



## Cardiovascular Morbidity in a Warming Climate: A Systematic Review of Vulnerability and Adaptation

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### ABSTRACT

Rising global temperatures and increasing frequency of extreme heat events have transformed thermal stress into a critical, systemic driver of cardiovascular and chronic disease burden worldwide. Despite growing recognition of heat-related health risks, substantial gaps remain regarding chronic sub-threshold exposure, morbidity outcomes, and the equity implications of adaptation strategies. This systematic review, conducted according to PRISMA 2020 guidelines, synthesizes contemporary epidemiological evidence from peer-reviewed studies published between 2020 and 2025 to characterize heat-health associations, identify vulnerability determinants, and evaluate policy implementation across diverse geographic and socioeconomic contexts. Following independent screening, quality appraisal, and data extraction, a structured narrative synthesis was performed due to significant methodological heterogeneity in exposure metrics and outcome definitions. The findings demonstrate a robust association between heat exposure and elevated risks of stroke, coronary heart disease, and accelerated progression of metabolic, respiratory, and mental health conditions, with chronic thermal stress emerging as an underrecognized contributor to long-term physiological deterioration. Vulnerability is highly stratified, disproportionately affecting older adults, women, outdoor workers, socioeconomically marginalized communities, and populations in low- and middle-income countries, particularly within urban heat island environments. Current adaptation measures exhibit limited behavioral uptake and insufficient equity-focused design. Addressing these disparities requires standardized exposure metrics, context-sensitive early warning systems, multisectoral policy integration, and targeted research on chronic thermal stress to build inclusive, climate-resilient health systems.

### KEYWORDS

Heat Exposure, Cardiovascular Morbidity, Climate Vulnerability, Health Equity, Adaptation Strategies.

Received: 06 April 2026

Revised: 29 May 2026

Accepted: 08 June 2026

*How to cite:* Fitri, Anggun Novia Indah et al. Cardiovascular Morbidity in a Warming Climate: A Systematic Review of Vulnerability and Adaptation. *Health Frontiers: A Multidisciplinary Journal for Health Professionals*, 4(1): 74-87.





## INTRODUCTION

Climate change represents one of the most profound public health challenges of the 21st century, with rising global temperatures and increasing frequency, intensity, and duration of extreme heat events fundamentally altering the environmental determinants of human health (Ebi et al., 2021). The Intergovernmental Panel on Climate Change (IPCC) projects that under current emission trajectories, many regions will experience unprecedented thermal conditions by mid-century, exposing billions of people to heat stress levels that exceed physiological adaptive capacity (Freychet et al., 2020; Lo et al., 2023; Thiaw et al., 2022). While heat-related mortality during acute heatwaves has garnered significant attention, a growing body of evidence suggests that chronic, sub-threshold heat exposure persistent thermal stress below extreme event thresholds may exert equally consequential, yet less visible, effects on long-term health trajectories (Chaseling et al., 2025; Zafeiratou et al., 2021). This evolving epidemiological landscape necessitates a comprehensive reassessment of how heat exposure influences not only acute cardiovascular events but also the progression and management of chronic diseases across diverse populations and settings (Liu, Varghese, Hansen, Zhang, Driscoll, Morgan, Dear, Gourley, & Capon, 2022; Singh et al., 2024).

Cardiovascular diseases remain the leading cause of global mortality, and emerging research positions ambient heat as a potent, modifiable risk factor that interacts synergistically with established determinants such as hypertension, diabetes, and socioeconomic disadvantage (Fan et al., 2023; Singh et al., 2024; Zafeiratou et al., 2021). Physiological mechanisms linking heat exposure to cardiovascular strain include increased cardiac output, peripheral vasodilation, electrolyte imbalance, systemic inflammation, and heightened sympathetic nervous system activity all of which can precipitate acute events in vulnerable individuals or accelerate underlying disease processes over time (Desai et al., 2023; Vita et al., 2024). Beyond cardiovascular outcomes, thermal stress has been increasingly associated with exacerbations of respiratory conditions, dysregulation of glucose metabolism, deterioration of mental health, and compounded morbidity among individuals with multimorbidity (Uibel et al., 2023; Wang et al., 2023). Critically, these health impacts are not distributed equitably: biological susceptibility, occupational demands, urban living conditions, and structural inequities intersect to concentrate risk among older adults, outdoor workers, low-income communities, and populations in tropical and lower-middle-income regions where adaptive resources are most constrained (Ellena et al., 2020; Slesinski et al., 2025).

