Natural Hazards (2024) 120:6923–6941
https://doi.org/10.1007/s11069-024-06440-4

REVIEW ARTICLE

Conceptualizing heat vulnerability: equity-centered approaches for comprehensive resilience in a changing climate

Consolata Wangechi Macharia[1] · Lawrence M. Kiage[1]

Received: 28 August 2023 / Accepted: 21 January 2024 / Published online: 23 March 2024

Abstract

The year 2023 set summer temperature records, stressing the urgency of tackling greenhouse gas emissions and climate change, highlighting the need for a comprehensive approach that addresses vulnerable members of human society in urban, suburban, and rural environments. Vulnerability can be understood through the lens of equity, encompassing unjust social and political structures that dictate individuals' sensitivity and resilience to natural disasters. It also signifies an imbalance between structural factors, system dynamics, and the environment, resulting in varying susceptibility patterns across geographical scales. Addressing vulnerability's root causes involves examining structural factors, system dynamics, and the environment, alongside mapping heat vulnerability using diverse metrics for comparison and coherence. The intricate relationship between environmental hazards and human vulnerability underscores the need to comprehend the multifaceted concept of vulnerability. This involves understanding exposure, sensitivity, and adaptive capacity, collectively shaping an entity's susceptibility to extreme natural events. This review examines the intricate interplay between human vulnerability and environmental hazards, focusing on the context of heat-related risks. A more comprehensive understanding of heat challenges emerges by considering vulnerability variations influenced by human and environmental conditions. Population dynamics, often overlooked in vulnerability assessments, are recognized as critical determinants. We propose an integrated framework that advocates for incorporating changes in human and environmental conditions within vulnerability assessments, utilizing statistical predictive models to anticipate shifts due to population dynamics. Infrastructure and environmental factors are highlighted as essential components of vulnerability, requiring inclusion for accurate assessments at local levels. Challenges in vulnerability analysis, including defining outcomes and considering non-human species, are explored. Transformative heat policies are proposed to be concrete, inclusive, and responsive, emphasizing equity and involving stakeholders for effective governance. This review calls for more accurate, inclusive, and practical strategies for addressing heat-related vulnerabilities and enhancing community resilience.

Keywords Heat vulnerability · Heat policies · Climate change · Vulnerability assessment · Equity · Holistic strategies · Transformative policies

Extended author information available on the last page of the article

1 Background

Hazards and human vulnerability are intricately linked. They would not manifest without the backdrop of vulnerable human situations. Within the realm of environmental hazards, vulnerability is a multifaceted concept. Grasping its fundamental components is crucial. These components encompass the exposure to disturbances, the sensitivity of entities, and the adaptive prowess of individuals, institutions, or systems dealing with environmental pressures (Wilson & Chakraborty 2019). Similarly, Cutter et al. (2003) perceive vulnerability as a product of three basic principles: exposure of people to extreme natural events, societal resilience to hazards, and incorporation of the place dimension in the exposure model. Whenever humans interact with the environment, they become susceptible to environmental disturbances. Sensitivity refers to the capacity to experience harm to one's health due to exposure to an extreme natural event (Wilson & Chakraborty 2019). Adaptive capacity, on the other hand, refers to the ability of individuals, institutions, and systems to adjust to and cope with the negative impacts of hazards (Wilson & Chakraborty 2019). For instance, accessible greenspaces can enhance one's capacity to mitigate the adverse effects of sweltering days on health and well-being. Consider a two-year-old child who has asthma. While the child is susceptible, their vulnerability is reduced if they are not exposed to extremely high temperatures and their parents can afford health insurance to manage the negative impacts. Individuals with high exposure, low adaptive capacity, and similar sensitivity would be more vulnerable.

Assessing the magnitude of vulnerability changes involves employing a heat vulnerability index (HVI) based on specific community environmental and socioeconomic attributes (Ho et al. 2015), while a social vulnerability index (SVI) is used to measure the level of individual vulnerability to a hazard. Census datasets offer sociodemographic information, which acts as vulnerability indicators (Aubrecht & Özceylan, 2013).

The HVI is a tool to pinpoint regions and populations grappling with pronounced vulnerability. Given the uneven distribution of risks, like higher morbidity and mortality rates linked with extreme heat exposure, the HVI aids local administrations in allocating resources to the neediest sectors (Reid et al. 2012). In the SVI, socioeconomic indicators such as income, education, and age are woven together (Tate 2012). A combination of socioeconomic, political, and environmental factors influence vulnerability. For example, consider an individual with access to an air conditioning system. This person possesses a higher capacity to cope with sweltering days, reducing their sensitivity to the adverse effects of heat exposure. In this case, the availability of resources and infrastructure plays a significant role in determining an individual's vulnerability. SVI is a metric that measures a population's social vulnerability level (Tate 2012). It considers various individual characteristics, such as socioeconomic and political factors, which shape an individual's response to the negative impacts of heat exposure. By comparing SVI and HVI, we can gain valuable insights and predict the patterns of heat-related morbidity and mortality rates in highly vulnerable regions. By examining the interplay between social and environmental factors, we can better understand and address the complex dynamics of vulnerability to heat. This knowledge is crucial for developing targeted interventions and policies to reduce the disproportionate impacts of heat on vulnerable communities.

