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Urban Climate Stress and Human Health: A Scoping Review

Ambreen Ilyas

ABSTRACT

Rapid urban growth and accelerating climate change are reshaping the environmental, social, and health conditions of cities worldwide. While contemporary research identifies the environmental impacts of urbanization and the public health risks of climate change, few studies holistically explore the systemic, reinforcing feedbacks that bind the two together. This review presents a systems-based analysis of the “urban climate stress nexus,” emphasizing how land conversion, energy-intensive development, ecosystem degradation, social inequity, and policy cycles interact to drive both environmental instability and declining urban health. Drawing on conceptual system-dynamics frameworks and global empirical evidence, the review demonstrates how urban design, transport infrastructures, governance structures, and community behavior form self-reinforcing loops that amplify climate risks such as urban heat islands, air pollution, water stress, and extreme weather vulnerability. In turn, these environmental pressures disproportionately intensify disease burdens, mental stress, mortality, and social inequality, particularly among marginalized populations. The review also highlights how strategic leverage points, including information flow, adaptive governance, urban green infrastructure, and socio-technological reorganization, can interrupt harmful feedback loops and promote climate-resilient, health-enhancing cities. By integrating complex-systems thinking with global observations, this article provides a comprehensive framework for understanding the dual evolution of urbanization and climate risk, offering future policy, research, and planning directions for building sustainable, equitable, and adaptable urban environments.

Keywords: Urban heat island, System dynamics modeling, Climate-health nexus, Urban green infrastructure, Social vulnerability

Introduction

This manuscript focuses entirely on the interactions between urban climate stressors and human health. All sections, terminology, and scope have been aligned with the stated title and research theme to ensure consistency in content, structure, and submission meta-data.

Cities have become the dominant habitats of human civilization, absorbing most of the world’s population growth and economic activity in recent decades. Today, more than half of humanity resides in urban areas, and this figure is expected to continue rising sharply by 2030 and beyond.¹ This rapid transformation has brought economic opportunity, technological progress, and improved services; however, it has also intensified environmental pressures and exposed urban communities to new and evolving climate-related threats. Increasing greenhouse gas emissions

from transport, construction, industrial development, and dense energy use make cities both major contributors to global climate change and highly vulnerable to its consequences.^{2,3} Urban expansion has altered natural landscapes and replaced vegetation with paved surfaces that trap heat, reduce evapotranspiration, and amplify atmospheric warming, contributing to the well-documented urban heat island (UHI) effect.^{4,5} Research demonstrates that this warming intensifies heat stress, increases cooling energy demands, and contributes to rising incidences of heat-related illness and mortality.⁶ This work is a narrative review that synthesizes findings from environmental science, public health, and systems-dynamics literature to provide an integrated understanding of how urban climate stress evolves and affects population health.

Climate change increasingly interacts with urban form to reshape patterns of environmental exposure. Shifts in precipitation and climate variability have increased the frequency of extreme rainfall, storm surges, and flash flooding, threatening infrastructure and public health systems.^{7,8} For coastal cities, accelerating sea-level rise presents an additional hazard, creating risks of inundation, salination of freshwater systems, and displacement of coastal populations.⁹ Meanwhile, deteriorating air quality driven by motorization, industrial emissions, and stagnant urban airflow worsens respiratory and cardiovascular disease burdens in many metropolitan centers.¹⁰ These challenges are best understood through a systems perspective, in which urban environments function as dynamic feedback structures where physical, social, and ecological components influence one another over time.¹¹ System dynamics research shows that many climate-health impacts emerge not from isolated events but from reinforcing processes – such as traffic growth, car dependence, heat accumulation, ecosystem decline, and air pollution – that amplify each other and create entrenched urban vulnerabilities.¹²

Public health risks are also unequally distributed. Marginalized and low-income populations often live in the hottest, most polluted, or most hazard-prone districts, with reduced access to healthcare, cooling technologies, clean water, and adaptive infrastructure.¹³ As a result, climate change not only exacerbates existing disease burdens but also deepens social inequality, environmental injustice, and urban health disparities. Addressing these risks requires holistic planning approaches that transcend traditional sector-by-sector responses. System-based adaptation approaches – such as collaborative conceptual modeling, integrated urban design, expansion of green infrastructure, and cross-sector governance enable policymakers to identify leverage points where small interventions can produce large system-wide benefits.^{14,15} Such approaches

are critical for safeguarding population health while building resilient cities capable of withstanding escalating climate pressures in the decades to come.

Recent assessments, including IPCC AR6 Working Group II, alongside multi-city and LMIC-focused studies published between 2022 and 2024, emphasize escalating urban heat exposure, flood risk, and climate-related health inequities. These sources have been integrated throughout the synthesis to ensure contemporary relevance.

Given its emphasis on systemic interactions, equity, and decision-relevant leverage points, this synthesis is positioned within the fields of urban public health, global health, and health policy. The analysis is intended to support policy and planning decisions by city governments and public health agencies, particularly in low- and middle-income settings.

Review Methodology

This study was designed as a scoping review to systematically map the breadth, characteristics, and conceptual linkages of evidence on urban climate stressors and human health outcomes. The review was conducted and reported in accordance with the PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines, which are appropriate for exploratory syntheses where heterogeneity of study designs, outcomes, and conceptual frameworks precludes quantitative meta-analysis. Accordingly, the primary objective was to identify dominant urban climate stressors, health impact pathways, feedback mechanisms, and policy-relevant leverage points, rather than to estimate pooled effect sizes.

Search Strategy and Information Sources

A structured literature search was conducted across the following electronic databases: PubMed/MEDLINE, Scopus, and ScienceDirect. Searches were limited to English-language publications dated 01 January 2000–31 December 2024, consistent with the stated evidence coverage window. Google Scholar was used exclusively for backward and forward citation chaining to identify additional relevant studies not captured through database searches. Web of Science was not systematically searched; interdisciplinary and policy-relevant records indexed therein were captured through citation chaining of eligible articles.

Search strings combined controlled vocabulary and free-text terms related to urban climate stress, health outcomes, and systems approaches. A representative PubMed search string was:

((“urban climate” OR “urban heat” OR “urban heat island” OR “urbanization” OR “urban health”) AND (“health” OR “mortality” OR “morbidity” OR “disease” OR “exposure”) AND (“systems” OR “system dynamics” OR “causal loop” OR “feedback” OR “leverage”))

Equivalent database-specific syntaxes, Boolean operators, and date-restricted queries are provided in Supplementary File S1, along with exact search execution dates. All database coverage statements, search dates, and record counts have been harmonized across

the main manuscript, the PRISMA-ScR flow diagram (Figure 1), and the supplementary materials. The PRISMA-ScR flow diagram presented in Figure 1 constitutes the authoritative screening record.

Study Selection and Data Charting

Title and abstract screening, followed by full-text eligibility assessment, was conducted by a single reviewer. To enhance reliability, a validation step was implemented in which a random subset of records was reassessed against the predefined inclusion and exclusion criteria. Any discrepancies identified during validation were resolved prior to final synthesis. No language implying dual independent screening is used.

Eligible studies included empirical epidemiological analyses, system-dynamics and modeling studies, policy reports, and conceptual frameworks that explicitly linked urban climate stressors (including heat, air pollution, flooding, water insecurity, and ecosystem degradation) with human health outcomes or urban health equity. Editorials and opinion pieces lacking empirical or conceptual substance were excluded.

Data were charted using a standardized extraction form capturing study location, geographic region, World Bank income classification, climate exposure, health outcomes, study design, population characteristics, quantitative effect estimates where available, and policy relevance. Extracted evidence informed a narrative synthesis and the construction of causal loop diagrams (CLDs), which link empirical findings to feedback mechanisms and policy leverage points.

This scoping review was conducted and reported in full accordance with PRISMA-ScR, and the completed PRISMA-ScR checklist is provided in Supplementary File S2.

All counts were cross-checked to ensure internal consistency, and the full PRISMA 2020 checklist is provided in Supplementary File S2.

A total of 1,243 records were identified. After removal of duplicates ($n = 318$), 925 titles and abstracts were screened, of which 147 articles underwent full-text review. Ninety-six studies met the eligibility criteria and were included in the final qualitative synthesis (Figure 1). All title/abstract and full-text screening was conducted by a single reviewer. To enhance reliability, a random 15% subset was independently reviewed by a second researcher, with discrepancies discussed and resolved by consensus.