Despite rapid growth in heat-health research over the past decade, significant knowledge gaps persist that limit the development of standardized, globally applicable guidance for clinicians, policymakers, and public health practitioners (Conti et al., 2022). First, the predominant focus on mortality outcomes and acute heatwave events has obscured the substantial burden of heat-related morbidity and the health implications of chronic thermal exposure (Çulpan et al., 2022; Xu et al., 2025). Second, methodological heterogeneity in heat exposure definitions, lag structures, outcome ascertainment, and analytical approaches constrains cross-study comparability and meta-analytic synthesis (Graffy et al., 2023; Liu, Varghese, Hansen, Zhang, Driscoll, Morgan, Dear, Gourley, Capon, et al., 2022). Third, evidence from low- and middle-income countries, where vulnerability may be highest and adaptive capacity most limited, remains disproportionately scarce (Aydin-Ghormoz et al., 2025). Fourth, while adaptation strategies such as early warning systems and public advisories are widely promoted, rigorous evaluation of their effectiveness, equity impact, and behavioral uptake particularly among high-risk subgroups





remains limited (Bassey et al., 2025; Rao et al., 2025). These gaps collectively impede the translation of emerging evidence into context-sensitive, actionable interventions capable of reducing heat-related health disparities (Johar et al., 2024).

To address these limitations, this systematic review synthesizes contemporary epidemiological evidence on the association between heat exposure and cardiovascular and chronic disease outcomes, with explicit attention to vulnerability determinants, adaptation strategies, and policy implementation across diverse geographic and socioeconomic contexts (Pasquini et al., 2020). Guided by the PRISMA 2020 framework and an intersectional vulnerability lens, the review aims to: (1) characterize the strength and consistency of associations between acute and chronic heat exposure and cardiovascular morbidity and mortality; (2) identify population subgroups and settings at heightened risk due to biological, occupational, urban, or socioeconomic factors; (3) evaluate the effectiveness and equity implications of existing heat-health adaptation and mitigation interventions; and (4) delineate methodological priorities and research gaps to inform future investigation. By integrating rigorous evidence synthesis with an equity-centered analytical approach, this review seeks to advance a more nuanced, actionable understanding of heat-health dynamics and to support the development of resilient, inclusive public health responses in an era of accelerating climate change.

## MATERIALS AND METHODS

### Study Design & Protocol Registration

This study was conducted as a systematic review strictly adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The review protocol was developed a priori to ensure methodological transparency, predefine analytical plans, and minimize selective reporting bias. The complete protocol, search strategy, and data extraction framework are available from the corresponding author upon reasonable request. The synthesis was designed to evaluate the epidemiological evidence linking heat exposure to cardiovascular and chronic disease outcomes while critically appraising vulnerability determinants, adaptation strategies, and policy implementation gaps across diverse geographic and socioeconomic contexts.

### Eligibility Criteria

Studies were selected based on predefined inclusion and exclusion criteria structured around the Population, Exposure, Comparator, Outcomes, and Study design (PECO/S) framework. Eligible publications comprised peer-reviewed observational research (cohort, case-control, cross-sectional, time-series, and case-crossover designs) and intervention studies examining human populations exposed to ambient heat, heatwaves, or chronic thermal stress. Primary outcomes included cardiovascular morbidity and mortality, stroke, coronary heart disease, and exacerbation of chronic conditions such as diabetes, respiratory, and mental health disorders. Articles were required to be published in English between January 2020 and December 2025. Studies were excluded if they lacked explicit heat exposure metrics, focused on animal models, were limited to editorials, commentaries, or conference abstracts without original data, or did not report quantifiable health outcomes related to thermal stress.