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change shows that anthropogenic activities, primarily through emissions of greenhouse gases (GHGs), have contributed to global surface temperatures of 1.1 ℃ above 1850–1900 in the decade ending in 2020 (IPCC, 2023). The report predicts global temperatures will surpass a 1.5 ℃

increase in the next two decades. This alarming trend poses a significant risk to human health and the well-being of other species worldwide. For instance, anomalies in temperature and rise in sea levels can cause forced displacement and elevated morbidity and mortality rates, especially among the poorest and most vulnerable populations. Vulnerable individuals, often with a limited capacity to adapt to extreme natural events, bear the brunt of the effects of climate change. An example of Las Vegas, Nevada, shows that extreme temperatures disproportionately affect low-income communities and people of color (The Nevada Independent 2023). More so, increased vulnerability to heat stress for Nevadans is linked to economic inequalities, health care inequality, redlining, and homelessness (The Nevada Independent 2023). Climate change not only exacerbates human suffering but also exposes social disparities. For instance, extreme temperatures disproportionately affect outdoor workers and unhoused individuals, with limited access to air conditioning systems hindering their ability to cope with and recover from heat-related risks. (The Nevada Independent 2023).

Although the United States government, through the Environmental Protection Agency, has improved on reducing GHGs and carbon footprint via regulatory measures, some loopholes still exist in the fight against climate change. The federal government has sometimes failed to address the climate crisis and advance environmental justice. In 2021, the Biden administration formulated the Office of Climate Change and Health Equity (OCCHE), but the lack of funding led to its collapse (Rosenthal & Johns 2023). These shortcomings introduce uncertainties, equity, and sustainability concerns. Conceptualizing environmental justice requires a central focus on the historical-social and political structures, power relations, and disparities that shape and increase individual susceptibility to external stressors. Prioritizing marginalized groups in response to extreme natural events and climate change crises is crucial to reducing inequalities and balancing between those with greater and less adaptive capacity. Effectively addressing climate change risks and associated disparities underscores the equity issue. The government must prioritize marginalized communities in its response efforts, fostering a more equitable and sustainable future for all.

2 Heat-related vulnerability in the face of changing climate and emissions patterns

A population's susceptibility to extreme heat hinges on many factors, including but not limited to socioeconomic factors, underlying illnesses, access to resources, age, and educational level (Szagri et al. 2023). However, climate change and population growth underpin and increase future exposure to intense heat (Vahmani et al. 2019). Densely populated regions, such as metropolitan areas, are at a higher risk of heat exposure, predominantly minority groups (Vahmani et al. 2019; US Environmental Protection Agency 2023). Although a rise in population raises sustainability concerns and questions the government's capacity to invest in vulnerable populations, awareness of climate and population dynamics is critical in resolving climate-related challenges. Most importantly, a key question is how population dynamics, increased GHG emissions, and climate change intensify the existing vulnerabilities to intense heat. Comprehensive strategies must encompass urban and suburban domains, considering each context's unique socioeconomic dynamics and energy consumption behaviors. This holistic approach would significantly enhance climate change mitigation efforts and foster sustainability across varied geographical settings.

Climate change is expected to increase the frequency and intensity of sweltering days globally, posing challenges in predicting future heat trends (Reid et al. 2012). The incessant increase in carbon dioxide levels has introduced uncertainties in temperature anomalies, thereby creating an uphill task for climate models in estimating future heat patterns (Buis 2020). Within the United States, extreme heat has been designated as one of the most perilous weather patterns, contributing to an average of 131 yearly fatalities over the last thirty years (Wilson & Chakraborty 2019). Summer 2023 marked a distressing milestone as it was categorized as the deadliest summer heatwave in the Southwestern U.S., Mexico, Southern Europe, and China (Yuhas 2023). States like Arizona in the Southwestern U.S. have borne the brunt of severe heat, exemplified by July 2023 being recorded as Phoenix's hottest summer month, and this period witnessed average daytime temperatures exceeding 110 ˚F and above-normal nighttime temperatures (CBS News 2023). Vulnerable populations, including the unhoused, are disproportionately affected by heat-related illnesses, with homelessness accounting for around 40 percent of heat-related deaths in Maricopa County in 2022(CBS News 2023). In July 2023, countries such as Greece, Spain, and Italy experienced temperatures of more than 113 ˚F (Copernicus Climate Change Service 2023). The 2023 European summer heatwave led to an upsurge in heat-related stress. In 2022, over 60,000 individuals succumbed to the severe summer heat waves (Copernicus Climate Change Service 2023). Even regions unaccustomed to extreme heat, like the Pacific Northwest, have witnessed its devastating impacts, such as aquatic life deaths and the liquefaction of asphalt during the summer of 2021 (Goodell 2023). These practical instances underscore the grave health risks of prolonged exposure to high temperatures. A critical research avenue is investigating how exceedingly high temperatures exacerbate health disparities. Marginalized populations often encounter obstacles in accessing quality healthcare, compounded by the lack of health insurance coverage. Crafting strategies that alleviate climate change, minimize heat-related hazards, and prioritize equitable healthcare access and support systems for vulnerable communities is imperative. Embracing this all-encompassing approach holds the key to minimizing health repercussions caused by extreme heat and bolstering resilience in the face of a changing climate.