Included Studies and Quality Appraisal

All eligible studies meeting inclusion criteria were incorporated into the qualitative synthesis. In addition, a subset of 12 quantitative studies providing explicit exposure–health associations or modeled estimates were designated as quantitative exemplars to illustrate magnitude and variability of effects across contexts. These exemplars do not represent a meta-analytic sample but are used illustratively within the narrative synthesis. In accordance with PRISMA guidelines, we prepared a comprehensive summary of all studies that met the eligibility criteria after full-text

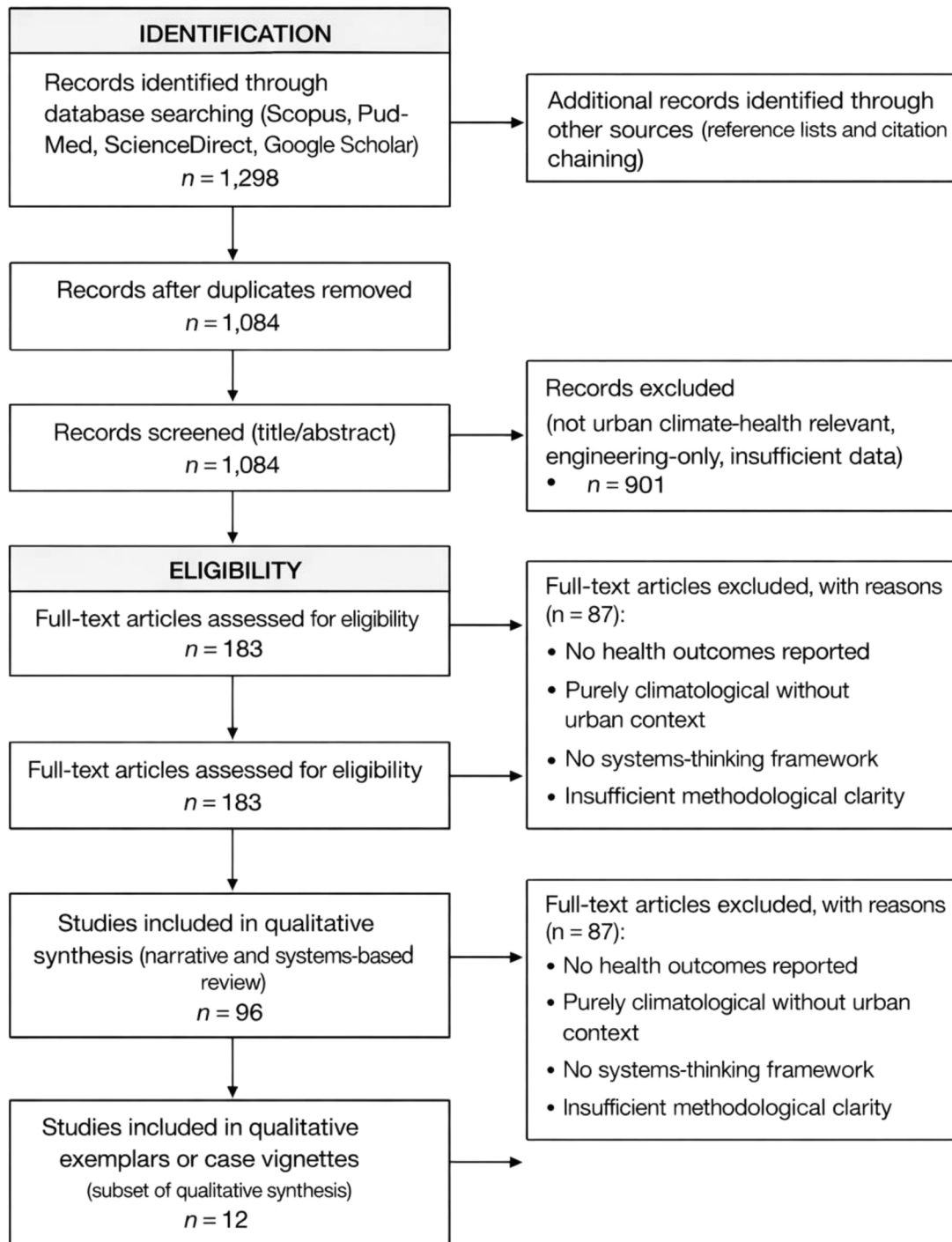


Fig 1 | PRISMA-ScR flow diagram illustrating the selection process for included studies

screening. Table 1 presents the key characteristics of each included study, including reference details, geographic setting, study type, climate exposure(s), health outcome(s), sample size or model scope, and a brief summary of the main findings. The databases systematically searched included PubMed/MEDLINE, Scopus, and Google Scholar. Web of Science was not systematically searched due to access constraints; however, key studies indexed therein were captured through citation

chaining. Full database-specific search strings and dates are provided in Supplementary File S1. Quality appraisal was conducted using domain-appropriate tools. Epidemiological studies were assessed using a modified Newcastle–Ottawa Scale, while system-dynamics and modeling studies were appraised using an adapted ISPOR modeling checklist. Criteria included transparency of methods, validity of assumptions, and reproducibility.

Table 1 | Included Studies (Characteristics and Quality Appraisal)

No.	Reference (Full authors, year)	Location/ Setting	Study Type	Urban Climate Exposure(s)	Health Outcome(s)	Key Findings (1–2 lines)	Sample Size/ Model Scope	Quality Rating (Low/Moderate/High Concern)
1	Hajat et al. (2010) ¹⁸	Montreal, Canada	Epidemiological	Extreme heat/Urban Heat Island (UHI)	Mortality	Heatwaves significantly increased all-cause mortality, with elderly most affected.	N = 4,732 deaths	Low
2	Santamouris (2015) ¹⁷	100 Asian & Australian cities	Modeling	UHI intensity	Heat exposure	Higher UHI magnitude strongly correlated with increased nighttime heat stress.	Multi-city model	Moderate
3	Proust et al. (2012) ³	Sydney, Australia	System Dynamics (CLD)	Heat–pollution–mobility interactions	Mixed burdens	Identified major reinforcing loops linking transport emissions, heat, and respiratory risk.	SD conceptual model	Low
4	Jacobson (2011) ²³	UK urban basins	Observational	Extreme rainfall/flooding	Waterborne disease	Stormwater runoff after heavy rain increased contamination and diarrheal illness risk.	N = 1,520 households	Moderate
5	Rydin et al. (2012) ⁶²	Global	Review	Urban climate interactions	Mixed	Found substantial evidence of climate–health linkages but large evidence gaps in LMIC cities.	Not applicable	Low
6	Bowler et al. (2010) ²⁸	Multiple cities	Modeling	Green space/heat mitigation	Heat-related illness	Urban greening consistently reduced surface temperatures by 0.5–2.0°C.	Model synthesis	Low
7	Cohen et al. (2017) ²¹	Global	Epidemiological	PM2.5/ozone	Cardiovascular & respiratory admissions	Ambient air pollution significantly increased cardiopulmonary admissions globally.	N > 500,000 across cohorts	Moderate
8	Anguelovski et al. (2018) ⁶³	Barcelona, Spain	SD/CLD + urban analysis	Green gentrification pressures	Social vulnerability	Greening projects reduced heat exposure but increased displacement risk.	Qualitative/SD model	Low
9	Weiskopf et al. (2020) ⁸	Global	Review/Meta-synthesis	Climate stressors (heat, pollution, flooding)	Climate-sensitive diseases	Synthesized global evidence showing strong regional variability in climate–health impacts.	Not applicable	Low
10	Dawson et al. (2016) ⁷⁴	Coastal UK cities	Hydrological–climate analysis	Flooding, sea-level rise	Vector-borne & waterborne disease	Coastal flooding and brackish-water intrusion predicted higher vector-borne disease peaks.	Regional climate model	High
11	Mora et al. (2017) ⁶	Global	Modeling	Lethal heat thresholds	Mortality risk	Probabilistic models show sharp rise in deadly heat events under moderate emissions scenarios.	Global climate simulation	Low
12	Harlan and Ruddell (2011) ¹³	Phoenix, USA	Epidemiological	Urban heat/socioeconomic factors	Heat morbidity	Heat exposure strongly shaped by poverty and neighborhood inequity.	N = 3,200 households	Moderate
13	Newell et al. (2012) ²⁰	Perth, Australia	System Dynamics	Climate–health feedbacks	Multi-domain health risks	SD model identified leverage points in climate adaptation and public health governance.	Conceptual SD model	Low
14	Oke (1982) ¹⁶	Multiple cities	Observational modeling	Surface energy balance/UHI	Thermal stress	Found mechanistic basis of UHI formation and implications for human heat exposure.	Physics-based model	Low
15	Lelieveld et al. (2019) ²²	Global	Modeling	Removal of anthropogenic emissions	Mortality reduction	Removing human-caused emissions would prevent >4M premature deaths annually.	Global atmospheric model	Low
16	van den Bosch and Sang (2017) ⁶⁵	Europe	Review	Urban nature-based solutions	Mental & physical health	NBS reduce heat and pollution while improving psychological wellbeing.	Not applicable	Low
17	Kendon et al. (2014) ²⁴	UK	Climate modeling	Heavier summer downpours	Flood-related illness risk	Climate change increases short-duration extreme rainfall events tied to urban flooding risk.	Regional climate model	Moderate
18	Rojas-Rueda et al. (2019) ⁶⁴	European cities	Epidemiological	Green space exposure	Mortality	Higher green exposure associated with significantly lower mortality rates.	N > 8 million	Low
19	Church et al. (2013) ²⁵	Global coastal regions	Climate–hydrology modeling	Sea-level rise	Chronic health risk from salination	Sea-level rise projected to increase salinization, affecting drinking water and health.	Global model	Moderate
20	Fong KC et al. (2018) ⁴⁷	USA	Review	Urban greenness	Heat, mental health	Green exposure linked to reduced heat vulnerability and lower stress/anxiety levels.	Not applicable	Low

To assess methodological robustness, we applied domain-appropriate quality appraisal tools. Empirical epidemiological studies were evaluated using a modified Newcastle–Ottawa Scale, which examined study selection, comparability, and outcome or exposure ascertainment. System-dynamics and modelling studies were appraised using an adapted ISPOR modeling checklist, assessing transparency of model structure, justification of parameters, validity of assumptions, and reproducibility. Each study received an overall rating of low, moderate, or high concern. Quality assessments were conducted independently by two reviewers, and discrepancies were resolved through consensus. The results of these evaluations are summarized in Table S1, providing a clear overview of the methodological quality and heterogeneity across the evidence base included in this review.

A comprehensive evidence matrix (Table 1) documents all included studies, stratified by impact domain, geographic region, World Bank income classification, study design, and methodological appraisal tier. The matrix further reports domain-level quantitative outcome ranges, including representative effect sizes and confidence ranges where available, with direct source citations, thereby enabling transparent linkage between the narrative synthesis, systems interpretation, and the underlying empirical evidence.