### Information Sources & Search Strategy





A comprehensive and reproducible literature search was executed across five major electronic databases: PubMed/MEDLINE, Embase, Scopus, Web of Science Core Collection, and Cochrane Library. The search strategy was developed in consultation with a health sciences librarian and combined controlled vocabulary (MeSH, Emtree) with free-text terms using Boolean operators. Core search strings included: (“heat exposure” OR “high temperature” OR “heatwave” OR “thermal stress” OR “urban heat island”) AND (“cardiovascular diseases” OR “stroke” OR “coronary heart disease” OR “chronic disease” OR “morbidity” OR “mortality”) AND (“vulnerability” OR “adaptation” OR “resilience” OR “health equity”). Database-specific filters were applied to restrict results to human studies and peer-reviewed articles published within the designated timeframe. The search was supplemented by backward and forward citation tracking of included studies and systematic screening of grey literature from authoritative organizations including the World Health Organization, the Intergovernmental Panel on Climate Change, and national public health agencies. The final search was completed on 20 November 2025.

### Study Selection Process

All retrieved records were imported into EndNote for automatic deduplication and subsequently uploaded to the Rayyan platform for blinded, independent screening. The selection process followed a two-stage approach consistent with PRISMA 2020 standards. Initially, two reviewers independently screened titles and abstracts against the eligibility criteria, with inter-rater reliability calculated using Cohen’s kappa. Full-text articles of potentially relevant studies were then retrieved and assessed in duplicate. Discrepancies at both screening stages were resolved through structured discussion or arbitration by a third senior methodologist. The number of records identified, screened, assessed for eligibility, and ultimately included, along with explicit reasons for exclusion at the full-text stage, were documented in a PRISMA 2020 flow diagram.

### Data Extraction & Management

A standardized, pilot-tested data extraction form was developed to ensure systematic and consistent data capture across reviewers. Extracted variables encompassed study characteristics (authors, publication year, country, design, sample size), exposure assessment methods (temperature thresholds, heatwave definitions, duration, acute versus chronic exposure classifications), outcome definitions, demographic profiles, vulnerability indicators, adaptation or mitigation strategies, reported effect estimates, and author conclusions. Data extraction was performed independently by two reviewers, followed by cross-verification to minimize transcription errors and subjective bias. All extracted data were stored in a secure, password-protected relational database with version control and audit trails to guarantee traceability and reproducibility.

### Risk of Bias & Quality Assessment

Methodological quality and risk of bias were appraised independently by two reviewers using validated, design-specific tools. Observational cohort and case-control studies were evaluated using the Newcastle-Ottawa Scale (NOS), while time-series and ecological designs were assessed with the Critical Appraisal Skills Programme (CASP) checklist for analytical studies. Quasi-experimental or intervention-focused research was appraised using the Cochrane Risk of Bias Tool (RoB 2). Each study





was rated across domains including selection bias, exposure measurement validity, confounding adjustment, outcome ascertainment, handling of missing data, and selective reporting. Discrepancies in quality ratings were resolved through consensus, and studies were categorized as low, moderate, or high risk of bias. Sensitivity analyses were predefined to evaluate whether the exclusion of high-risk studies would materially alter the synthesis conclusions.

### Data Synthesis & Analysis

Given substantial clinical, methodological, and statistical heterogeneity across the included literature particularly in heat exposure thresholds, temporal lag structures, and health outcome classifications a quantitative meta-analysis was not statistically appropriate. Instead, a structured narrative synthesis was conducted following the Synthesis Without Meta-analysis (SWiM) reporting guidelines. Extracted findings were tabulated and thematically organized according to six predefined domains aligned with the research objectives: cardiovascular and chronic disease risks, urban and occupational vulnerability, differential population susceptibility, adaptation and mitigation effectiveness, methodological and evidence gaps, and policy integration. Where comparable effect estimates were available, the direction and magnitude of associations were qualitatively compared, and consistency of evidence was evaluated across geographic, climatic, and demographic strata. Potential publication bias was assessed through visual inspection of funnel plots and Egger's regression test for subsets of studies reporting homogeneous outcomes. The overall certainty of evidence was informally graded based on study design, precision, consistency, and directness of findings.

### Ethical Considerations & Methodological Limitations

As this systematic review exclusively utilized publicly available, de-identified data from published academic and policy literature, formal institutional ethical approval was not required. All sources were rigorously cited in accordance with international academic standards, and deliberate efforts were made to ensure equitable representation of low- and middle-income country contexts to mitigate geographic bias in heat-health evidence. Several methodological limitations warrant explicit acknowledgment. The restriction to English-language publications may have introduced language bias, potentially excluding regionally significant studies. Publication bias remains a concern, as null or inverse findings are historically underrepresented in environmental epidemiology. Additionally, the inherent variability in thermal exposure metrics, health outcome definitions, and analytical frameworks across studies constrained direct comparability and precluded pooled effect estimation. Finally, the post-2020 publication window, while prioritizing contemporary evidence, may have omitted foundational historical research. Despite these constraints, strict adherence to PRISMA 2020 standards, dual-independent reviewer processes, and transparent synthesis methodology strengthen the validity, reproducibility, and policy relevance of the findings.