Most heat vulnerability studies conceive susceptibility as merely a threat to be managed through practical heat action plans and policies (Morgan & Yablonski 2011). Vulnerability is not an orthogonal concept. It is an equity issue. Susceptibility involves a confluence of factors such as socioeconomic, political, and environmental factors and variations in human conditions (Arbit et al. 2023; Perry & Sealey-Huggins 2023; Davies 2022; Parsons 2023; Colucci et al. 2021). To better conceptualize vulnerability, the paper takes on an equity-centered approach that addresses the underlying drivers of susceptibility, i.e.,, the persistent historical-social and political structures and power relations that dictate who can access quality health care, resources, and other adaptive capacity determinants. Understanding vulnerability requires a critical analysis of the underlying causes, such as socioeconomic factors, political factors, gender discrimination, unequal access to and control of resources, and justice issues in heat policies (Colucci et al. 2021; Natarajan et al. 2019). Careful consideration of the root causes of vulnerability should shift the focus of policy design from managing risk caused by individual heat exposure to strategies aimed at modifying social and political structures and power relations. Another critical aspect that needs to be integrated into policy and practice is enhancing the participation of the local community members in heat policies and programs (Morgan & Yablonski 2011). Additionally, active community involvement in policymaking is vital, ensuring intersectional language and addressing underlying issues. Integrating these elements will yield more equitable, transformative, and socially responsible heat policies, fostering resilience in the face of climate change.

This review systematically examines the intricate interplay of equity concerns, structural factors, and system dynamics in shaping individual vulnerability to heat-related challenges. Additionally, it evaluates the methodologies employed in mapping heat vulnerability while identifying gaps in scale choice and technique application. We address existing vulnerability analysis limitations and offer innovative conceptual frameworks to address these shortcomings. The conceptual framework depicted in Fig. 1, presented below, calls for a profound exploration of the root causes of susceptibility, encompassing socioeconomic and political structures. This approach emphasizes integrating equity and intersectionality principles into policy design and implementation, promoting social justice within heat-related policies. Additionally, we propose adopting a practical conceptual framework, illustrated in Fig. 2, which guides local experts, government bodies, and urban planners. This framework is mainly designed to assist in formulating effective policies and programs to mitigate the impacts of heat challenges.

The comprehensive examination of these frameworks within the study contributes to a more holistic understanding of vulnerability dynamics. It offers potential pathways to enhance societal resilience and well-being in the face of increasing heat-related adversities.

2.1 Equity issues in the context of heat vulnerability

Reid et al. (2012) revealed a concerning association between elevated temperatures and a rise in heat-related illnesses and fatalities. This connection disproportionately impacts specific societal segments, accentuating existing inequalities. Vulnerability to intense heat is most pronounced among specific groups, including the elderly, low-income individuals,

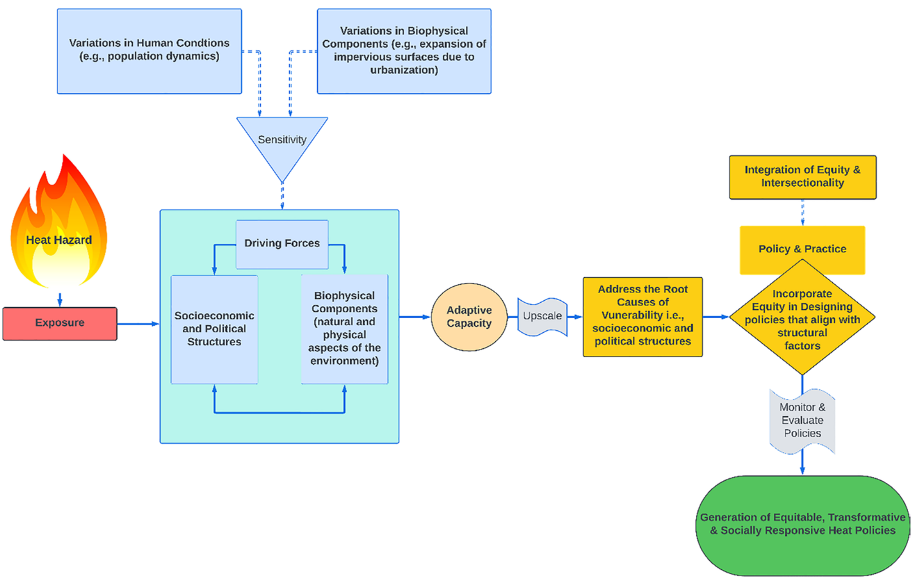

Fig. 1 A conceptual framework highlighting the core dimensions of vulnerability and offering insights into addressing its fundamental root causes