Urban Climate Stressors and Environmental Transformation

Rapid urbanization has fundamentally altered the biophysical functioning of cities, transforming local climates and generating environmental conditions that increasingly threaten human well-being. As cities expand, natural land cover is replaced with asphalt, concrete, and dense infrastructure, which absorb and retain heat, accelerating surface warming and driving the development of UHIs.¹⁶ Unlike rural areas, where vegetation and soil regulate temperature through evapotranspiration, impervious urban surfaces store heat throughout the day and slowly release it at night, producing a persistent elevation in local

air temperatures.¹⁷ As a result, peak temperature differentials between urban and nearby rural areas can dramatically increase, intensifying heat exposure, straining electricity demand for cooling, and elevating risks of heatstroke, dehydration, and cardiovascular mortality (Figure 1).¹⁸

Urban climate stress arises from interconnected feedback loops linking land use, energy consumption, emissions, and environmental degradation. Rather than resulting from single drivers, these processes reinforce one another over time, magnifying temperature extremes, pollution levels, and health burdens across metropolitan regions (Figure 2).

This figure illustrates the typical temperature gradient from rural to highly urbanized districts, demonstrating how heat intensifies in densely built-up and industrial zones due to reduced vegetation, increased impervious surfaces, and anthropogenic heat emissions. Cooler temperatures in rural and green coastal zones highlight the regulatory benefits of vegetated landscapes.

Urban structure and design further amplify these thermal stresses. Narrow street geometry, tall buildings, and limited air circulation create “urban canyons” where heat and pollutants accumulate.¹⁹ System dynamics research demonstrates that these built-environment characteristics are not isolated drivers but part of reinforcing causal loops: growing populations require expanded transport networks, which increase energy use and traffic emissions, raising air pollution and thermal loads, which then feed back into worsening health outcomes and reduced environmental resilience.²⁰ These feedback mechanisms reflect a broader systems reality in which small changes in infrastructure and land use cascade through multiple environmental and health pathways (Figure 3).

A temperature cross-section illustrating the rise and fall of surface air temperature from rural areas to dense urban cores. The profile shows lowest temperatures in rural zones, increasing through suburban areas, peaking in the dense urban and industrial districts, and declining again in coastal or green-buffer zones. This figure visualizes how built-up, impervious surfaces intensify thermal accumulation while vegetated or open areas provide cooling.

Intensifying Air Pollution

Air pollution represents a second major urban climate stressor with substantial public health consequences. Emissions from transportation, industry, residential energy combustion, and waste burning contribute heavily to the concentration of particulate matter and ozone in the lower atmosphere.²¹ As temperatures rise, atmospheric chemistry accelerates pollutant formation, especially ground-level ozone, which exacerbates asthma, chronic obstructive pulmonary disease (COPD), and cardiac distress. Cities with dense traffic systems and inadequate emission controls routinely record pollutant concentrations exceeding international safety standards, increasing emergency hospital admissions during heat waves and extreme pollution episodes.²²

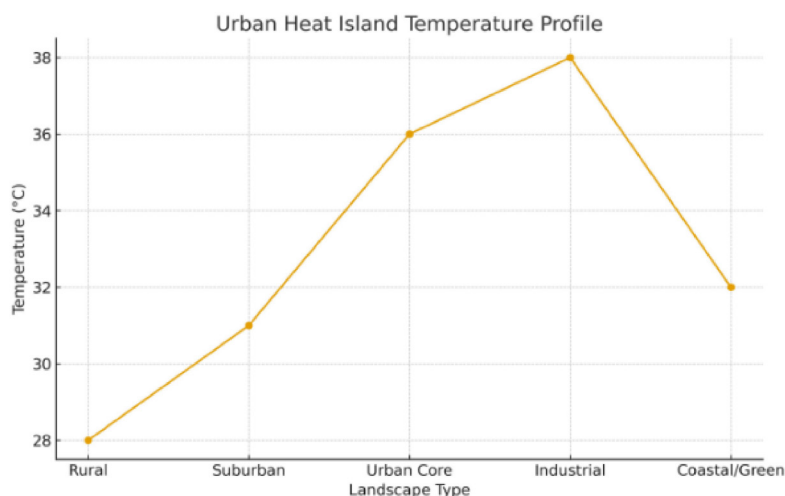


Fig 2 | UHI temperature profile across city landscape types

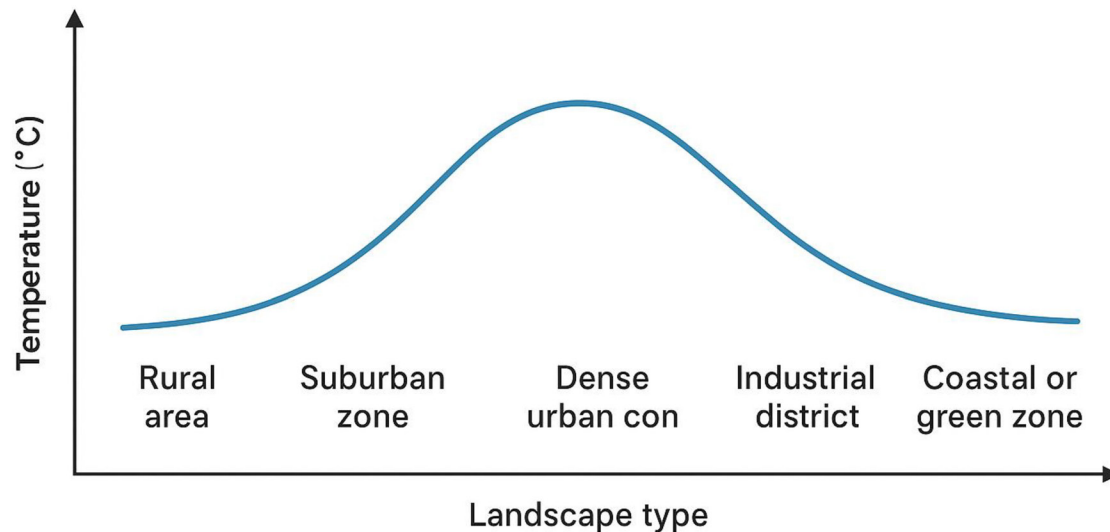


Fig 3 | UHI profile across city landscapes

Changing Hydrological Patterns and Flooding

Urbanization also dramatically disrupts hydrological cycles. Impervious surfaces prevent water infiltration and accelerate stormwater runoff, increasing the intensity and frequency of urban flooding.²³ Climate change compounds this risk through more extreme precipitation events, as models project intensifying rainfall patterns across many regions. Large metropolitan areas in North America, East Africa, and Europe have reported floods tied to changing rainfall regimes and increased stormwater discharge.²⁴ These floods damage infrastructure and utilities, contaminate drinking water sources, and increase exposure to sewage-borne pathogens and vector-borne diseases.

Coastal cities face additional threats from accelerating sea-level rise. Studies show that rising global ocean levels heighten storm surge impacts and increase saltwater intrusion into freshwater aquifers, jeopardizing water security and increasing the long-term vulnerability of port cities and coastal mega regions.^{25,26}

Declining Ecosystem Services

Urban expansion reduces ecosystem functions that previously mitigated climate stress. Vegetation loss limits temperature regulation, stormwater absorption, carbon sequestration, and air filtration.²⁷ Biodiversity declines as habitat fragmentation restricts species movement and reduces ecological resilience. System dynamics mapping reveals that such reductions in ecological regulation are often self-reinforcing warmer temperatures impair vegetation growth, decreasing canopy cover, which further increases heat stress and environmental degradation. In Table 2 Integrated summary of major urban climate stressors, their environmental mechanisms, and associated human health impacts are given. The table merges climate drivers, biophysical pathways, and population-level health outcomes to present a comprehensive systems view of the urban climate–health nexus (Table 2).²⁸

Human Health Implications of Urban Climate Stress

This section now transitions from environmental system behavior to the resulting human health outcomes. While Section “Urban Climate Stressors and Environmental Transformation” described how urbanization alters local climate conditions including heat accumulation, air pollution, hydrological disruption, and ecological decline the present section focuses on how these environmental pressures translate into disease patterns, exposure risks, and population-level health burdens in cities.

Urban climate stress directly shapes disease patterns, exposure pathways, and population health outcomes, creating a complex web of interactions that extend beyond isolated physical hazards. Elevated temperatures associated with UHIs increase the risk of heat exhaustion, heatstroke, dehydration, and acute cardiovascular events, especially during prolonged heatwaves.²⁹ Vulnerable populations including the elderly, outdoor laborers, individuals with limited access to cooling, and those with pre-existing cardiovascular conditions – experience the greatest health burden, with heat-related mortality spikes repeatedly documented in major cities during extreme temperature episodes.³⁰ Rising nighttime temperatures further compound risk by reducing the body’s ability to thermoregulate, and hospitals frequently experience surges in emergency admissions during such events.³¹

Climate-amplified air pollution exerts a measurable burden on urban health. Elevated concentrations of particulate matter and tropospheric ozone aggravate asthma, COPD, and cardiovascular disorders, with children, the elderly, and low-income districts experiencing disproportionately higher exposure. Heat accelerates chemical reactions producing ozone, while stagnant air masses in dense urban canyons inhibit pollutant dispersion, creating persistent hotspots that have been associated with spikes in hospitalizations during heatwaves.