## RESULTS

### Cardiovascular and Chronic Disease Risks Associated with Heat Exposure

The synthesis of current evidence demonstrates a robust association between heat exposure and increased cardiovascular disease mortality and morbidity, with particularly pronounced effects observed





for stroke and coronary heart disease. This relationship is not uniform across populations; women, older adults, and individuals residing in tropical or lower-middle income regions exhibit heightened susceptibility, suggesting that biological, socioeconomic, and environmental factors interact to modulate heat-related health risks. Importantly, emerging research underscores that chronic heat exposure distinct from acute heatwave events represents an underrecognized determinant of long-term health deterioration, potentially contributing to cumulative physiological stress and accelerated progression of chronic conditions. These findings highlight the necessity of expanding the conceptual framework of heat-health research beyond episodic extreme events to encompass sustained thermal stress as a persistent public health concern.

### **Urban and Occupational Vulnerability to Heat-Related Health Impacts**

Urban environments emerge as critical hotspots for heat-related health risks, driven by the compounding effects of the urban heat island phenomenon, high population density, and reliance on infrastructure systems that may falter under thermal stress. Within these settings, occupational groups particularly outdoor workers and those required to wear personal protective equipment face disproportionately elevated risks of heat-related illnesses, encompassing cardiovascular strain, neurological impairment, and respiratory compromise. The convergence of environmental exposure and work-related physical demands creates a unique vulnerability profile that necessitates targeted occupational heat safety guidelines, adaptive work-rest schedules, and accessible cooling interventions to mitigate adverse health outcomes in this essential workforce segment.

### **Differential Vulnerability Across Population Subgroups**

Vulnerability to heat-related morbidity and mortality is markedly stratified across demographic and socioeconomic lines. Older adults, children, individuals with pre-existing chronic conditions, and socioeconomically disadvantaged communities consistently demonstrate reduced adaptive capacity and heightened exposure, rendering them disproportionately affected by rising temperatures. Beyond cardiovascular outcomes, emerging evidence links heat exposure to exacerbated risks of mental and behavioral disorders, complications in diabetes management, and worsened respiratory disease trajectories. These patterns underscore the importance of adopting an intersectional lens in heat-health research and policy, recognizing that vulnerability is shaped by the interplay of age, health status, economic resources, and social support systems.

### **Adaptation and Mitigation Strategies: Evidence and Implementation Gaps**

Effective adaptation to heat-related health risks requires a nuanced understanding of vulnerability determinants, including sensitivity factors and adaptive capacity at individual and community levels. Current best practices emphasize the deployment of heat-health warning systems, actionable response plans, and tailored educational materials for both healthcare providers and the general public. Practical interventions include promoting hydration, facilitating physiological acclimatization, implementing environmental and personal monitoring, enabling access to cooling resources, and establishing clear emergency protocols. However, notable gaps persist in the uptake of certain coping strategies; for instance, water-based adaptation measures remain underutilized among elderly populations despite their





potential benefits, indicating a need for more context-sensitive and behaviorally informed intervention design.

### **Research Gaps and Methodological Challenges in Heat-Health Science**

The current evidence base faces several methodological limitations that constrain the development of standardized, globally applicable heat-health guidelines. Key challenges include heterogeneity in exposure definitions, outcome measures, and analytical approaches across studies, as well as a persistent scarcity of data from low- and middle-income regions where heat vulnerability may be most acute. Furthermore, the predominant focus on mortality outcomes in existing literature overlooks the substantial burden of heat-related morbidity, while the health implications of chronic, sub-threshold heat exposure remain inadequately characterized. Longitudinal assessments of heat vulnerability indices (HVIs) and their predictive validity across diverse settings also warrant further investigation to enhance the precision and equity of risk stratification tools.

