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ORIGINAL SCHOLARSHIP

Determinants and indicators of healthy, climate resilient cities: a scoping review

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ABSTRACT
Cities are major contributors to global greenhouse gas emissions, and urban residents are experiencing escalating health impacts from climate change. It is therefore essential that city planning focuses on creating resilient, healthy built environments. This research explored the key determinants of healthy, climate resilient cities and identified indicators that could inform evidence-based planning internationally. We conducted a scoping review of academic and grey literature on healthy and climate resilient cities indicators. We identified three groups of determinants and indicators: climate hazard-specific, general resilience to climate hazards, and policy-specific. Across these groups, there were 12 categories of determinants, and 371 indicators. There was some consensus about urban heat, air pollution and flood being key climate-related health hazards, and the importance of green space; building quality; access to diverse amenities; low-carbon transport; and policymaking processes that promote urban climate resilience. However, the number and diversity of indicators may provide limited guidance to researchers and policymakers about optimal measures of healthy, climate resilient cities. We highlight specific gaps in current indicators and measurement considerations, including the need to validate indicators for cities internationally. Indicators that measure urban adaptive and transformative capacity are needed to track and guide policy progress towards healthy, climate resilient cities.

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Introduction

Health and climate change are among the most pressing challenges for cities in the twenty-first century, as highlighted in the Sustainable Development Goals (SDGs) (UN General Assembly 2015, Watts et al. 2015, 2021, van Daalen *et al.* 2024). The World Health Organization reports that 23% of the deaths globally are linked to people's living environments (Prüss-Üstün *et al.* 2016). Urban environments – where the majority of people now reside – present both health risks and opportunities through their built environments (e.g. housing, transport, parks) and non-built factors (e.g. employment, education) (Pineo *et al.* 2018). Urban environments are responsible for 75% of global energy-related greenhouse gas emissions, making cities a key driver of the health impacts of climate change (Frumkin and Haines 2019).

Climate change affects human health through multiple pathways (Li *et al.* 2020). Direct and indirect impacts include climate-related illnesses (e.g. water-, food-, and vector-borne diseases, cardiovascular disease), injuries and deaths from extreme weather, involuntary displacement, physical damages to buildings, and income losses (IPCC 2022, Thompson *et al.* 2023, Skevaki *et al.* 2024, van Daalen *et al.* 2024). Such factors threaten both physical and mental health and can have cascading and compounding effects, especially on vulnerable populations (IPCC 2022, van Daalen *et al.* 2024), which can exacerbate existing social and health inequities in urban areas (Friel *et al.* 2011, Badland and Pearce 2019, Freitas *et al.* 2020, Khanal *et al.* 2022). It is therefore essential for city planning to focus on enhancing urban resilience in the face of climate change-related environmental hazards that impact health (Ferguson *et al.* 2020, United Nations Environment Programme & International Science Council 2024). These include hazards that exacerbate climate change (e.g. light pollution, solid waste) and those that are

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a consequence of climate change (e.g. heatwaves, storms, floods) (IRDR 2014, UNDRR 2020, IPCC 2023).

Building urban climate resilience has emerged as a multisectoral approach to address climate change through mitigation and adaptation. Although a single, universally accepted concept or definition of urban resilience does not exist (Meerow *et al.* 2016), it has recently been defined as 'the capacity of individuals, communities, institutions, businesses, and systems within a city to adapt, survive and thrive no matter what kind of chronic stresses and acute shocks we experience, and to positively transform as a result' (Lowe *et al.* 2024, p. 7). This definition reflects more recent evolutionary understandings of resilience that extend beyond the traditional notion of 'bouncing back' to a pre-disaster state. Instead, it emphasizes the capacity of urban systems to adapt and transform in ways that optimise human and planetary health (Wilkinson 2011, Meerow and Stults 2016). In this context, transformative capacity refers to the ability 'to cross thresholds into new development trajectories' (Folke *et al.* 2010, p. 20), delivering systemwide change towards healthy and climate resilient cities, at scale (UNFCCC 2024).

Climate resilient cities offer numerous health benefits by promoting active, low-carbon urban lifestyles, and enhancing the ability of residents to survive, adapt, and thrive amidst climate-related shocks and stresses (World Health Organization 2021, 2022, Giles-Corti *et al.* 2022, IPCC 2022). In addition, healthy and thriving urban populations contribute to resilience. The built environment can play a key role in reducing the risks of non-communicable and infectious diseases, mitigating greenhouse gas emissions and limiting the impacts of extreme weather events and coastal flooding (IPCC 2022). For example, urban green spaces can help cool cities during heatwaves, and provide additional health benefits through supporting physical activity, improving air quality, and offering contact with nature (Nieuwenhuijsen 2020, Iungman *et al.* 2023). While resilience to specific climate change-related hazards such as urban heat or flooding is important, general resilience focuses on the capacity of cities to adapt to and respond to all known or unknown disruptions, including those associated with climate change (Meerow and Newell 2019, Lowe *et al.* 2021).