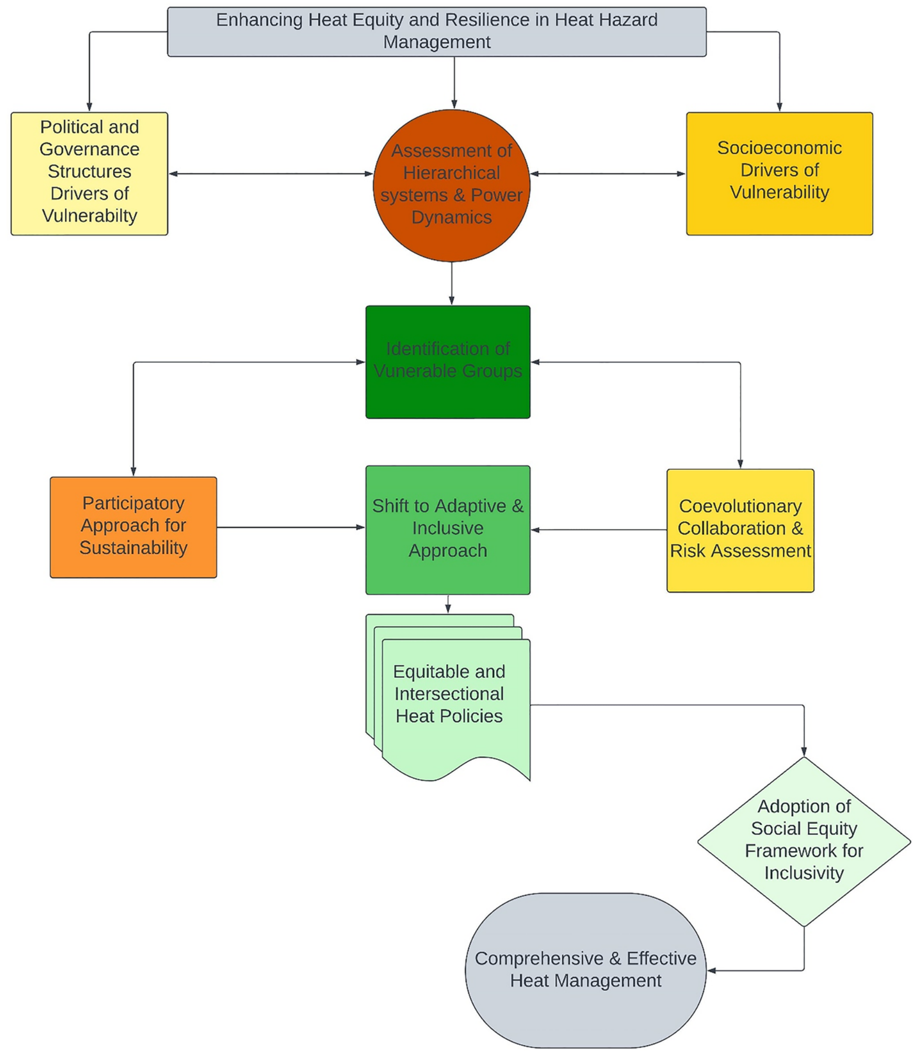

Fig. 2 Social equity framework illustrating the key components of advancing social justice and inclusivity in policy and practice

African Americans, those without access to air conditioning, and communities previously marginalized through redlining practices. Economic and political factors inherent in a community contribute to the differential sensitivity of individuals exposed to extreme temperatures. Recent research in 481 US cities demonstrates that heat-related burdens disproportionately fall on low-income and non-white neighborhoods (Owen 2023; Chakraborty et al. 2023). Notably, the pattern of heat-related inequalities is consistent across all these urban areas. Prolonged exposure to extreme heat can exacerbate mental and respiratory health issues (Owen 2023). The existing literature raises critical issues of equity and social justice. For instance, seniors are particularly vulnerable to extreme heat and often have limited capacity to manage its adverse consequences. This accentuates the significance of examining the strategies adopted by government bodies, urban planners, and local experts to mitigate vulnerability and enhance resilience among at-risk populations. Effective urban heat policies must be equity-centered, guaranteeing that vulnerable communities receive support and social safeguards against extreme heat. An initiative-taking and inclusive approach is essential to address the specific needs of vulnerable populations and foster resilient and sustainable communities.

Preliminary studies have addressed public health concerns using heat vulnerability indices to predict changes in heat-related illnesses and death rates over space and time (Ho et al. 2018). The use of HVI maps has proved beneficial in identifying locations and populations most susceptible to extremely high temperatures, aiding the government in resource allocation, especially for minority groups (Reid et al. 2012). However, to ensure the accuracy of such predictions, the authors emphasize the need to align heat data, such as 911 calls and hospitalization rates, with vulnerability data to verify that an increase in heat-related morbidity and mortality rates is a result of heat anomalies (Reid et al. 2012). It is essential to merge heat information and vulnerability data to gain comprehensive insights into the impacts of extreme heat (Ho et al. 2015). The catastrophic impacts of exposure to extremely high temperatures have raised many public health concerns, especially in cities. This glaring issue has led to the desire to conceptualize the spatial–temporal trends of heat-related illness and death rates (Aubrecht & Özceylan 2013). Despite using HVI and SVI to visualize the severity of extreme heat impacts on vulnerable populations, little attention is devoted to consistently assessing whether heat policies incorporate the concept of equity. Ongoing analysis of heat policies is necessary to track progress and highlight emerging issues such as environmental justice concerns. Monitoring and evaluating heat policies and local government action plans are vital to ensure that institutions frame equitable urban heat policies.

Furthermore, it is essential to consider the intersectionality of age, gender, social status, and religious identity in vulnerability studies. These factors create unique dynamics that impact an individual's vulnerability to extreme heat. Addressing heat vulnerability while considering minority groups requires a deliberate emphasis on equity. We can protect vulnerable populations and promote resilience in climate change impacts by proactively prioritizing equity in policy formulation and implementation.

2.2 How variations in human and environmental conditions influence vulnerability

Most research on vulnerability to heat-related illnesses and mortality has treated spatial and temporal components as independent variables, neglecting the crucial variabilities in susceptibility when planning for heat risks (Ho et al. 2018). This oversight in considering coherent variations in heat vulnerability has led to conceptual frameworks for predicting susceptibility caused by climatic changes that assume social vulnerability to be static, hindering a comprehensive understanding (Vescovi et al. 2005). Consequently, the impact of population dynamics, such as population growth, on heat vulnerability remains uncertain and unexplored (Ho et al. 2018). Eakin & Luers (2006) acknowledge that the failure of a system to notice alterations leads to dysfunctionality and inefficient coping mechanisms toward exogenous stressors. A system's social and biophysical components determine its susceptibility across disparate scales (Turner II et al., 2003). Turner II et al. (2003) suggest that conceptualization of vulnerability is best captured when changes in human and environmental conditions are considered within a system.