### **Policy Integration and Multisectoral Coordination for Heat-Health Resilience**

Addressing the complex health challenges posed by rising temperatures demands coordinated action across multiple sectors, including public health, urban planning, disaster risk reduction, and social welfare. Sustainable and equitable responses integrate long-term resilience-building measures such as green infrastructure development, housing improvements, and community capacity strengthening with robust emergency preparedness systems that prioritize the needs of vulnerable communities. This multisectoral approach recognizes that heat-health risks are not solely biomedical phenomena but are embedded within broader social, economic, and environmental systems that require integrated governance and participatory planning to achieve meaningful risk reduction.

### **Synthesis of Challenges and Strategic Solutions**

The principal challenges impeding effective heat-health action include methodological inconsistencies in research, limited awareness and preparedness among healthcare professionals and communities, and insufficiently tailored adaptation strategies for high-risk groups in occupational and urban contexts. To address these barriers, three strategic priorities emerge: (1) the development and implementation of comprehensive, context-adapted heat-health action plans and early warning systems; (2) expanded research investment focused on chronic heat exposure, morbidity outcomes, and the specific needs of vulnerable populations; and (3) the fostering of sustained multisectoral collaboration to ensure that interventions are scientifically grounded, socially equitable, and operationally feasible. Collectively, these actions can strengthen societal resilience to a warming climate while advancing health equity and sustainable development objectives.

Rising global temperatures and increasing frequency of extreme heat events pose a significant and escalating threat to public health worldwide. Heat exposure is no longer just an environmental concern it is a critical determinant of cardiovascular morbidity, chronic disease progression, and health inequity. Current evidence confirms that heat-related risks are not evenly distributed; they are shaped by biological susceptibility, occupational demands, urban living conditions, and socioeconomic barriers. To support clear decision-making and targeted action, the table below distills the most essential findings





from recent literature into a concise, actionable format. It is designed to help stakeholders quickly grasp where to focus resources, how to protect vulnerable groups, and what strategies offer the greatest potential for building heat-resilient health systems.

**Table 1. Heat-Health Essentials: Risks, Vulnerability & Actions**

<b>Core Issue</b>	<b>Key Impact</b>	<b>High Risk Populations</b>	<b>Recommended Interventions</b>
<b>Heat &amp; Heart Health</b>	↑ Risk of stroke, heart disease, and chronic disease progression	Older adults, women, people with pre-existing conditions	Monitor chronic heat exposure; update clinical guidelines
<b>Urban &amp; Work Exposure</b>	Heat islands + physical labor = ↑ heat illness, cardiovascular strain	Outdoor workers, urban residents, PPE users	Adaptive work schedules; cooling stations; occupational safety rules
<b>Social Inequity</b>	Heat worsens mental health, diabetes, respiratory issues; limited coping capacity	Low-income groups, children, elderly, marginalized communities	Intersectional policies; targeted outreach; community support
<b>Adaptation Gaps</b>	Warning systems exist, but behavioral uptake (e.g., hydration) is low	Elderly, low health-literacy populations	Co-design simple, context-sensitive interventions
<b>Research Needs</b>	Data gaps in LMICs; focus on mortality overlooks morbidity	Populations in low-resource settings	Standardize metrics; invest in morbidity & longitudinal studies
<b>Policy Coordination</b>	Siloed responses reduce effectiveness	Communities lacking voice/resources	Integrated governance: health + urban planning + social welfare

Addressing heat-related health risks demands more than technical solutions it requires an equity-centered approach that recognizes vulnerability as a product of intersecting social, economic, and environmental factors. Prioritizing inclusive policies, context-adapted interventions, and cross-sector collaboration is essential to safeguarding health in a warming world.

## DISCUSSION





This systematic review synthesizes contemporary evidence to affirm that heat exposure constitutes a critical and escalating determinant of cardiovascular and chronic disease burden globally. The findings underscore that thermal stress operates not merely as an acute environmental hazard but as a persistent physiological challenge with cumulative health consequences (Ding & Gao, 2025; Martinez et al., 2022). Importantly, the review reveals that heat-related risks are profoundly shaped by intersecting biological, occupational, urban, and socioeconomic factors, producing stark disparities in vulnerability and adaptive capacity (Alonso & Renard, 2020; Sandholz et al., 2021). By integrating an intersectional lens and prioritizing both mortality and morbidity outcomes, this synthesis advances a more nuanced understanding of heat-health dynamics and provides a foundation for equity-centered policy and practice (Clark et al., 2024; Liu, Varghese, Hansen, Zhang, Driscoll, Morgan, Dear, Gourley, & Capon, 2022).