However, promoting urban climate resilience can sometimes create unintended conflicts with health objectives. For example, while public transport systems support healthy lifestyles, they are vulnerable to extreme weather events (Bolte *et al.* 2023, Gössling *et al.* 2023). Due to the interconnectedness of urban health and climate change resilience, it is imperative to adopt a holistic approach to integrating these concepts, with a focus on maximising co-benefits and minimising potential trade-offs (Sharifi *et al.* 2021, Simpson *et al.* 2021).

Evidence-based and transformative planning policies are necessary for achieving healthy and sustainable development (Giles-Corti *et al.* 2022). Utilising indicators to measure how policies and built environment features (e.g. transport, energy use, air quality, urban greening, housing) support healthy, climate resilient cities provides valuable insights for planning and prioritisation, and enables ongoing progress monitoring (Lowe *et al.* 2015, Giles-Corti *et al.* 2022).

There has been increasing interest in the development and use of indicators to measure aspects of urban environments and health (Pineo *et al.* 2018, Davern *et al.* 2023). Many of these indicator frameworks focus on urban sustainability, exemplified by the global effort to localise UN SDG indicators across cities worldwide (HLPF-UN 2024). Other indicators address determinants of urban health and liveability (Boeing *et al.* 2022; Lowe *et al.* 2022; Pineo *et al.* 2018; WHO 2010), while some measure urban resilience specifically (ARUP 2014, Wardekker *et al.* 2020). Rothenberg *et al.* (2015) notes a lack of standardization among the various indicator collections developed by international organisations such as the WHO, UN-Habitat, and the World Bank, as well as regional frameworks like those from the US Department of Health and Human Services. A 2022 *Lancet Global Health* Series on Urban Design, Transport and Health called for the development of additional policy and spatial indicators of climate resilient cities (Giles-Corti *et al.* 2022). However, comprehensive reviews of current indicators that can be used to assess the health and climate resilience of urban areas are lacking.

To fill this gap, we aimed to identify key determinants of healthy, climate resilient cities and examine how these determinants have been measured. The study sought to address the following research questions:

- What determinants of healthy, climate resilient cities are measured in the literature?
- What existing measures or indicators have been used to assess these determinants of healthy, climate resilient cities?

This review was designed to inform the selection and development of indicators that could be calculated for cities internationally, to enhance the ability to comprehensively benchmark and monitor cities. Further, by helping to clarify the concepts and determinants of healthy and climate resilient cities, this review was undertaken to inform a risk-based decision support system for delivering healthy, climate resilient cities.

Methods

A scoping review methodology was used to identify and summarise existing research on indicators and determinants of healthy and climate resilient built environments. This review followed the PRISMA process for scoping reviews (PRISMA 2018).

Search strategy

We developed lists of keywords and their synonyms in four relevant categories: built environment and city planning; climate resilience; health; and indicator (Table 1). These keywords were selected based on the research questions and an initial scoping of relevant articles to determine the most commonly used keywords and synonyms. Appropriate combinations of these keywords were entered into the Scopus database in July 2023 to search for peer-reviewed, scholarly literature published since 2009. First, a broad search query including all search terms was used to identify relevant review articles. Second, a narrower search query was used to find research studies that defined or included indicators for healthy, climate resilient cities. Given the broad nature of the research topic and large number of potentially relevant papers, for feasibility, this more targeted search with fewer search terms was used to identify the most relevant research articles. Reference lists were screened to find additional promising articles. Reputable grey literature was identified by using the same keyword categories in knowledge repositories of relevant research centres, associations and institutions, including WHO, the United Nations, Rockefeller Foundation, Federal Emergency Management Agency (FEMA) and the OECD along with subject-related searches in the Google search engine.

Literature selection

Titles and abstracts were initially screened for relevance to the research questions. Promising papers were then retrieved in full-text and further reviewed against the inclusion and exclusion criteria (Table 2). We included literature published since 2009, as this aligned with the time when the health impacts of climate change and climate resilience began receiving increased attention. For example, resilience became a central theme for the United Nations in the early 2000s, as reflected in the 'Hyogo Framework for Action: Building the Resilience of Nations and Communities to Disasters' (United Nations Specialised Conferences 2005). Meanwhile, *The Lancet* published its first report from the commission on climate change and health in 2009 (Costello *et al.* 2009).

Data extraction and analysis

Based on the aim and scope of research, the following details from the included literature were extracted into a summary table: publication information, study location, study methodology, climate change-related hazards addressed, determinants of healthy, climate resilient cities, and indicators and their data sources.