To address these challenges, we propose using a conceptual framework (Fig. 1) that considers the spatial vulnerability variations caused by system dynamics. Statistical predictive modeling enables anticipating changes in vulnerability from population dynamics, allowing exploration of “what-if” scenarios. Such models can help identify emerging vulnerability issues, including equity considerations. Comprehensive visualization of overall vulnerability empowers policymakers to implement adaptation measures, devise strategies for community resilience, and enact plans to mitigate the impacts of heat exposure on marginalized populations. Recognizing the dynamic nature of vulnerability and incorporating population dynamics into vulnerability assessments leads to developing more effective and inclusive policies in addressing extreme heat challenges. By continuously monitoring and evaluating these policies, we can respond proactively to emerging concerns and work toward building a more resilient and equitable society.

2.3 Infrastructural and environmental factors and heat vulnerability

Ho et al. (2018) acknowledge the significance of infrastructural and environmental factors in determining heat vulnerability despite the lack of such data at coarse geographical scales. Yet, this information is essential in determining vulnerability at local levels. Infrastructural and environmental factors are not treated as orthogonal indicators of vulnerability but are collectively termed as socioeconomic factors (Ho et al. 2018). For instance, lack of access to green spaces is perceived as an economic factor, as inaccessibility to green spaces is associated with low-income neighborhoods. Due to the geographically dispersed nature of urban regions, cities depend highly on the infrastructural and built environment for sustenance (Borden et al. 2007). The overreliance of cities on transportation, employment opportunities, and crowded residential areas has led to health disparities, traffic congestion, and redlined neighborhoods (Borden et al. 2007). Ho et al. (2015) point out that when heat maps are used as substitutes for heat exposure in a particular spatial unit of analysis, temperature is affected by the land cover features. For instance, a neighborhood close to a recreational park or vegetation is expected to be cooler than areas lacking such amenities. This highlights the importance of considering the local environment when assessing heat vulnerability. Integrating socioeconomic factors with infrastructural and environmental factors in vulnerability analysis would help account for multiple vulnerability indicators and track changes in sensitivity to hazards over time. Focusing on specific characteristics, such as access to green spaces, could help identify and compare neighborhood inequalities between predominantly white and black communities. This approach can shed light on environmental justice issues within a given community. By comprehensively considering the various factors contributing to vulnerability, policymakers and researchers can develop targeted interventions to address inequalities and promote resilience in the face of heat-related challenges. Understanding the interplay between socioeconomic, infrastructural, and environmental factors is essential in creating effective and equitable strategies to address heat vulnerability.

2.4 Preparedness in the context of heat.

Amid the periodic nature of natural hazards, urban inhabitants often struggle to cope with their impacts, particularly as population density rises, limiting adaptive capacity (Borden et al. 2007). Only a few governments across all geographical scales tackle the heat issue systematically. Furthermore, a small portion of research has focused on the issue of heat precisely, while a majority of the action plans pay more attention to climate change adaptation and mitigation (O’Neill et al. 2010; Pietrapertosa et al. 2019; Berrang-Ford et al. 2021;

Turner et al. 2022). Previous studies have highlighted that urban planners in small and intermediate urban regions in the U.S. have paid little attention to the heat issue. Additionally, municipal plans do not incorporate all the stakeholders, techniques, and the needs and concerns of the local community members, critical determinants of a transformative heat governance process (Turner et al. 2022). The identified loopholes in framing heat policies raise concerns about their effectiveness and practicality. It is essential to ensure that heat action plans and policies go beyond abstract documents and are implemented with concrete actions to address heat-related challenges.

Furthermore, these policies must holistically consider and address the needs and concerns of marginalized groups disproportionately affected by extreme heat. A comprehensive understanding of the structural factors and drivers that influence individual vulnerability is necessary to enhance preparedness for heat hazards. For instance, it is crucial to examine how historical practices like redlining impact the adaptive capacity of African American neighborhoods. Identifying and addressing such systemic barriers is essential to promote resilience and reduce disparities in vulnerability. Institutions can develop more effective and inclusive strategies to address heat-related challenges by critically examining existing heat policies and identifying gaps. Proactive measures to incorporate equity and consider the unique needs of vulnerable populations will be essential in shaping heat policies that are both responsive and transformative. In light of these, we propose a conceptual framework, as shown in Fig. 1, to guide the government, urban planners, and local experts in incorporating integral aspects for sustainable heat interventions.

2.5 Other challenges in vulnerability analysis

Consensus on what constitutes a vulnerability outcome, such as economic losses and health deterioration, remains elusive due to the complexity of external stressors within a system (Eakin & Luers 2006). Linking the drivers of vulnerability to specific outcomes, like disease outbreaks and climate change, is challenging, as multiple factors can influence the final results. For instance, individuals with lung disease may suffer severely from yellow fever outbreaks, yet other exogenous stressors may impact the adverse outcomes. Due to the indefinite linkages of specific factors to vulnerability outcomes, previous studies have developed universal ways of perceiving disparities in resource access and distribution without considering the unique characteristics of a population that could potentially influence sensitivity and adaptive capacity (Eakin & Luers 2006). Additionally, the techniques used to increase the adaptive capacity of a particular population tend to consider the impacts of the variations of human and environmental conditions on vulnerability more than other sensitivity indicators (Eakin & Luers 2006). Therefore, placing more importance on social and biophysical components of vulnerability visualizes humans as the only endangered species of susceptibility. Comprehensive vulnerability conceptualization requires understanding the influence of all vulnerability indicators and dynamics within a system. Hence, local governments and urban planners should adopt an integrated planning approach that considers the most susceptible plant and animal species alongside human populations. Future research should focus on identifying the impacts of natural hazards on other species to ensure a holistic approach to vulnerability analysis and planning. By taking a broader view of vulnerability, policymakers can develop more effective strategies to address the challenges posed by external stressors and promote resilience across various aspects of ecosystems. The fundamental questions warranting consideration are outlined in Table 1, which serves as a tool to identify gaps in the existing body of literature.