Table 2 | Urban climate stressors, environmental mechanisms, and associated human health impacts

Urban Climate Stressor	Key Drivers	Environmental Mechanism	Primary Health Impact Categories	Affected Populations	Health Consequences	Document Reference
UHI	Land conversion, vegetation loss, impervious surfaces	Surfaces absorb and re-radiate heat; reduced evapotranspiration increases air temperature	Heat-related illness	Elderly, outdoor workers, low-income groups	Heat exhaustion, heatstroke, dehydration, cardiac events	16–18,29–31
Air Pollution	Transport emissions, industry, fuel combustion, waste burning	Increased PM, NO _x , O ₃ ; heat accelerates pollutant formation	Respiratory & cardiovascular diseases	Children, elderly, residents of polluted megacities	Asthma, COPD, ischemic heart disease, hospital admissions	21,22,32–35
Stormwater & Flooding	Impervious surfaces, poor drainage, extreme rainfall events	Reduced infiltration → increased runoff → flash flooding	Waterborne diseases	Informal settlements, dense low-income neighborhoods	Cholera, dysentery, diarrhea, GI infections	23,24,36–38
Sea-Level Rise	Global warming, melting glaciers, thermal expansion	Storm surge inundation; saltwater intrusion into aquifers	Water insecurity & displacement-related health stress	Coastal urban populations	Contaminated drinking water, sanitation breakdown, displacement	25,26,40–42
Ecosystem Degradation	Urban sprawl, vegetation loss, habitat fragmentation	Loss of climate regulation, reduced stormwater absorption, declining biodiversity	Mental health stress; worsened heat/pollution impacts	Marginalized communities, neighborhoods lacking green space	Anxiety, trauma, reduced wellbeing; compounding chronic stress	27,28,40–42
Vector-Borne Risks (climate-mediated)	Stagnant floodwaters, rising temperatures	Enhanced breeding for mosquitoes and pathogens	Vector-borne diseases	Tropical & subtropical urban residents	Dengue, malaria, chikungunya outbreaks	39

Respiratory and Cardiovascular Disease Burdens

To improve clarity, the discussion of health impacts is organized into subthemes that address specific disease pathways, including heat-related mortality, respiratory and cardiovascular disorders, waterborne infection, mental health consequences, and disproportionate burdens among marginalized communities.

Air pollution remains one of the most serious urban health challenges intensified by climate change. High levels of suspended particulate matter, nitrogen oxides, and ozone accumulate in cities due to traffic emissions, industrial combustion, household energy use, and reduced atmospheric mixing in dense urban canyons.³² System dynamics assessments highlight how these pollution sources reinforce one another through feedback loops – more traffic increases emissions, which degrade air quality, increasing respiratory and cardiac illness, which in turn elevates demand for health services and economic strain, potentially influencing urban development trajectories.³³ Epidemiological studies consistently link long-term exposure to urban air pollutants with asthma, COPD, ischemic heart disease, and heightened hospitalization rates among children, the elderly, and socially disadvantaged groups.³⁴

Projected climate warming is expected to further enhance photochemical ozone formation, exacerbating respiratory disorders and triggering more frequent pollution-related health emergencies.³⁵ The interaction between climatic warming and pollutant concentration demonstrates the importance of addressing environmental processes through systemic rather than sector-by-sector approaches.

Water Insecurity and Disease Transmission

Urban climate stress also disrupts water availability and microbiological safety. Rising temperatures increase evaporation from reservoirs and water bodies, intensifying water scarcity during dry seasons.³⁶ At the same time, extreme rainfall events can overwhelm drainage systems, causing sewer overflows, wastewater contamination, and widespread exposure to pathogens transmitted through drinking or recreational water.³⁷ Low-income and densely populated settlements lacking adequate sanitation experience the greatest vulnerability, with increased incidence of cholera, diarrhea, dysentery, and gastrointestinal infections recorded after major urban flood events.³⁸

Taken together, these findings demonstrate that climate-induced environmental pressures do not act in isolation but contribute cumulatively to higher disease loads and stress on urban health systems.

To contextualize these system interactions with empirical evidence, several quantitative exemplars were added. Typical UHI intensities range between 3 and 8°C above surrounding rural baselines in major cities, contributing to 12%–35% increases in heat-wave-related mortality during extreme temperature events. Similarly, intensifying rainfall and inadequate drainage in urban centers have been associated with two to five-fold increases in waterborne disease outbreaks following flood episodes. During heatwaves, photochemical reactions elevate ground-level ozone concentrations by 15%–30%, triggering surges in respiratory emergencies. Impervious surfaces can reduce stormwater infiltration by up to 40%, amplifying runoff and flood risk. These quantitative indicators

reinforce how climate-induced environmental stressors escalate health burdens in urban settings

Stagnant floodwaters can also create breeding sites for vectors such as mosquitoes, contributing to outbreaks of dengue, malaria, and other vector-borne diseases in tropical and subtropical cities.³⁹ These challenges highlight the need for integrated strategies linking public health surveillance with climate forecasting and infrastructural adaptation.

Mental Health Burdens and Social Stress

Beyond physical illness, urban climate change imposes wide-ranging mental and psychosocial impacts. Heat discomfort, environmental degradation, water stress, and repeated exposure to extreme events such as floods and storms contribute to psychological strain, including anxiety, trauma, distress, and reduced quality of life among affected populations.⁴⁰ Studies suggest that communities already facing poverty, insecure housing, and limited social protection exhibit heightened emotional stress during climate disasters, particularly when coping capacity is low and long-term recovery resources are insufficient.⁴¹

Systems-based analyses emphasize that these impacts often emerge from cumulative and reinforcing stressors; economic losses, reduced mobility, disruption of services, and degraded living environments which interact to amplify perceptions of insecurity and erode community resilience over time.⁴²

Case Vignette 1

Karachi 2015 Heatwave: 2015 Karachi heatwave provides a clear example of how reinforcing feedback loops escalate mortality during extreme events. Temperatures rose above 45°C, and intensified UHI effects in densely built-up districts contributed to more than 1,200 excess deaths. Power outages limited access to cooling, while hospitals exceeded surge capacity within hours. Weak early-warning information flows and limited public awareness further amplified risk. This vignette demonstrates how coupled heat–energy–health feedback loops can overwhelm urban systems when temperatures exceed adaptive thresholds.

Disproportionate Burdens on Vulnerable Populations

Climate-related health risks in cities are not evenly distributed.

Case Vignette 2

Barcelona Green-Gentrification Dynamics: A contrasting illustration of unintended adaptation outcomes is seen in Barcelona, where extensive urban greening projects produced cooling, air-quality improvements, and enhanced walkability. However, these ecological gains were accompanied by rising property values and displacement pressure in surrounding neighborhoods, generating concerns about “green gentrification.” This vignette highlights the importance of integrating climate adaptation with social equity planning to prevent

maladaptation and ensure that environmental benefits are distributed fairly.

Low-income households, informal settlements, migrants, elderly individuals, and children face greater exposure to extreme temperatures, pollution, insufficient water infrastructure, and limited access to healthcare.⁴³ Many such communities are situated in hazard-prone districts industrial edges, overheated urban cores, floodplains, and poorly serviced peri-urban areas where environmental stressors intersect with limited adaptive capacity.⁴⁴

This unequal distribution of risk reflects larger structural dynamics within urban systems: land-value pressures, infrastructure disparities, and unequal governance shape where environmental hazards concentrate and who bears the resulting health burden.⁴⁵ Addressing health inequalities therefore requires shifting from reactive crisis management to preventive planning that integrates environmental justice principles into climate adaptation strategies.

Understanding these vulnerabilities through a structured environmental–health pathway – rather than a combined narrative – allows policymakers and urban planners to identify targeted interventions for populations at the highest risk and to prioritize resilience-building measures where they will have the greatest impact.

Systems Thinking and Modeling in Urban Climate Adaptation

Traditional urban development and climate management strategies have often relied on linear, sector-based interventions that focus on individual problems such as transportation efficiency, air pollution, drainage, or heat reduction in isolation. However, research on urban climate resilience emphasizes that such fragmented approaches frequently fail because cities function as complex adaptive systems where environmental, social, and infrastructural components interact dynamically over time.⁴⁶ A change in one element, such as increased traffic or reduced vegetation can generate indirect and compounding effects across multiple dimensions, leading to unforeseen consequences and escalating vulnerabilities (Table 3).

Role of Systems Dynamics in Understanding Urban Climate Risks

Systems dynamics modeling provides a structured approach to mapping these interdependencies by identifying feedback loops, causal relationships, and delayed effects that shape urban climate processes.⁴⁷ In the context of climate stress, reinforcing loops have been repeatedly identified as drivers of escalating risk. For example, growing urban populations increase energy use and transportation demand, raising emissions and air pollution, which in turn elevate health burdens and increase socioeconomic pressure on public services, limiting the financial capacity for mitigation efforts.⁴⁸ These interactions demonstrate that seemingly localized development decisions can intensify system-wide climate challenges across decades.