After extracting the data, inductive thematic analysis was used to categorise the identified indicators according to the determinants of healthy, climate resilient cities that they measured (Willis 2010, Neuman 2011). Aligned with previous urban indicator review methods (Badland *et al.* 2014), the extracted indicators were aggregated into themes or domains (e.g. active transport), and then further grouped into determinant categories (e.g. transport), through an iterative process. The determinants were further analysed in terms of whether they reflected general resilience to all climate change-related hazards or were specific to certain hazards; and how they related to the pathways

Table 1. Keywords used in search queries and their categories.

Built environment and city planning	Climate change resilience	Health	Indicator
• urban environment	• climate change	• health	• indicator*
• land use	• urban resilience	• urban health	• measur*
• transport planning	• climate resilience	• health inequit*	• index
• city planning	• climate change resilience	• health equity	• indice*
• urban planning	• city resilience	• healthy cit*	• benchmark*
• urban policy	• resilient cit*	• public health	• criteria
• built environment	• climate resilient cit*	• population health	• criterion
• spatial planning	• disaster resilience		• model*
• urban design	• sustainability		• monitoring
			• decision support tool

*Indicates truncation used to retrieve all related words with different endings.

Table 2. Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
General inclusion criteria ● Focus on determinants, measures and/or indicators at the nexus of the built environment, health and climate resilience (or resilience to climate change-related hazards) ● Published in English	**General exclusion criteria** ● Publications dated before 2009 ● Opinion piece ● Publications that did not include all three areas of built environment, health and climate resilience (for example urban health or resilience studies without a built environment aspect were excluded) ● Publications that did not mention or include relevant indicators at the nexus of built environment, health and climate resilience
Review articles ● Peer-reviewed review articles	
Research articles ● Peer-reviewed journal articles, books, book chapters and editorials	
Grey literature ● Grey literature from reputable and credible sources	

through which city planning impacts human and planetary health, according to Giles-Corti *et al.* (2022) framework from the *Lancet Global Health* Series on Urban Design, Transport and Health. This framework highlights how policies for a range of urban systems influence the development of built environment features. Through direct and indirect pathways, built environments shape travel behaviours and environmental and health risk exposures, which ultimately determine health and climate resilience outcomes.

Previous research has highlighted the need to measure built environment characteristics and environmental exposure outcomes related to health and climate resilience, as well as the 'upstream' policy determinants and governance considerations, which shape those outcomes (Giles-Corti *et al.* 2020). The indicators identified were categorised as either quantitative and/or spatial indicators, or policy indicators. Policy indicators measure the development, presence and quality of policies that shape healthy, climate resilient cities (Lowe *et al.* 2022). Quantitative indicators numerically measure built environment features or climate change-related hazards and population exposure to these, while spatial indicators are used to assess their distribution and accessibility across a geographical area.

Results

Included literature

The results of the literature selection process are shown in the PRISMA flowchart (Figure 1). In total,