Table 1 Exploring vulnerability and equity: important research questions

Concept	Questions addressed in this review	Questions that need to be examined in the future
Equity issues in the heat context	Do urban heat policies integrate the concept of equity in the design and implementation phases? [Turner et al. 2022; Meerow et al. 2019; Preston et al. 2011] Without monitoring and evaluating heat policies and local government action plans, how can we acknowledge if institutions frame equitable urban heat policies? [Fastiggi et al. 2021; Bolitho & Miller 2017] How do the age, gender, social status, and religious identity of an individual intersect to create eccentric dynamics in vulnerability studies? [Alber et al. 2009; Koivunen et al. 2018]	What are the government, urban planners, and local experts doing to reduce sensitivity and increase the resilience of these vulnerable populations? [Turner II et al., 2003; Meerow et al. 2019; Preston et al. 2011]
Variations in human and environmental conditions	How do population dynamics influence vulnerability? [Alber et al. 2009; McLeman 2009; Donner & Rodríguez 2008] How does urbanization impact the spatial pattern of vulnerability? [Cutter 2003; Huang et al. 2011] How does an increase in GHG emissions influence heat vulnerability? [Alber et al. 2009; Yang et al. 2022] How do changes in social and political structures and relations affect individual sensitivity to heat hazards? [Turner II et al., 2003; Morgan, & Yablonski 2011]	How do extremely high temperatures worsen health disparities? [Reid et al. 2012; Gabbe et al. 2022; Sorensen et al. 2018]
Infrastructural and biophysical components		How does imperviousness influence health disparities? [Ziter et al. 2019] How do alternations in the biophysical aspects of the environment impact public health? [Reis, et al., 2015; Wilhelmi & Hayden 2010]
Heat governance	Do heat policies address the needs and concerns of marginalized groups? [Turner et al. 2022; Grabowski et al. 2022; De Rosa et al. 2022]	Are heat action plans and policies mere abstracts? [Turner et al. 2022] Is redlining a factor that limits the adaptive capacity of African American neighborhoods in the context of extreme heat? [Chakraborty et al. 2023; Jerneck & Olsson 2008; Webber 2016; Hansen et al. 2013]

3 A conceptual framework for addressing the shortcomings of the root causes of vulnerability

The conceptual framework (Figure 1) illustrates the intricate nature of vulnerability. Exposure to external stressors like natural hazards is necessary for individuals to experience harm, leading to property loss, loss of life, and diminished income. Unique community characteristics, political structures, and environmental elements collectively influence individual sensitivity. The alteration of human and environmental conditions also impacts an individual's vulnerability to heat-related risks, such as illnesses and mortality linked to high temperatures. The capacity of individuals, institutions, and systems to adapt to heat hazards hinges on socioeconomic, political, and environmental factors. For instance, the unhoused population is particularly vulnerable with limited adaptive capacity due to lack of shelter, inaccessibility to air conditioning, and health insurance. Enhancing adaptive capacity entails addressing structural factors to bolster community resilience and minimize the adverse consequences of extreme heat exposure.

Intersectionality emphasizes the interconnectedness of various social and political identities that shape individual experiences. Strategies incorporating equity into heat policies should involve advocating for participatory and all-encompassing approaches and fostering collaborations among community members, local experts, urban planners, and governmental bodies. The ongoing monitoring and evaluation of heat policies should ascertain their effective implementation at the local level. Consistently assessing these policies would also aid in identifying emerging issues that require systematic intervention.

This study proposes integrating concepts that can effectively address the multifaceted nature of heat-related issues within the context of vulnerability. The aim is to formulate equitable, transformative, and socially responsible heat policies that reflect this complexity.

3.1 The loopholes

3.1.1 Selection of scale

The choice of the spatial unit of analysis, such as block groups, zip codes, and census tracks, poses a significant challenge in vulnerability mapping. A prevalent issue in previous research has been the misalignment between the spatial unit of analysis and heat vulnerability maps, leading to scale-related problems like the Modifiable Areal Unit Problem (MAUP) (Ho et al. 2015). The choice of the spatial unit of analysis is an essential component when mapping vulnerability as it affects the visualization of marginalized populations (Eakin & Luers 2006). Commonly used spatial units of analysis, such as census tracks and block groups, have an extremely coarse spatial resolution of about 1 km (Ho et al. 2015; Reid et al. 2009). This makes it challenging to visualize fine-grained heat vulnerability patterns.

Unfortunately, this issue persists due to the lack of alternative spatial units with finer resolution. Given the dynamic nature of systems, distinct socioeconomic and political structures interact with environmental stressors in varying ways across geographical scales (Karanja & Kiage 2021). A critical question arises concerning the accuracy and reliability of the social vulnerability index (SVI) and heat maps in visualizing vulnerability levels across diverse regions. Given the challenges in choosing a spatial unit of analysis that aligns with heat data, researchers suggest using statistical models that account for spatial variability in vulnerability data (Ho et al. 2018; Johnson et al. 2012).