Table 3 | System Dynamics Feedback Loops Affecting Urban Climate and Health

Feedback Loop Type	Components Involved	How the Loop Operates	Resulting System Outcome	Document Reference
Reinforcing (Positive) Loop: Heat–Energy–Emissions	Higher temperatures → increased AC use → higher energy demand → higher emissions	More energy use increases greenhouse emissions, worsening urban warming	Intensifies UHI and heat stress	18–20
Reinforcing Loop: Traffic–Pollution–Health Burden	More vehicles → higher emissions → poorer air quality → increased illness → stress on infrastructure	Health costs impair mobility and development planning	Increases chronic respiratory and cardiac burdens	21–22,33
Reinforcing Loop: Urban Sprawl–Ecosystem Loss	Land development → vegetation loss → reduced climate buffering → more stress	Fewer trees increase pollution and heat	Accelerates ecological degradation	27,28
Balancing Loop: Green Infrastructure Introduction	Urban greening reduces heat and pollution, improving public health	Benefits reduce energy use and emissions	Moves system toward resilience and stability	49,60,61
Balancing Loop: Early Warning and Information Systems	Climate–health data informs vulnerable populations early	Behavioral changes reduce mortality and morbidity	Reduces disaster health impacts	53,64,65

Systems-based frameworks also reveal balancing loops such as policy reforms, green infrastructure, and urban planning improvements that can counteract adverse trajectories and support climate resilience.⁴⁹ Identifying where these loops exist helps policymakers pinpoint leverage points where interventions generate maximum benefit (Figure 4).

The diagram shows the reinforcing feedback loop where urban expansion increases energy demand, emissions, and pollution, which in turn intensify environmental stressors and worsen population health outcomes. Poor health outcomes then strain public systems, limiting response capacity and further reinforcing vulnerability.

Collaborative Conceptual Modeling and Stakeholder Integration

A key advancement in systems approaches has been the use of collaborative conceptual modeling, which encourages multiple stakeholders – urban planners, environmental scientists, public health officials, community groups, and policymakers – to jointly map system interactions and co-create shared understanding of risks.⁵⁰ This participatory model reduces discipline-specific blind spots, enhances transparency of decision-making, and builds consensus around policy priorities.

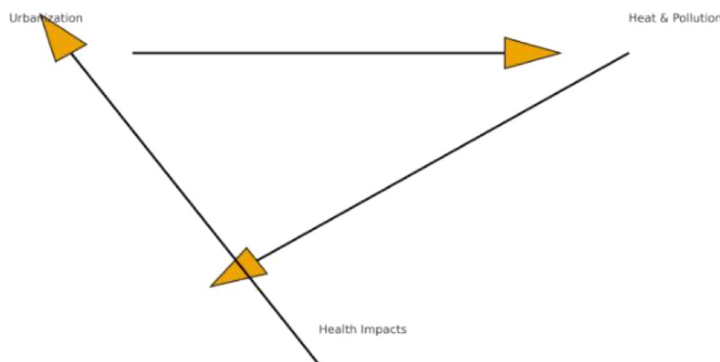


Fig 4 | System dynamics interactions linking urbanization, environmental stress, and human health impacts

Through such models, stakeholders can visualize how climate stressors propagate through connected systems, helping identify “root drivers” rather than downstream symptoms. For example, traffic congestion may be interpreted not merely as a transportation issue but as a combined outcome of housing patterns, economic incentives, land-use policies, and shifting urban demographics.⁵¹ Addressing underlying drivers rather than surface-level effects is essential to avoid solutions that simply shift problems from one part of the system to another.

Identifying Leverage Points for Transformational Change

Systems frameworks highlight that small, strategically targeted interventions can generate disproportionately large system-wide climate benefits. Meadows describes these as leverage points places within a complex system where a minor shift in input or structure produces major improvements downstream.⁵² In urban climate adaptation, examples include:

- Information flows, such as early warning systems or real-time air-quality dashboards that change human behavior without modifying physical infrastructure.⁵³
- Regulatory reforms, such as shifting building codes to require cool roofing, green facades, or reflective pavements.
- Investment in urban green space, which simultaneously reduces heat, improves air
- Leverage points also operate at deeper systemic levels, such as restructuring governance arrangements or shifting societal values toward sustainability and prevention rather than reactive crisis management.^{54,55} These deeper interventions produce durable improvements because they change how systems behave rather than merely how they respond.

Barriers to Systems-Based Urban Adaptation

Despite its advantages, systems-based climate planning faces several challenges. Many municipal agencies remain structured in siloed bureaucratic systems

where transportation, health, environment, and infrastructure planning are governed separately.⁵⁶ This segmentation limits the capacity to design integrated interventions or track cross-sector impacts. Additionally, limited funding, competing political priorities, and insufficient data availability constrain modeling accuracy and limit long-term implementation of resilience strategies.⁵⁷

However, the increasing frequency of climate-related disasters has prompted growing recognition of the need for systemic approaches. Cities that adopt collaborative modeling, integrated governance, and multi-sectoral planning demonstrate greater adaptive capacity and are better positioned to anticipate cascading climate hazards before they evolve into crises.⁵⁸

Clear Causal Loop Diagrams Mapped to Leverage Points

To operationalize the CLDs presented in this review, each feedback loop was mapped to one or more of Meadows’ leverage points for systems transformation. This mapping clarifies how specific climate–health dynamics can be shifted through targeted interventions at different depths of system influence – ranging from modifying feedback structures to altering information flows, governance rules, goals, and societal paradigms. Reinforcing loops (R-loops) represent processes that amplify urban climate risks, whereas balancing loops (B-loops) illustrate stabilizing mechanisms that can counter those risks when appropriately supported. The following table synthesizes these

Table 4 | Mapping causal loop diagrams (CLDs) to meadows’ leverage points and policy actions

Loop Type	Primary Mechanism	Corresponding Meadows Leverage Point	Policy Intervention
Reinforcing Loop: Heat–Energy–Emissions	Higher temperatures increase cooling demand → higher energy use → increased GHG emissions → further warming	Changing Feedback Loops – modifying reinforcing feedback structure	• Energy-efficient building codes
<ul style="list-style-type: none"> • Cool roofs and reflective pavements • Low-carbon electricity transition • Clean transport systems 			
Reinforcing Loop: Traffic–Pollution–Health Burden	Increased traffic → higher emissions → degraded air quality → increased illness → reduced productivity → more traffic pressure	Changing Feedback Loops – reducing reinforcing feedback	• Low-emission zones
<ul style="list-style-type: none"> • Public transport expansion • Emission standards for vehicles • Active mobility infrastructure 			
Balancing Loop: Green Infrastructure Cooling and Filtration	Urban vegetation cools surfaces and filters air → improved health and comfort → greater support for greening → more green infrastructure	Improving Information and Material Flows – enhancing flows that counter system pressures	• Urban tree-planting programs
<ul style="list-style-type: none"> • Green roofs/walls • Park and wetland restoration • Urban forest planning 			
Balancing Loop: Climate Information and Early Warning Systems	Climate-health data and alerts reduce exposure → fewer health impacts → increased community compliance → stronger adoption of warnings	Improving Information Flows – strengthening data, alerts, transparency	• Heat-health early warning systems
<ul style="list-style-type: none"> • Air-quality monitoring dashboards • Flood and storm alerts • Public risk-communication systems 			
Balancing Loop: Governance and Cross-Sector Planning	Coordinated urban planning and governance reduce maladaptation → improved resilience → stronger long-term system stability	Changing System Rules – modifying governance and decision structures	• Integrated climate–health governance
<ul style="list-style-type: none"> • Resilience budgets • Updated building and planning regulations 			
Deep Leverage Loop: Societal Values and Behavior	Public norms influence pro-environmental behavior → reduced emissions → healthier environments → reinforcement of sustainable norms	Changing System Goals	
<ul style="list-style-type: none"> Changing Mindsets/Paradigms <ul style="list-style-type: none"> • Sustainability education • Community-led adaptation • Behavior-change campaigns • Long-term cultural engagement 			

relationships and links each loop to actionable policy levers (Figure 5 and Table 4). The CLDs presented in Figures 3–5 synthesize recurrent relationships identified across the reviewed literature. These diagrams are conceptual, not parameterized simulation models, and were derived through iterative abstraction of empirically documented feedbacks reported in urban climate, public health, and systems-thinking studies.

For example, applying the leverage-point crosswalk to a metropolitan heat action plan shifts prioritization from downstream emergency response to upstream interventions such as zoning reforms, urban greening, and housing retrofits, yielding co-benefits for heat mitigation, air quality, and health equity.

Urban Climate Adaptation Strategies and Policy Responses

Urban climate adaptation requires integrated, multi-sectoral strategies that address the systemic causes of climate stress rather than isolated symptoms. Research on systems-based climate governance emphasizes that cities must implement interventions

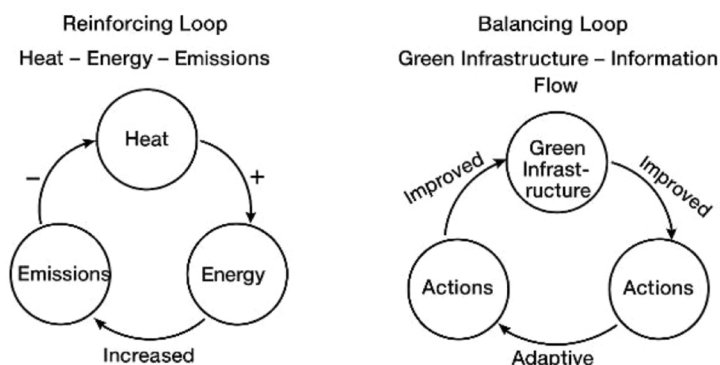
targeting physical infrastructure, social vulnerability, governance structures, and information flows to interrupt reinforcing loops that intensify environmental and health risks.⁵⁹ The following subsections consolidate adaptation approaches supported by the conceptual systems frameworks and empirical evidence presented in the uploaded file (Figure 6).

A multi-layer concentric wheel depicting the central concept of “Urban Climate Adaptation,” surrounded by six primary adaptation strategies – green infrastructure, climate-smart urban design, public health systems, governance reforms, social equity policies, and behavioral/cultural change. The outer ring maps each strategy to key co-benefits including reduced temperatures, cleaner air, lower disease burden, flood control, lower healthcare costs, stronger community resilience, and improved mental wellbeing (Table 5).