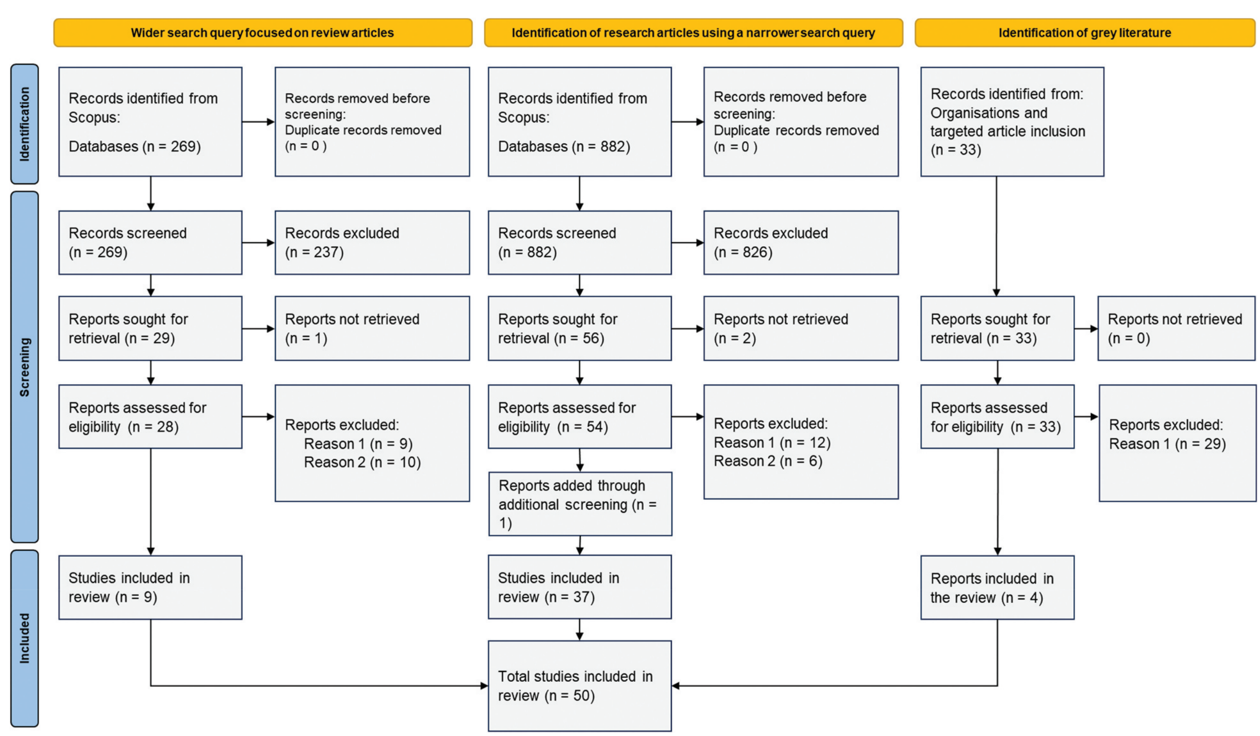

Figure 1. PRISMA process flowchart for the scoping review.

50 documents were included in the review. There were 29/269 (10.8%) review articles identified that were eligible for full-text review, one of which could not be retrieved. After full-text screening, nine review articles (9/28; 32.1%) were included and the others were excluded for two reasons: 1) not sufficiently covering all three areas of health, climate resilience and built environments (nine articles); and 2) not including indicators (10 articles).

Only 56/882 (6.3%) of the research studies identified in the second search were eligible for full text review after the initial screening of titles and abstracts according to the inclusion and exclusion criteria. Of these, 36/56 research studies were included (64.3%). Two could not be retrieved and 18 were excluded after full-text review; 12 for reason one and six for reason two, as outlined above. Additional reference list review resulted in one other article being included, bringing the total number of research studies to 37.

In terms of grey literature, 33 documents underwent full-text review. Four met the inclusion criteria, with 29 (87.9%) being excluded as they did not mention relevant indicators. The included reports were published by WHO (2022), UN-Habitat (2022), and ARUP (2014, 2019). The WHO report (2022) titled 'Review of indicator frameworks supporting urban planning for resilience and health' summarised and analysed six indicator frameworks related to urban resilience and health (Table 3). Since the six frameworks were reviewed as part of this overarching publication, the individual frameworks were not sourced separately. Therefore, while only four reports were included, a total of nine grey literature indicator frameworks were reviewed (Table 3).

We found that the nexus of urban health, climate change and the built environment was a relatively recent research focus. While literature published prior to 2009 was excluded, the included review articles were all published since 2020, the research articles since 2015 and the grey literature since 2014.

The review articles and grey literature did not focus on a specific country or city. Of the 37 research articles, the majority examined European urban contexts (11/37; 29.7%) followed by the United States (6/37; 16.2%) and China (4/37; 10.8%). Details of the countries covered in the research studies are summarised in Table 4.

Determinants

The review identified 12 categories of determinants and several domains within each category based on thematic analysis of the indicators. These determinants, domains and their associated indicators were further aggregated into climate hazard-specific, general resilience to climate change-related hazards and policy-specific. Much of the included literature did not explicitly address relationships between determinants, indicator categories or domains, possibly due to the complex, multi-directional nature of these connections. Based on our analysis, Figure 2 proposes a high-level framework of the relationships between the main determinants and indicator categories used to measure the health and climate resilience of urban areas.

In terms of climate hazard-specific determinants, most of the literature (38/50; 76%) focused on one or more environmental hazards that exacerbate and/or are a consequence of climate change, such as heat, pollution and flooding. Exposures to these hazards can be considered intermediary outcomes or 'downstream' determinants of health and climate resilience (Giles-Corti *et al.* 2022) (Figure 2). Notably, the relationship between urban heat and population health, often referred to as 'heat-health nexus' (Ellena et al. 2020, 2023) was explored more extensively than other climate change-related hazards (33/50 documents; 66%).

Table 3. List of grey literature indicator frameworks included in the scoping review.

Framework	Scale	Developer	Year
WHO (2022) report 'Review of indicator frameworks supporting urban planning for resilience and health'			
SDG indicators United Nations (2015)	Country	United Nations	2015
New Urban Agenda Monitoring Framework and related indicators UN-Habitat (2020)	City	UN-Habitat	2020
Disaster Resilience Scorecard for Cities UNDRR (2017)	City	UNDRR – Making Cities Resilient 2030 campaign	2019
Indicators for resilient cities Figueiredo *et al.* (2018)	City	OECD	2018
Risk Systemicity Questionnaire SMR (2021)	City	ICLEI European Secretariat – Smart Mature Resilience project	2018
ThinkHazard! tool GFDRR (2020)	Region/ district	Global Facility for Disaster Risk Reduction	2007
Other sources			
Global urban monitoring framework UN-Habitat (2022)	City	UN-Habitat	2022
City resilience index ARUP (2014)	City	ARUP	2014
The city water resilience approach ARUP (2019)	City	ARUP	2019

Table 4. Countries studied in the included research studies (excluding reviews and grey literature).