The core epidemiological evidence consistently links heat exposure to elevated risks of stroke, coronary heart disease, and accelerated progression of chronic conditions, with chronic, sub-threshold thermal stress emerging as an underrecognized contributor to long-term physiological deterioration (Desai et al., 2023; He et al., 2024). Vulnerability is highly stratified: older adults, women, individuals with pre-existing conditions, outdoor workers, and socioeconomically marginalized communities experience disproportionate harm due to reduced adaptive resources and heightened exposure (Arnberger et al., 2024; Núñez-rodríguez et al., 2025). Urban environments further amplify these risks through the heat island effect, infrastructure strain, and population density, creating synergistic hazards that extend beyond cardiovascular outcomes to include exacerbated mental health disorders, dysregulated diabetes management, and progressive respiratory decline (Cleland et al., 2024; Curtis et al., 2025). These patterns highlight that heat vulnerability is not an inherent trait but a product of modifiable social and environmental conditions.

Translating these insights into action requires reorienting public health and clinical systems toward proactive, equity-focused heat resilience. Clinical guidelines should integrate thermal risk screening into chronic disease management, while occupational policies must enforce adaptive work-rest schedules, cooling infrastructure, and ergonomic PPE redesign (Ireland et al., 2023; Yoon et al., 2021). Heat-health warning systems need to incorporate behavioral science and community co-design to improve uptake among high-risk groups, particularly the elderly (Heidenreich, 2024; Issa et al., 2020). Urban planning and public health policy must converge to treat accessible cooling through green infrastructure, reflective surfaces, and community cooling centers as essential health infrastructure, prioritized for neighborhoods with high vulnerability indices (Marando et al., 2022). Critically, interventions must be tailored to intersecting vulnerabilities rather than relying on uniform approaches that inadvertently widen health disparities.

This review has several limitations. First, restricting the search to English-language publications may have introduced geographic bias, potentially overlooking regionally significant studies. Second, the focus on literature published from 2020 onward, while ensuring contemporary relevance, may have excluded foundational historical evidence. Third, substantial heterogeneity in heat exposure metrics, outcome definitions, and analytical approaches across studies precluded quantitative meta-analysis.





Despite these constraints, strict adherence to PRISMA 2020 guidelines, dual-independent screening, and an intersectional analytical framework strengthen the validity and policy relevance of the synthesis. Future research should prioritize standardized exposure definitions, longitudinal studies in low- and middle-income settings, and pragmatic evaluations of equity-focused adaptation interventions.

These findings highlight an urgent need to translate heat-health evidence into operational frameworks that bridge clinical practice, urban governance, and labor protection. Future interventions must move beyond one-size-fits-all advisories toward context-specific, equity-driven models that integrate real-time exposure monitoring with community-led adaptation. Strengthening institutional capacity in low-resource settings and embedding thermal risk metrics into routine public health surveillance will be critical to closing the gap between emerging evidence and on-the-ground resilience.

## CONCLUSIONS

Heat exposure has unequivocally evolved from an episodic environmental hazard into a persistent, systemic driver of cardiovascular and chronic disease burden, with its health impacts profoundly shaped by intersecting biological, occupational, urban, and socioeconomic vulnerabilities. As global temperatures continue to rise, the disproportionate toll on older adults, outdoor workers, low-income communities, and populations in low- and middle-income countries underscores the urgent need to shift from fragmented, reactive measures to integrated, equity-centered resilience strategies. Protecting public health in this new thermal reality requires standardizing exposure metrics, expanding research on chronic sub-threshold heat and morbidity outcomes, and institutionalizing accessible cooling, adaptive labor policies, and behaviorally informed early warning systems as essential health infrastructure. Ultimately, building climate-resilient health systems demands sustained multisectoral collaboration, participatory governance, and the deliberate prioritization of marginalized populations, as the window for proactive, justice-driven adaptation rapidly closes and the choices made today will dictate whether societies mitigate or amplify the health consequences of a warming world.

### Acknowledgement

No Acknowledgement

### Funding Source

No Funding Source

### Conflict of Interest

No Conflict of Interest

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