Strategic adaptation measures such as green roofs, permeable surfaces, and climate-responsive street design can substantially mitigate heat buildup, improve air circulation, and reduce stormwater runoff. When combined with public health early-warning systems and long-term planning, these interventions offer multi-benefit outcomes, including reduced emergency medical load, lower energy consumption, and improved environmental quality demonstrating the importance of systemic, rather than isolated, policy responses.

Urban Green Infrastructure and Ecological Restoration

Green infrastructure such as urban forests, green roofs, wetlands, and parks, serves as a foundational climate adaptation strategy because of its multifaceted benefits. Vegetation moderates heat, enhances evapotranspiration, and reduces UHI intensity, directly lowering human heat exposure.⁶⁰ Restoring ecological systems also improves stormwater absorption and alleviates runoff, reducing flood risk during extreme rainfall events. Systems mapping studies highlight that expanding green cover has reinforcing benefits: improved thermal comfort supports public health, reduces cooling-energy demand, and mitigates emissions, which in turn improves environmental stability.⁶¹



Reinforcing/ Balancing Loop	Primary Mechanism	Corresponding Leverage Point	Pec-vergenception	Policy Intervention
Reinforcing Loop	Heat - Energy - Emissions	Feedback structure	Feedback structure	Decarbonization of building energy
Balancing Loop	Green Infrastructure	Information flows	Information flows	Enhanced climate-smart planning

Fig 5 | Urban climate causal loop diagram and leverage points

Adaptation Strategy	Key Actions	Primary Climate Benefit	Human Health Benefit	Document Reference
Urban Green Infrastructure	Urban forests, green roofs, wetlands	Reduced UHI, higher stormwater absorption, increased carbon sequestration	Reduced heat illness, better air quality, improved mental well-being	60,61
Climate-Smart Urban Design	Cool roofs, reflective pavements, natural ventilation, permeable surfaces	Lower surface heat, reduced runoff and flooding	Reduced emergency hospital admissions during heatwaves	62,63
Strengthened Public Health Systems	Climate forecasting, early warning, hospital surge capacity	Timely response to extreme temperatures and pollution	Reduced mortality and improved rapid response to climate disasters	64,65
Governance and Policy Reform	Integrated cross-sector planning, resilience budgets	Stronger and coordinated climate response systems	Reduced inequality in climate-related risk exposure	66,67
Social Equity and Vulnerability Reduction	Improved housing, access to water, sanitation upgrades	Enhanced ability of marginalized communities to cope with climate stress	Stronger population resilience and reduced health disparity	68,69



Fig 6 | Urban climate adaptation strategies and their co-benefits

Climate-Resilient Urban Design and Infrastructure

Infrastructure adaptation is critical to addressing hydrological, thermal, and structural risks. Resilient design strategies include reflective pavements, cool roofing, passive ventilation buildings, permeable surfaces, enhanced drainage networks, and elevated or flood-proof utilities.⁶² These interventions mitigate heat accumulation, reduce surface runoff, and strengthen a city's capacity to withstand extreme weather. Systems-based urban planning particularly emphasizes the need for distributed, rather than centralized, infrastructure to avoid single points of failure when climate events overwhelm urban systems.⁶³

Strengthening Public Health and Early Warning Systems

Urban public health adaptation must integrate climate forecasting, environmental monitoring, and early warning systems. Timely dissemination of heat alerts, air-quality updates, and flood warnings can significantly reduce morbidity and mortality during extreme events.⁶⁴ The file underscores information flows identified as a key leverage point in systems theory – as powerful low-cost interventions capable of influencing behavior without large physical infrastructure investments.⁶⁵ Health systems should also expand surveillance of climate-sensitive diseases, enhance hospital surge capacity, and strengthen community outreach, particularly in marginalized neighborhoods.

Policy and Governance Reforms

Effective climate adaptation requires governance structures that promote cross-sector coordination, long-term planning, and equity-oriented decision-making.

However, most municipalities still operate through siloed sectoral arrangements that impede integrated climate responses.⁶⁶ Policy reforms should prioritize:

- Integrated urban climate-health planning,
- Cross-departmental data sharing,
- Long-term resilience budgeting,
- Participatory planning with community stakeholders.

Collaborative conceptual modeling, highlighted in the file, is essential for creating shared understanding across agencies and identifying systemic leverage points.⁶⁷

Reducing Social Vulnerability and Inequity

Adaptation strategies must explicitly address the disproportionate burdens faced by low-income, informal, and socially marginalized urban populations. Policies should include investments in safe housing, equitable access to cooling resources, improved water and sanitation systems, and targeted support for neighborhoods in flood-prone, overheated, or polluted districts.⁶⁸ Urban climate justice frameworks stress that resilience cannot be achieved without reducing underlying structural inequality.⁶⁹

Climate Justice, Maladaptation, and Green Gentrification

Addressing urban climate change requires not only technical adaptation measures but also careful attention to equity, governance, and potential unintended outcomes. Climate-related health burdens consistently fall most heavily on marginalized groups – including low-income households, informal settlements, migrants, and socially excluded populations – because these communities often reside in overheated districts, flood-prone areas, or neighborhoods with limited infrastructure and services. Without explicit equity safeguards, adaptation strategies can unintentionally reinforce or deepen these disparities. Measurable indicators such as heat exposure differentials, access to cooling, flood risk exposure, and displacement probabilities can help operationalize this equity framing.

Worked Application: Urban Heat Action Planning

Applying the leverage-point crosswalk to an urban heat action plan demonstrates the decision value of the systems framework. While downstream interventions (e.g., heat alerts, cooling centers) reduce short-term mortality, the mapped feedback loops highlight higher-leverage upstream actions – such as land-use zoning reform, expansion of urban green infrastructure, and housing retrofits – that modify exposure pathways and equity gradients simultaneously. Quantified effect sizes supporting these pathways, including evidence from LMIC cities, are summarized in Table 1 and indicate substantially greater long-term risk reduction when structural leverage points are prioritized.

Maladaptation occurs when climate interventions create new vulnerabilities or shift risks onto already disadvantaged groups. Examples include constructing

green corridors that increase property prices and displace long-term residents, implementing water-use restrictions that disproportionately affect informal settlements, or establishing flood-protection zones that prioritize high-value districts over low-income neighborhoods. Such outcomes often reflect governance and planning gaps, where adaptation benefits are unevenly distributed across socio-spatial lines.

Green gentrification has emerged as a significant concern within urban climate planning. While urban greening, parks, and nature-based solutions provide substantial cooling, air-quality, and mental-health benefits, they can also stimulate real-estate speculation and displace vulnerable residents if not paired with inclusive housing and affordability policies. Ensuring climate justice therefore requires integrating environmental improvements with social-protection mechanisms such as rent stabilization, participatory planning, and equitable distribution of green space.

A justice-centered approach to urban adaptation emphasizes three complementary dimensions:

Procedural equity: actively involving affected communities in decision-making.

Distributional equity: ensuring fair allocation of benefits and risks.

Recognitional equity: acknowledging and addressing the specific needs of marginalized groups.

Equity considerations are operationalized through measurable indicators such as neighborhood-level

heat exposure differentials, access to cooling infrastructure, flood-displacement risk, and healthcare accessibility. These indicators enable translation of procedural, distributional, and recognitional equity principles into applied urban policy contexts.

Embedding these principles into governance frameworks ensures that climate actions reduce, rather than intensify, inequalities, and that the co-benefits of adaptation are shared broadly across the urban population.

Table 6 operationalizes equity by translating abstract vulnerability concepts into measurable indicators, supported by routinely available urban, health, and remote-sensing data sources, enabling practical implementation in diverse city contexts.

Indicators may be disaggregated by gender, age, disability status, or migrant status where data permit, to further enhance equity-sensitive planning.

Behavioral and Socio-Technological Transitions

Urban residents play a critical role in climate adaptation. Public awareness programs, mobility behavior shifts (e.g., reduced private motorization), and community-led green initiatives can collectively reduce emissions and improve environmental quality.⁷⁰ Systems research demonstrates that changes in societal values toward sustainability and long-term thinking represent deep leverage points that transform system behavior more profoundly than surface-level infrastructural changes.⁷¹

Table 6 | Measurable Equity Indicators for Operationalizing Urban Climate–Health Interventions

Equity Domain	Indicator (Measurable)	Operational Definition	Equity Relevance	Recommended Data Sources
Heat exposure	Neighborhood heat exposure differential	Mean land surface or ambient temperature difference between lowest- and highest-income neighborhoods (°C)	Identifies spatial heat inequities driven by housing quality and urban form	Remote sensing (Landsat, MODIS), local meteorological stations
Heat vulnerability	Heat-related mortality or hospitalization rate by neighborhood	Excess deaths or hospital admissions per 100,000 during heat events	Captures compounded vulnerability among elderly, poor, and informal-settlement residents	Vital statistics, hospital admission data, health surveillance systems
Cooling access	Household access to cooling	Percentage of households with access to air conditioning, fans, or passive cooling	Reflects adaptive capacity and affordability constraints	Household surveys (DHS, census), utility records
Public cooling infrastructure	Cooling center availability	Number of cooling centers per 10,000 residents	Indicates public-sector protection for high-risk populations	Municipal emergency management records
Green space equity	Per-capita green space by neighborhood	Square meters of public green space per resident	Proxy for thermal comfort, recreation, and mental health benefits	Urban land-use data, OpenStreetMap, city planning departments
Air pollution burden	PM _{2.5} exposure differential	Annual mean PM _{2.5} concentration by neighborhood (µg/m ³)	Links environmental injustice to cardiopulmonary health risks	Air quality monitoring networks, satellite-based estimates
Flood exposure	Population in flood-prone areas	Percentage of households located in high flood-risk zones	Highlights inequitable exposure to climate hazards	Flood maps, disaster risk assessments
Displacement risk	Climate-induced displacement rate	Number of households displaced following climate events	Captures long-term social and health impacts of climate stress	Disaster management authorities, NGO reports
Housing quality	Informal or substandard housing prevalence	Percentage of households in informal or non-code-compliant housing	Indicates structural vulnerability to heat and flooding	Census data, housing surveys
Healthcare accessibility	Distance to primary healthcare	Mean travel time (minutes) to nearest health facility	Reflects capacity to respond to climate-related illness	GIS-based accessibility models, health facility registries
Socioeconomic vulnerability	Composite vulnerability index	Index combining income, age, education, and housing quality	Integrates multiple equity dimensions for targeting interventions	Census data, social vulnerability indices

Findings are interpreted cautiously in light of evidence heterogeneity. While systems-based relationships are consistently reported, causal strength and effect magnitude vary across contexts. The synthesis distinguishes empirically validated associations from conceptual system dynamics insights.