Country	Number of publications
High income economies	
USA	6
Italy	5
Germany	3
South Korea	3
France	2
UK	2
Hong Kong	1
Upper middle-income economies	
China	4
Thailand	1
Turkey	1
Lower middle-income economies	
Vietnam	1
Low-income economies	
Uganda	1
Not a specific country	
Global	5
No specific location	1
EU capital cities	1

The general resilience determinant categories included green and blue spaces, buildings, access to amenities and services, transport, land use, infrastructure resilience, and population vulnerability. With the exception of population vulnerability, these categories focused on built environment features and related policies as 'upstream' determinants of hazard exposure, urban climate resilience and health (Giles-Corti *et al.* 2022) (Figure 2). Population vulnerability, which includes demographic, social, cultural, health, economic and environmental characteristics, interacts with the built environment to influence downstream outcomes. Policy-specific determinants were governance considerations, which were 'upstream' determinants of health and resilience outcomes but were not related to a particular climate change-related hazard or built environment category (Giles-Corti *et al.* 2022).

Indicators

In total 371 indicators were identified after duplicates were removed, with the large majority being quantitative and/or spatial indicators (313; 84.4%) compared with only 58 policy indicators (15.6%) (Table 5). The full list of the extracted indicators, their categorisations and their corresponding reviewed documents can be found in the Appendix.

General resilience to climate hazards indicators were the most numerous group (204/371; 55%), followed by climate hazard-specific indicators (134/371; 36.1%), and a much smaller number of policy-specific indicators (33/371; 8.9%). Determinant categories with the most indicators were green and blue spaces (60/371; 16.2%) and heat (58/371; 15.6%), reflecting the strong focus in the included literature on urban heat and greening as a key mitigation strategy. In addition, the pollution (50/371; 13.5%) and buildings (45/371; 12.1%) determinants had a relatively high proportion of indicators overall.

Climate hazard-specific indicators

Heat

All climate hazard-specific indicators, including those related to heat, were quantitative and/or spatial. Within the heat category, the temperature domain had the largest number of indicators, focused on measuring heat as a key climate risk exposure. Heatwaves amplified by climate change have negative health impacts such as heat stroke, and exacerbation of non-communicable diseases such as respiratory and cardiovascular disease and mental health issues (Ebi *et al.* 2021, Münzel *et al.* 2022, Amoatey *et al.* 2025). Land surface

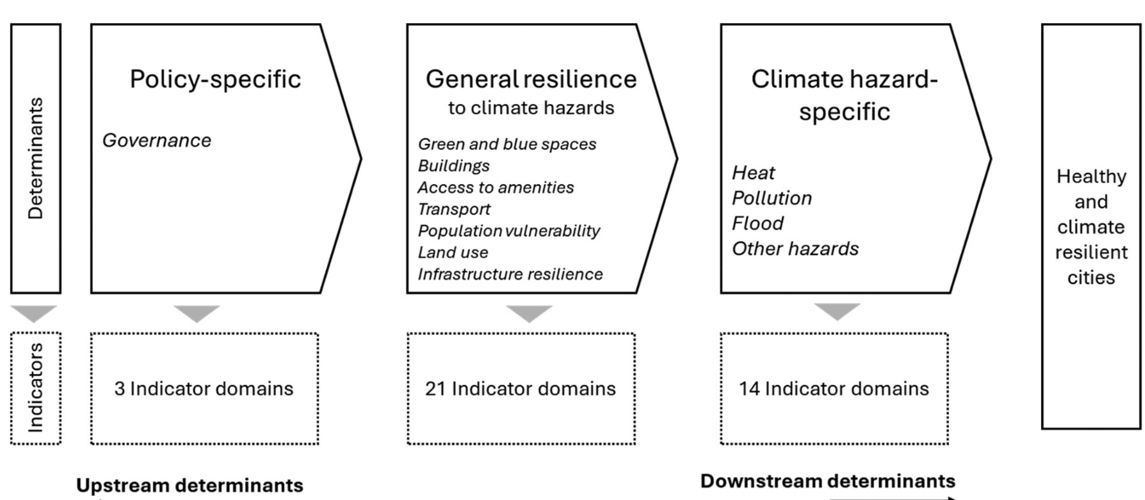

Figure 2. Framework of determinants and indicators for measuring healthy, climate resilient cities.

Table 5. Categorisation of the extracted indicators.