Additionally, as proposed by Tate (2012), sensitivity analysis can be employed to assess the robustness of SVI outcomes by considering variability in the index through Monte Carlo simulation. Acknowledging that equity issues often manifest at the neighborhood level is essential. However, due to their coarse resolution, modeling based on census tracts might not adequately capture neighborhood characteristics, which are crucial for understanding and addressing inequality. Fine-tuning vulnerability mapping to more minor spatial scales is essential to better identify and address disparities within communities. By utilizing appropriate spatial units and statistical methods, researchers and policymakers can improve the accuracy and effectiveness of vulnerability assessments, thus enhancing the development of targeted interventions to address heat-related challenges and promote resilience among vulnerable populations.

3.1.2 Heat mapping

Temperature data are commonly used in spatial interpolation, with most researchers utilizing data from weather stations to predict the temperatures in neighboring locations. However, due to the scarcity of weather stations at the community level and the influence of environmental features, spatial interpolation is a less reliable metric for temperature estimation. For instance, a neighborhood with more green spaces and a local weather station may not accurately represent adjacent neighborhoods' temperatures (Ho et al. 2015). The impact of heat varies in different regions due to a combination of factors such as indicators, structures, and system variations. Therefore, there is no clear method for estimating temperatures in these regions. (Aubrecht & Özceylan, 2013). Wilson & Chakraborty (2019) propose using a combination of temperature and relative humidity when utilizing weather stationed data to estimate the heat of a given place. Aubrecht & Özceylan (2013) underscore the importance of using temperature and relative humidity in heat index construction. This combination is essential for constructing heat indices and assessing heat-related impacts such as morbidity and mortality rates (Aubrecht & Özceylan 2013; Arsad et al. 2022).

Identifying heat risks is crucial to understanding emerging issues in heat vulnerability, such as health disparities. This aids in correlating unequal access to health care with the potential drivers of health inequalities. Liang et al. (2022) suggest using surrogate modeling techniques, employing simulation models to predict what-if scenarios based on a variation of the predictor variables that could be used to estimate the thermal loads of the built environment. Cross-validation techniques could be used to assess the validity and reliability of the spatial interpolation technique selected.

Landsat satellite data can generate urban surface temperatures with a fine spatial resolution. However, Landsat's 16-day temporal resolution limits its ability to systematically capture heat events over longer durations (Wilson & Chakraborty 2019). Additionally, cloud cover could obstruct satellite images, which translates to less coverage of land cover features. Land surface temperature (LST) derived from satellite data assumes a surface emissivity of 1.0, which may not accurately reflect the actual heat radiated from land cover features (Chakraborty et al. 2021). For instance, a satellite may pick the temperature of a tree canopy, yet the canopy blocks the satellite from identifying the temperature of impervious surfaces beneath the tree. The absence of a consensus on the most accurate method to estimate LST in previous studies contributes to uncertainty in vulnerability mapping in terms of space and time (Eakin & Luers 2006; Klemm et al. 2015; Li et al. 2023). To improve accuracy, comparing LST data with MODIS data, which offers disparate temporal resolutions, is suggested (Chakraborty et al. 2021). Additionally, comparing LST maps produced from different software, such as ArcGIS Pro and Google Earth Engine, could help refine vulnerability mapping and analysis by utilizing different algorithms for geospatial analysis.

3.1.3 Principal component analysis

Principal component analysis (PCA) is a data reduction technique that reduces a large dataset of variables to a few main orthogonal components. However, PCA has limitations, as it undermines the individual importance of the predictor variables and assumes equal weighting of single variables in a particular principal component (Abson et al. 2012; Reckien 2018). According to Tate (2012), input variables highly influence the output vulnerability index. The number of input variables used in PCA does not account for variability in the data, leading to potential issues in vulnerability index construction (Reckien 2018; Karanja & Kiage 2021). For instance, a study using ten input variables accounted for 87% of the variance, while twenty input variables were used in a different study which explained 73% of the variance in the data (de Sherbinin & Bardy 2015). To overcome these challenges, Conlon et al. (2020) suggest using the overlay method, an additive model that superimposes multiple layers to create a composite index. The additive model assumes that each predictor variable adds a different component to the overall index, thereby contributing to the robustness of the model. Researchers can explore alternative approaches beyond PCA to distinguish between the most susceptible and less vulnerable neighborhoods to heat hazards. Adopting disparate weighting techniques and comparing different metrics, such as SVI and HVI, can aid in understanding various spatial and temporal vulnerability trends in diverse geographical locations. Moreover, integrating additional data and employing more comprehensive modeling techniques, such as the overlay method, can improve the accuracy of vulnerability assessments and support the development of targeted interventions for high-risk communities.

4 Policy and practice

In this review, we propose focusing on socioeconomic and political structures as the primary drivers of vulnerability. Political ecologists contend that equilibrium must be maintained between a system's social and environmental dynamics, emphasizing the inclusion of these external variations in policy design and implementation (Eakin & Luers 2006). To achieve this, we suggest adopting an assessment tool to guide local experts, urban planners, and governments in conceptualizing the diverse echelons of the hierarchical system and power relations that determine individual vulnerability. For instance, the elite members of society are less sensitive and have high adaptive capacity based on their economic endowment. Ultimately, tackling the underlying structural causes of vulnerability calls for a shift from rigid and oppressive systems to a more flexible and all-inclusive approach, which would help reduce health disparities and foster heat equity policies.

Integrating a participatory approach in policy design and implementation enhances policy sustainability. Emergency planners postulate that allowing community members to participate in designing the most crucial aspects that define their susceptibility to natural hazards aids in minimizing the negative impacts of disasters (Eakin & Luers 2006).