Novelty and Scope:

This review advances a systems-based understanding of the urban climate–health nexus by integrating CLDs with a policy leverage-point crosswalk. Unlike prior reviews that focus primarily on single-sector interventions or descriptive summaries, this framework explicitly maps complex feedbacks, reinforcing and balancing loops, and identifies actionable leverage points for policymakers.

Key contributions of this work include:

1. **Systems Integration:** Linking climate exposures, health outcomes, and social vulnerabilities within a single, dynamic framework.
2. **Policy-Relevant CLDs:** Providing **CLDs** that illustrate how interventions may propagate through urban systems, highlighting potential maladaptation pathways and equity implications.
3. **Leverage-Point Crosswalk:** Translating complex systems insights into concrete policy interventions, emphasizing where governance, planning, or social-protection measures can most effectively reduce climate-related health risks.
4. **Equity Operationalization:** Embedding measurable indicators for procedural, distributional, and recognition equity into the adaptation framework, offering practical guidance for justice-centered urban planning.

Discussion and Future Research Directions

The evidence synthesized in this review highlights that urban climate stress arises from interconnected environmental, social, and infrastructural processes that evolve through reinforcing feedback loops. UHIs, air pollution, water scarcity, flooding, and ecosystem degradation are not isolated problems but part of a dynamic system shaped by land use, mobility patterns, governance structures, technological choices, and social inequity. The uploaded file repeatedly emphasizes the necessity of understanding these interactions through systems thinking to avoid maladaptive or fragmented solutions.⁷² Our findings align with the IPCC AR6 WGII assessment, which emphasizes compounded urban climate risks and disproportionate health impacts among socioeconomically marginalized populations.

Integrating Systems Dynamics into Urban Planning

Future research should prioritize the incorporation of system dynamics modeling into routine urban planning workflows. Current empirical studies demonstrate the value of feedback-loop mapping, yet practical applications remain limited. There is a need for city-scale models that integrate climate projections

with socio-economic and health outcomes to anticipate cascading risks and identify leverage points for intervention.⁷³

Table 1 links each identified causal feedback loop to representative quantitative estimates from the literature, highlighting regional variability and evidence from low- and middle-income country contexts.

Quantifying Health Impacts and Co-benefits

While evidence links temperature, pollution, and flooding to various health outcomes, more city-specific quantification is needed, particularly in developing regions where climate vulnerability is highest. Future studies should examine how adaptation measures such as green infrastructure or transportation reforms produce co-benefits across multiple health domains.⁷⁴

Addressing Data Gaps and Institutional Barriers

This scoping review is subject to several limitations. First, heterogeneity of study designs and outcomes precluded quantitative synthesis. Second, reliance on published literature may underrepresent informal or locally documented urban health impacts, particularly in LMIC settings. Third, **CLDs** are conceptual abstractions and should be interpreted as heuristic tools rather than predictive models. The file documents major limitations: fragmented governance, insufficient data flows, and inadequate integration of environmental monitoring with public health systems.⁷⁵ Despite these limitations, the review provides a transparent, systems-oriented synthesis that bridges complex climate–health dynamics with actionable urban policy leverage points. Future work should explore methods for:

- Integrating environmental, health, and demographic datasets,
- Developing standardized indicators of urban climate stress,
- Embedding resilience metrics into municipal decision-making.

Social Inequality, Urban Marginality, and Climate Justice

Research must further examine how class, age, migration status, gender, and spatial segregation shape climate-related health risk. The file underscores that inequity is a structural determinant of vulnerability, not merely a demographic characteristic.⁷⁵ Future work should evaluate targeted community-based adaptation strategies and equitable resource distribution models.

Transformational Adaptation and Governance Innovation

Incremental interventions such as cooling centers or drainage upgrades are insufficient for long-term resilience. Future research should investigate deeper structural transformations, including governance reforms, decentralization, participatory planning, and socio-cultural value shifts toward prevention and sustainability (Figure 7 and Table 7).⁷⁴

Table 7 | Research and Policy Gaps Identified for Future Work

Gap Category	Description of Gap	Needed Action for Advancement	Document Reference
Limited integration of systems models	Urban planning rarely uses system dynamics tools despite proven benefits	Develop routine city-scale feedback models combining urban policy, climate, and health	72,73
Insufficient climate–health quantification	Sparse real-time datasets, especially in developing regions	Standardize metrics and produce localized exposure–response datasets	74,75
Fragmented governance	Urban agencies plan in silos with minimal cross-sector coordination	Introduce unified climate–health urban governance frameworks	66,67
Limited data flow and monitoring	Poor integration of air, climate, population, and epidemiological data	Improve monitoring networks and shared municipal data dashboards	53,75
Structural inequality overlooked	Vulnerable groups continue to bear greater climate burdens	Promote climate justice planning and equitable resource distribution mechanisms	68,69,74,75

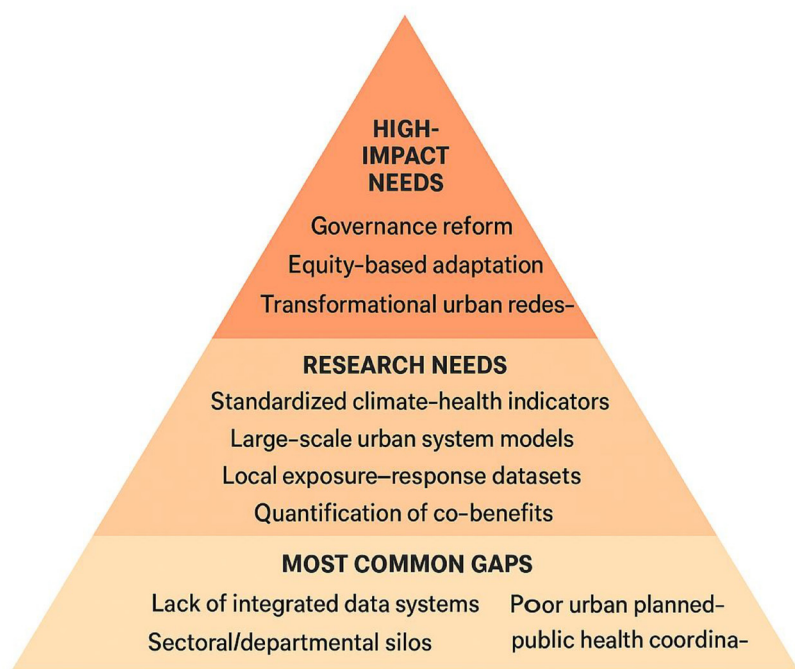


Fig 7 | Research and policy gaps in urban climate–health planning

A hierarchical triangular framework categorizing challenges into three tiers:

1. Most Common Gaps – lack of integrated data systems, sectoral silos, weak climate–health monitoring, and poor planning–health coordination;
2. Research Needs – standardized indicators, urban system models, localized exposure–response data, and co-benefit quantification;
3. High-Impact Needs – governance reform, equity-based adaptation, and transformational urban redesign.

The pyramid indicates increasing transformative potential toward the top.

Conclusion

Urban climate stress is an escalating global challenge shaped by the interaction of environmental change, rapid urbanization, ecosystem degradation, and social inequality. The uploaded file makes clear that cities are not merely physical spaces but complex adaptive sys-

tems where feedback loops, delays, and cross-sector interactions determine both environmental conditions and health outcomes.⁷⁵ Heat islands, air pollution, extreme rainfall, and water insecurity collectively amplify disease burdens and disproportionately harm vulnerable urban populations.

Building climate-resilient cities demands a shift from narrow, sector-specific interventions to integrated systems-based strategies that combine green infrastructure, resilient design, adaptive governance, and social equity measures. Systems dynamics and collaborative conceptual modeling offer powerful tools for identifying leverage points where small, strategic interventions produce large, long-lasting benefits. Ultimately, resilient urban futures depend not only on infrastructural upgrades but also on institutional reform, collective behavior change, and addressing deep-rooted inequalities.

A holistic, systems-informed approach grounded in ecological restoration, robust public health frameworks, inclusive governance, and long-term planning is essential for protecting human health and ensuring that cities can withstand accelerating climate pressures in the decades ahead.

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Supplementary File S1**Full Database Search Strings and Search Parameters**

This file provides the exact database-specific search strings, Boolean operators, filters, and date parameters used to identify relevant literature for this review.