#	Determinants	Domains	Number of indicators: Quantitative and/ or spatial	Policy	Total
Climate hazard-specific					
1	Heat	Temperature	26	0	26
		Radiation/reflection	11	0	11
		Cooling	6	0	6
		Sensation/comfort	6	0	6
		Ventilation	3	0	3
		Humidity	3	0	3
		Heat island/heat intensity	3	0	3
2	Pollution	Air pollution	35	0	35
		Non-air pollution	15	0	15
3	Flood	Flood risk	16	0	16
		Impervious surface	4	0	4
4	Other hazards	Cyclonic winds	2	0	2
		Water scarcity	2	0	2
		Wildfires	2	0	2
General resilience to climate hazards					
5	Green and Blue spaces	Provision/cover	23	3	26
		Green area characteristics	11	0	11
		Access	9	0	9
		Ecosystem services	5	3	8
		Blue space	3	3	6
6	Buildings	All buildings	26	5	31
		Housing	14	0	14
7	Access to amenities and services + satisfaction	Utilities and waste services	11	0	11
		Recreational amenities	7	0	7
		General access and satisfaction	7	0	7
		Healthcare	3	0	3
		Safety	1	0	1
		Food	1	0	1
8	Transport	Active transport	11	0	11
		Public transport	6	0	6
		Motor vehicle traffic	5	0	5
		Transport network planning and operation	0	2	2
9	Population vulnerability		14	0	14
10	Land use	Coverage	9	2	11
		Land use features	4	2	6
11	Infrastructure resilience		9	5	14
Policy-specific					
12	Governance	Strategy/Policy making and planning	0	19	19
13		Identifying, understanding and monitoring current and future risk	0	10	10
14		Resources (data, financial, institutional, human)	0	4	4
Total			**313**	**58**	**371**

temperature was the most reported temperature indicator (Prudent *et al.* 2016, Bernetti *et al.* 2020, Ellena *et al.* 2020).[1] Other indicators included air temperature metrics (e.g. ambient air temperature (Foshag *et al.* 2020, Peng and Maing 2021, Yin *et al.* 2021)), extreme heat events, and indoor temperature under extreme heat (Pascal *et al.* 2021, Hess *et al.* 2023). Heat island indicators, which measure the phenomena where urban areas are hotter than their surrounding rural environments (Mushtaha *et al.* 2021), included atmospheric urban heat island intensity, surface urban heat island, and urban local climate zones (Arifwidodo and Chandrasiri 2020, Badaloni *et al.* 2023, Técher *et al.* 2023). Five indicators measured how humans experience temperature, including the Physiological Equivalent Temperature index, heat index, heat vulnerability index, globe temperature and wet bulb globe temperature (Salvalai *et al.* 2022, Speak and Salbitano 2022, Xu *et al.* 2023).

There were also a range of indicators that measured subjective thermal sensation or comfort (e.g. Universal Thermal Climate Index, Thermal sensation and thermal acceptable vote, Discomfort Index). Humidity indicators incorporated relative humidity and a composite humidity index (Cheng *et al.* 2021, Schmidt and Walz 2021, Van De Walle *et al.* 2022). While humidity can affect thermal comfort and is believed to increase human heat stress, the relationship between humidity and mortality and morbidity needs further exploration (Baldwin *et al.* 2023).

Enhanced radiation and urban cooling interventions can lower temperatures, decreasing negative health effects of urban heat and bolstering cities' capacity to adapt to climate change (Baldwin *et al.* 2023). Indicators in the radiation domain measured surface reflection, absorption and emittance, how much radiation a surface receives, and radiation and heat passing through surfaces using indicators such as: surface albedo, global radiation, thermal radiation and heat flux and land surface emissivity (Schmidt and Walz 2021, Van De Walle *et al.* 2022). While most of these indicators can be measured both for built and natural environments, four of them had a more direct focus on the built environment: street and roof incoming solar radiation, and solar transmittance and reflectance indexes, which focus on glass material and roofs in built environments respectively (Cheng *et al.* 2021, Gonzalez-Trevizo *et al.* 2021).

Cooling indicators included accessibility to cooling facilities (e.g. number and capacity of accessible community cooling centres per elder person), shading in the built environment and energy required for cooling (Li *et al.* 2022, Kim *et al.* 2023). Ventilation indicators included horizontal and average wind velocity and measurement of ventilation corridors, which consist of green spaces, water bodies and roads (Eldesoky *et al.* 2020, Çağlak and Murat 2023). While wind and ventilation can alleviate heat islands (Al-Obaidi *et al.* 2021), more research is required to understand these relationships and assess the impacts of ventilation corridors on air pollution (Han *et al.* 2022, Guo *et al.* 2023).

Pollution

Pollution is an environmental hazard (UNDRR 2020) that can be a driver and/or an outcome of climate change (Kelly and Fussell 2015, Orru *et al.* 2017, Münzel *et al.* 2025). For example, air pollution is deeply interconnected with climate change (UNDRR 2020, p. 53). Many air pollutants are greenhouse gases or are co-emitted with greenhouse gases (Pinho-Gomes *et al.* 2023) and warmer conditions and wildfires and dust storms caused by climate change can exacerbate air pollution with significant negative health consequences such as respiratory and cardiovascular disease and premature mortality (Boogaard *et al.* 2023, Iungman *et al.* 2024). As another example, light pollution contributes to greenhouse gas emissions, but also disrupts ecosystems, potentially intensifying climate impacts (Karan *et al.* 2023).