The coevolutionary approach proposed by Eakin & Luers (2006) captures the interaction between social dynamics and climate change outcomes, involving various stakeholders in a participatory process. Such a model would aid in getting feedback from stakeholders, enhance collaboration based on simulations and risk assessments, inform decision-making, and lead to more effective policies. This approach is essential in making informed decisions grounded on the emerging issues observed from the model. Ultimately, this technique enhances policy sustainability and strengthens community resilience to natural disasters.

The design of heat policies that integrate the concepts of equity and intersectionality is an essential aspect of heat management. Unfortunately, numerous institutions frame heat policies without integrating equity and intersectionality (Turner et al. 2022). Intersectionality refers to the interaction of individual social and political identities to create disparate forms of discrimination and privilege. By adopting the social equity framework, as shown in Fig. 2, we can guide local experts, urban planners, and governments to create heat policies that are inclusive and equitable. Understanding the interactions of individual social and political identities that result in different forms of discrimination and privilege would help address communities' diverse needs and concerns, leading to more comprehensive and effective heat management strategies.

4.1 Strategies for enhancing equity and resilience in addressing heat vulnerability

The social equity framework (Fig. 2) highlights the essential dimensions on which social equity should be grounded. At the core of advancing social equity lies the need to systematically evaluate and address oppressive hierarchical systems and power relations. Power permeates all arenas of life. It determines who has access to and control of resources as well as opportunities (Jhpiego 2020). More so, power relations and social status determine individual treatment by diverse institutions and how different laws and policies influence personal lives (Jhpiego 2020). Therefore, confronting the social and political structures would bolster community resilience in the context of the heat hazard. The initial phase of the framework involves recognizing and understanding the vulnerable individuals and the factors exacerbating their susceptibility to external stressors. Equitable and intersectional heat policies call for the need for humans to advance and adjust to system dynamics and environmental changes. The coevolutionary approach is based on the notion that humans and the environment are interdependent (Porter 2006). As such, the human species must evolve and adapt to variations in the biophysical aspects of the environment. On the other hand, the environment must advance in relation to variations in human conditions (Porter 2006). For the attainment of resilient and sustainable heat governance, it is imperative for community members to participate in decision-making processes regarding the design and implementation of heat policies (Meerow et al. 2019). An inclusive approach ensures that the unique needs and concerns of individuals, especially minority groups, are incorporated into the action plans and programs. The aforementioned components provide the foundation for creating a comprehensive and all-inclusive social equity framework that addresses the root causes of vulnerability. By considering these dimensions, the local experts, government, and urban planners can collaborate to develop just and comprehensive heat policies that cater to the specific needs of individuals regardless of their social and political identities.

Establishing local heat offices could be a proactive strategy for addressing heat-related issues and relieving vulnerable populations. Minorities such as seniors, infants, and homeless individuals face heightened susceptibility to heat hazards due to existing health conditions, limited access to cooling systems, and inadequate health coverage. These heat offices could serve as cooling centers, offering a safe environment for marginalized communities. Furthermore, heat officers within these offices would enhance prompt responses to heat emergencies, including administering first aid to those impacted by heat-related effects. For example, Phoenix, Arizona, has implemented a heat office focused on social protection and addressing local heat concerns (Phoenix government 2023). The establishment of such heat offices holds the potential to enhance public health and mitigate vulnerability in regions prone to heat risks.

5 Conclusion

The intricate interplay between human vulnerability and environmental hazards, particularly in the context of heat-related risks, emphasizes the urgency of comprehensive and equitable strategies. The year 2023's record-breaking temperatures underscore the critical need to address greenhouse gas emissions and climate change while prioritizing the well-being of vulnerable populations across urban, suburban, and rural landscapes. Understanding vulnerability necessitates a holistic perspective considering exposure, sensitivity, and adaptive capacity, reflecting a comprehensive assessment of susceptibility to extreme natural events. Utilizing tools like the Heat Vulnerability Index (HVI) and Social Vulnerability Index (SVI) aids in gauging the impact of hazards on communities, revealing patterns that inform predictions of the heat-related effects in highly vulnerable areas. However, overlooking population dynamics in vulnerability assessments undermines the accuracy of such predictions. The proposed framework embraces changes in human and environmental conditions within vulnerability assessments. Utilizing statistical predictive models to anticipate shifts due to population dynamics offers a forward-looking perspective. The significance of infrastructure and environmental factors as essential components of vulnerability reinforces the need for accurate assessments at local levels. Challenges, such as outcome definition and non-human species consideration, underline the complex nature of vulnerability analysis. Transformative heat policies must prioritize concrete, inclusive, and responsive strategies emphasizing equity and engaging stakeholders for effective governance. Recognizing vulnerability as an equity issue and its multifaceted dimensions are crucial steps toward more accurate, inclusive, and practical strategies for addressing heat-related vulnerabilities and enhancing community resilience. By fostering collaboration and considering the unique needs, and social and political identities of diverse populations, we can pave the way for a more sustainable and resilient future in the face of escalating heat challenges.

Author contributions Both authors contributed to the conceptualization, and writing—review & editing.

Funding Not applicable.

Declarations

Conflicts of interest The authors (Consolata Macharia and Lawrence Kiage) declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent for publication The authors' consent to publication.

Ethical approval No human subjects were interviewed in this study.

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Authors and Affiliations

Consolata Wangechi Macharia[1] · **Lawrence M. Kiage**[1]

✉ Lawrence M. Kiage
lkiage@gsu.edu

[1] Department of Geosciences, Georgia State University, PO Box 4105, Atlanta, GA 30302, USA