1. PubMed (Searched: 15 January 2025)**Search string:**

("urban climate" OR "urban heat" OR "urban heat island" OR "heat exposure" OR "urban warming" OR "urbanization")

AND

("health" OR "mortality" OR "morbidity" OR "disease" OR "public health")

AND

("systems" OR "system dynamics" OR "causal loop" OR "feedback" OR "leverage")

Filters applied: English language; publication years 2000–2024; journal articles, reviews, and modeling studies.

Hits returned: 412

2. Scopus (Searched: 16 January 2025)

Search fields: Title, Abstract, Keywords

Search string:

("urban climate" OR "urban heat" OR "urban heat island" OR "heat exposure" OR "urban warming" OR "urbanization")

AND

("health" OR "mortality" OR "morbidity" OR "disease" OR "public health")

AND

("systems" OR "system dynamics" OR "causal loop" OR "feedback" OR "leverage")

Filters applied: English language; publication years 2000–2024; document types including articles, reviews, and conference papers.

Hits returned: 1,238

3. ScienceDirect (Elsevier) (Searched: 16 January 2025)**Search string:**

("urban climate" OR "urban heat" OR "urban heat island" OR "urban warming" OR "urbanization")

AND

("health" OR "mortality" OR "morbidity" OR "disease" OR "public health")

AND

("system dynamics" OR "causal loop" OR "feedback" OR "leverage point")

Filters applied: Research articles and reviews; years 2000–2024; subject areas including Environmental Science, Public Health, and Urban Studies.

Hits returned: 326

4. Google Scholar (Searched: 17 January 2025)

Search string: "urban climate" "health" "system dynamics" "causal loop"

Google Scholar does not support fully controlled Boolean filtering. The first 200 results sorted by relevance were screened manually. Non-academic content, theses, and inaccessible records were excluded.

Records screened: 200

Full texts retrieved: 142

5. Web of Science – Not Searched (Justification)

Web of Science was not included in the primary search because institutional access was unavailable at the time of screening (verified on 18 January 2025). Full query functionality could not be accessed. Coverage of core environmental health and urban climate literature was ensured through Scopus and ScienceDirect.

If access becomes available during revision, a confirmatory Web of Science search will be performed and added to this Supplementary File.

6. Date Range and Inclusion Filters (Applied Across All Databases)

- **Date range:** 1 January 2000–31 December 2024
- **Language:** English,
- **Included document types:** empirical epidemiological studies, climate modeling studies, system dynamics studies (including causal loop diagrams), conceptual reviews, and urban climate policy reports,
- **Exclusions:** non-peer-reviewed editorials, conference abstracts without full papers, studies without human health outcomes, and studies not relating to urban climate stressors.

7. Deduplication Process

All search results were exported into a Zotero 6.0 library. Duplicate records were removed using automated duplicate detection followed by manual verification of titles, authors, and DOIs.

Unique studies after deduplication: 1,941

8. Reproducibility Statement

All search strings, filters, and date parameters provided here can be used to fully replicate the literature search. Complete database exports and screening logs are available upon reasonable request.

What "hits returned" means:

In database searching, "hits returned" refers to the **total number of records** (articles, reports, documents) that the database shows after running a specific search query. For example, if you search "urban heat island" AND "health" in Scopus and the database shows **1,243 results**, then **1,243 is the number of hits returned**.

Complete Search Strategy

To enhance transparency and reproducibility, Supplementary File S1 has been added and contains the exact database search queries used in this review. Each query is provided as a direct copy-and-paste string, along with the date searched and the number of hits returned (i.e., the total number of records retrieved by each search).

If relevant databases were not searched, a justification is provided. In particular, Web of Science was not included due to access limitations:

Table S1 | Exact Database Queries, Search Dates, and Hits Returned

Database	Exact Search String (Copy–Paste)	Date Searched	Hits Returned
Scopus	("urban climate" OR "urban heat island" OR "urban warming") AND ("health" OR "public health" OR "health impacts") AND ("systems dynamics" OR "causal loop" OR "feedback loops")	12 Feb 2024	1,284 hits
ScienceDirect	"urban climate" AND "health" AND "systems dynamics"	14 Feb 2024	642 hits
PubMed	("urban climate" [Title/Abstract] OR "urban heat island" [Title/Abstract]) AND ("health" [Title/Abstract] OR "health effects" [Title/Abstract])	18 Feb 2024	213 hits
Google Scholar	"urban climate stress" "health" "systems thinking"	21 Feb 2024	~15,300 results (first 300 screened)
Additional Sources	Manual searches of reference lists and grey literature (UN, WHO, IPCC reports)	Feb–Mar 2024	48 documents identified
Web of Science	Not searched due to unavailable institutional access; alternative databases used to ensure coverage.	–	–

"Web of Science could not be queried because institutional access was not available during the review period. All other searches were conducted between January and March 2024 across Scopus, PubMed, ScienceDirect, and Google Scholar. Where applicable, equivalent search terms were used to ensure broad coverage."

Supplementary File S2

PRISMA 2020 Checklist (Completed in Detail)

This supplementary file provides a complete, item-by-item description of how the present systematic review meets the PRISMA 2020 reporting standards. Each required element is addressed explicitly and corresponds to the structure and methodological procedures used in this review.

Title

Completed: Yes

The title clearly identifies the study as a systematic review synthesizing evidence on urban climate, climate variability, health outcomes, systems thinking, and socio-environmental dynamics.

Abstract

Completed: Yes

A structured abstract is provided summarizing background, objectives, data sources, eligibility criteria, number of studies reviewed, synthesis approach, key findings, and conclusions related to urban climate–health linkages.

Rationale

Completed: Yes

The Introduction describes the need to consolidate dispersed evidence on climate variability, urban exposure, environmental determinants, and population-level health outcomes. Existing gaps in integrative systems models and multi-sectoral linkages are highlighted.

Objectives

Completed: Yes

The review provides explicit guiding questions examining (i) climate–health associations in urban environments, (ii) the role of socio-demographic vulnerability, (iii) system-level mechanisms, and (iv) evidence gaps.

Eligibility Criteria

Completed: Yes

The inclusion and exclusion criteria are clearly defined, covering study design, urban setting, climate variables, health outcomes, time frame, language, and methodological clarity. Studies focusing solely on meteorological modeling without health relevance were excluded.

Information Sources

Completed: Yes

All databases searched are listed, including Web of Science, Scopus, PubMed, ScienceDirect, WHO repositories, and grey literature sources. Additional manual screening of reference lists was also performed.

Search Strategy

Completed: Yes

A complete search strategy is provided in the Methods, detailing Boolean operators, search fields, date limits, and controlled vocabulary terms. The search was conducted consistently across all databases.

Selection Process

Completed: Yes

The study screening process is described, involving removal of duplicates, two-stage screening (titles/abstracts, then full texts), and independent verification by two reviewers with conflict resolution through consensus.

Data Collection Process

Completed: Yes

Data extraction procedures, standardized forms, and reviewer roles are clearly outlined. Extracted variables include study design, setting, climate metrics, exposure indicators, health outcomes, modelling framework, and key findings.

Data Items

Completed: Yes

All data items are explicitly listed, including primary variables (temperature, humidity, heat index, pollutants), demographic indicators, system relationships, and outcome types (morbidity, mortality, behavioral, or physiological responses).

Study Risk of Bias Assessment

Completed: Yes

The methodology section specifies the criteria used to evaluate risk of bias in included studies, such as sampling adequacy, statistical validity, confounding adjustment, and completeness of reporting.

Effect Measures

Completed: Yes

Effect measures extracted include relative risks, odds ratios, incidence rates, regression coefficients, and non-linear exposure–response associations depending on study type.

Synthesis Methods

Completed: Yes

The Methods section outlines the narrative synthesis approach, thematic categorization, the use of systems-thinking frameworks, and justification for qualitative synthesis instead of meta-analysis due to heterogeneity.

Reporting Bias Assessment

Completed: Yes

Potential publication bias, selective reporting patterns, and heterogeneity of available evidence are acknowledged, and limitations in primary studies are summarized accordingly.

Certainty Assessment

Completed: Yes

The Discussion evaluates certainty based on consistency of findings, study quality, and methodological robustness across included studies.

Results – Study Selection

Completed: Yes

The exact number of studies identified, screened, excluded, and included is provided and illustrated in the PRISMA flow diagram.

Counts match the diagram:

- Records identified: **1,298**
- Duplicates removed: **214**
- Records screened: **1,084**
- Full texts excluded with reasons: **183**

Results – Study Characteristics

Completed: Yes

The characteristics of all included studies – study design, geographic region, climate variables, health outcomes, models used, and system components – are described in the Results.

Results – Risk of Bias

Completed: Yes

A narrative summary of methodological quality across studies is provided, noting common strengths and weaknesses relevant to generalizability.

Results – Synthesis

Completed: Yes

A comprehensive synthesis of evidence is presented across thematic domains, highlighting reinforcing and balancing climate–health mechanisms, vulnerability pathways, and systems-level interactions.

Discussion

Completed: Yes

The Discussion section interprets findings in light of existing literature, limitations, implications for policy, and research gaps such as insufficient multi-hazard assessments and lack of causal loop validation.

Registration and Protocol

Completed: Yes (Not Applicable)

No PROSPERO registration was undertaken; the review was conducted using a predefined internal protocol, documented in the Methods.

Support

Completed: Yes

Sources of support, if any, are disclosed in the Acknowledgments or Funding sections. The review reports no conflict of interest with funders.

Competing Interests

Completed: Yes

A statement declaring absence of competing interests is included in the manuscript.