Most of the indicators in this category measured air pollution, as a key climate change-related health risk. Thirteen indicators measured the level of various types of particulate matter (PM), with five of these measuring percentage reduction in PM (Diener and Mudu 2021). PM2.5 and PM10 were the most commonly reported air pollution indicators and were included as part of the UN SDG indicator framework (United Nations 2015). Fine particulate matter (PM2.5), including from motor vehicle traffic, is the leading environmental health risk factor globally (Southerland *et al.* 2022). Other indicators measured particular gases (e.g. nitrogen oxides, sulphur dioxide) (Sera *et al.* 2019, Donzelli and Linzalone 2023), greenhouse gas emissions per capita, and an air quality index (Pineo *et al.* 2018, Lee *et al.* 2023). Air pollution exposure indicators included estimated average exposure, percentage of reduction in direct exposure and the percentage of population living within 500 meters of highways and major roads (Diener and Mudu 2021). There were also indicators of air pollutant deposition velocity and amount, climate-related environmental conditions that affect air pollution (e.g. colder winters, hotter and drier summers), the effect of acid rain on critical infrastructure, and behavioural and health impacts of air pollution (e.g. spending time outdoors, respiratory disease and mortality) (UN-Habitat 2020, SMR 2021).

Non-air pollution indicators measured other types of pollution linked to climate change and health: land, light, noise (day, night and due to proximity to roads), water (quality, bioswales, domestic and residential wastewater) (European Environment Agnecy 2019, IPCC 2019, Agathokleous 2023, Dao *et al.* 2024), solid waste and hazardous waste (Figueiredo *et al.* 2018, UN-Habitat 2022). Two indicators measured the accumulation of light, noise and other non-air pollution in urban areas (Gonzalez-Trevizo *et al.* 2021, Donzelli and Linzalone 2023).

Flood

Flood is another hazard exacerbated by climate change, with significant implications for urban health both short-term (e.g. injury, drowning, waterborne diseases) and long-term (e.g. displacement, psychological health) (Alderman *et al.* 2012, IPCC 2022). In the reviewed literature there were two main domains of flood indicators: flood risk (16 indicators) and impervious surfaces (4 indicators). Most of the flood risk indicators (14/16) were extracted from the grey literature. They included flood characteristics that impact of population exposure to flood (e.g. 100 year flood plain, inundation depth and return period); and vulnerability and exposure of urban areas to flood (e.g. state of the drainage system, informal settlements in flood prone areas, and impacts of flooding on electricity, sewage and drinking water supplies) (ARUP 2019, GFDRR 2020, SMR 2021). Two indicators focused on the provision of health services to reduce trauma linked to water hazards (Prudent *et al*. 2016, Houghton and Castillo-Salgado 2020). Meanwhile, impervious surfaces were measured as contributors to flooding (e.g. the proportion of cities covered by buildings, roads or paved surfaces) (Pascal *et al*. 2021, Wei *et al*. 2023). Impervious surfaces can increase flood risk by limiting natural infiltration and increasing stormwater runoff, and create additional health risks from contaminated water exposure (Zhang and Chui 2019).

Other hazards

While heat, pollution and flood were the most commonly measured climate change-related hazards in the reviewed documents, the ThinkHazard indicators developed by the Global Facility for Disaster Reduction and Recovery (GFDRR 2020) highlighted the importance of measuring other hazards that impact on human health and can be exacerbated by climate change, including cyclonic winds, wildfires, and water scarcity. The indicators measured severity of these hazards (i.e. mean wind speed, fire weather index, water availability), and their frequency (i.e. return period).

General resilience to climate hazards indicators

Whilst general resilience to climate hazards indicators were mostly quantitative and/or spatial measures, 26/59 policy indicators related to general resilience domains. With a few exceptions, most of these policy indicators were sourced from the grey literature.

Green and blue spaces

'Green and blue spaces' was the largest category of indicators (60 indicators), with the majority focused on green spaces. This reflects the multiple benefits of green spaces for absorbing carbon dioxide, and promoting health in the face of climate change by combating urban heat (Diener and Mudu 2021; Kabisch *et al*. 2017), providing contact with nature, and supporting biodiversity and physical activity (Hunter *et al*. 2023, van Daalen *et al*. 2024). Twenty-three quantitative and/or spatial indicators focused on measuring vegetation or greenery provision and/or cover (e.g. green spaces, vegetation, trees, grasses, cropland, domestic gardens, green roofs and walls, protected natural areas and green infrastructure as a whole) (Houghton and Castillo-Salgado 2020, Murage *et al*. 2020, Choi *et al*. 2022). Urban green space area, and urban vegetation measured by the Normalized Difference Vegetation Index (NDVI), were the most commonly occurring indicators in this domain (Braun *et al*. 2023, Klopfer and Pfeiffer 2023). Policy indicators in the provision/cover domain evaluated the existence of relevant policy, principles and responsible actors for developing and implementing green infrastructure, as well as levels of funding, subsidies, tax breaks and investment in urban green space (ARUP 2019, Slätmo *et al*. 2019).

