed to wildfires. *European Journal of Operations Research*.

Juliano, T. W., N. Lareau, M. E. Frediani, K. Shamsaei, M. Eghdami, K. Kosiba, J. Wurman, A. DeCastro, B. Kosović, and H. Ebrahimian (2023). Toward a better understanding of wildfire behavior in the wildland-urban interface: a case study of the 2021 marshall fire. *Geophysical Research Letters 50*(10), e2022GL101557.

Kalapodis, N., G. Sakkas, D. Kazantzidou-Firtinidou, F. Alcasena, M. Cardarilli, G. Eftychidis, C. Koerner, L. Moore-Merrell, E. Gugliandolo, K. Demestichas, et al. (2025). Towards resilient critical infrastructure in the face of extreme wildfire events: Lessons and policy pathways from the us and eu. *Infrastructures 10*(9), 246.

Kendall, M. G. (1938). A new measure of rank correlation. *Biometrika 30*(1-2), 81–93.

Maranghides, A., E. D. Link, C. U. Brown, W. Mell, S. Hawks, M. Wilson, W. Brewer, R. Vihnanek, and W. D. Walton (2021). A case study of the camp fire-fire progression timeline.

Masoudvaziri, N., P. Ganguly, S. Mukherjee, and K. Sun (2020, November). Integrated Risk-informed Decision Framework to Minimize Wildfire-induced Power Outage Risks: A County-level Spatiotemporal Analysis. *30th European Safety and Reliability Conference*. Accessed on February 06, 2026.

Masoudvaziri, N., P. Ganguly, S. Mukherjee, and K. Sun (2021). Impact of geophysical and anthropogenic factors on wildfire size: A spatiotemporal data-driven risk assessment approach using statistical learning. *Stochastic Environmental Research and Risk Assessment*, 1103–1129.

Michel, P.-O. (2018). Textbook of disaster psychiatry. *European Journal of Psychotraumatology 9*(1), 1468711.

Norris, F. H., M. J. Friedman, P. J. Watson, C. M. Byrne, E. Diaz, and K. Kaniasty (2002). 60,000 disaster victims speak: Part i. an empirical review of the empirical literature, 1981—2001. *Psychiatry 65*(3), 207–239.

Nussbaum, M. C. (2000). *Women and Human Development: The Capabilities Approach*. The Seeley Lectures. Cambridge University Press.

Radeloff, V. C., D. P. Helmers, H. A. Kramer, M. H. Mockrin, P. M. Alexandre, and A. Bar-Massada (2018). Rapid growth of the us wildland–urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences 115*(13), E3864–E3873.

Reid, C. E., M. Brauer, F. H. Johnston, M. Jerrett, J. R. Balmes, and C. T. Elliott (2016). Critical review of health impacts of wildfire smoke exposure. *Environmental health perspectives 124*(9), 1334.

Roy, P., S. Mukherjee, and P. Sankaran (2025). Blaze track: Developing dynamic wildfire risk maps leveraging modis satellite imagery and advanced ai algorithms. In *IISE Annual Conference. Proceedings*, pp. 1–6. Institute of Industrial and Systems Engineers (IISE).

Sen, A. (2001). *Development a Freedom*. Oxford University Press.

Shear, M. K., K. A. McLaughlin, A. Ghesquiere, M. J. Gruber, N. A. Sampson, and R. C. Kessler (2011). Complicated grief associated with hurricane katrina. *Depression and Anxiety 28*(8), 648–657.

United Nations Development Programme (2014). *Sustaining human progress: Reducing vulnerabilities and building resilience*. UN.

U.S. Environmental Protection Agency (2025, December). Create a Clean Room to Protect Indoor Air Quality During a Wildfire. *U.S. Environmental Protection Agency*. Accessed on February 06, 2026.

Verisk Analytics (2024). Verisk Wildfire State Risk Report 2024. Technical report, Verisk Analytics, Inc. Accessed: 2025-06-15.

Vitelli, V., Ø. Sørensen, M. Crispino, A. Frigessi, and E. Arjas (2018). Probabilistic preference learning with the mallows rank model. *Journal of Machine Learning Research 18*(158), 1–49.

Wang, D., D. Guan, S. Zhu, M. M. Kinnon, G. Geng, Q. Zhang, H. Zheng, T. Lei, S. Shao, P. Gong, et al. (2021). Economic footprint of california wildfires in 2018. *Nature Sustainability 4*(3), 252–260.

Watson, J. T., M. Gayer, and M. A. Connolly (2007). Epidemics after natural disasters. *Emerging infectious diseases 13*(1), 1.

Wei, Z. and S. Mukherjee (2023). Examining income segregation within activity spaces under natural disaster using dynamic mobility network. *Sustainable Cities and Society 91*, 104408.

Wei, Z. and S. Mukherjee (2024a). Analyzing and forecasting service demands using human mobility data: A two-stage predictive framework with decomposition and multivariate analysis. *Expert Systems with Applications 238*, 121698.

Wei, Z. and S. Mukherjee (2024b). An integrated approach to analyze equitable access to food stores under disasters from human mobility patterns. *Risk Analysis*, 1–14.