Green area characteristics that may impact on the ability of these spaces to afford health and climate benefits were measured by indicators of live/dead grass, tree dimensions (height and width), and the richness and percentage of native species, as a measure of biodiversity (Pineo *et al*. 2018, Badaloni *et al*. 2023). Green space access indicators focused on proximity to parks and green spaces and number or area of green spaces per person (Pineo *et al*. 2018, Arifwidodo and Chandrasiri 2020, Kim *et al*. 2023). The reviewed studies also measured ecosystem services offered by green spaces, including cooling services, carbon stock and sequestration services and biodiversity (Schmidt and Walz 2021, Wang 2023). There were also policy indicators focused on the management of ecosystem services, which may impact on the effectiveness of green infrastructure for supporting urban health and climate resilience (e.g. assessing whether ecosystem services are specifically identified and managed as critical assets) (ARUP 2014, UNDRR 2017).

While less researched than green spaces, blue spaces can contribute to healthy, climate resilient cities by mitigating urban heat, reducing obesity and all-cause mortality, and improving general health and mental health (Smith *et al*. 2021, Hunter *et al*. 2023, Fricke *et al*. 2024). There were only three quantitative and/or spatial blue space indicators: proportion of water bodies (Sharifi *et al*. 2021, Wei *et al*. 2023), accessibility to water bodies (Ellena *et al*. 2020, Cheng *et al*. 2021, Li *et al*. 2022) and Normalized Difference Water Index (NDWI) (Gonzalez-Trevizo *et al*. 2021), which maps the coverage of water bodies. Similarly, there were three policy indicators that measured the enhancement of urban water amenities and land development and place-making around water bodies (ARUP 2019).

Buildings

The buildings category included two indicator domains: housing and 'all buildings'. Quantitative and/or spatial housing indicators considered general characteristics such as housing size, type, age, condition, and affordability (Cheng *et al*. 2021, Sharifi *et al*. 2021), as factors that can shape the contribution of housing to greenhouse gas emissions and climate adaptation. Other indicators more directly assessed housing aspects that impact on greenhouse gas emissions (energy efficiency, electricity use per capita, compliance with building codes), and the ability to safeguard residents from extreme weather (whether houses have been retrofitted to withstand climate change-related hazards) (ARUP 2014, United Nations 2015, UN-Habitat 2020, Hess *et al.* 2023). An indicator of the proportion of people living in slums or inadequate housing can be used to measure population vulnerability to climate-related hazards (Ezeh *et al.* 2017).

Quantitative and/or spatial indicators in the 'all buildings' domain measured general building characteristics and materials similar to the housing domain, as well as garden vegetation, sky, and building view factors, and building height and density (Peng and Maing 2021, Makvandi *et al.* 2023, Wei *et al.* 2023), which can all impact on urban temperature regulation and energy consumption. Climate resilience and sustainability of buildings have also been considered via the following indicators: thermal performance of buildings, insulation, shading, building footprint, energy consumption, number of new and refurbished buildings certified with a sustainability standard, vulnerability of buildings to climate hazards and whether buildings have insurance cover for high-risk hazards (Figueiredo *et al.* 2018, Ellena *et al.* 2020, Técher *et al.* 2023). Policy indicators in the 'all buildings' domain focused on the existence and enforcement of building resilience and sustainability codes, standards and principles, which impact on the ability of buildings to protect and promote health in the face of climate change.

Access to amenities and services

Indicators measured access to a wide variety of amenities that shape physical and mental health and the ability of communities to survive, adapt and thrive in the face of climate change. The utilities and waste services domain measured access to essential services, including water and sewage networks, electricity, communication technology, affordable energy, waste collection and disposal services (United Nations 2015, Cheng *et al.* 2021, Schmidt and Walz 2021). Recreational amenities indicators measured access to playgrounds, outdoor and indoor physical activity facilities, open spaces and seating (Pineo *et al.* 2018, Li *et al.* 2022, UN-Habitat 2022). Some indicators did not target any specific service, instead measuring access and satisfaction with amenities in general, such as living environment index of multiple deprivation, satisfaction with neighbourhood living environment and access to city centre (Murage *et al.* 2020, Lee *et al.* 2023, Wang 2023). Other indicators in this category measured access to health care and emergency medical care, number of health care beds, neighbourhood safety and access to affordable food supply (ARUP 2014, Ellena *et al.* 2020, Cheng *et al.* 2021).

Transport

The largest transport domain was quantitative and/or spatial indicators related to active transport (11 indicators), highlighting the importance of walking and cycling for reducing transport emissions, promoting physical activity, and reducing non-communicable disease (Sallis *et al.* 2015, Yin *et al.* 2021, Van De Walle *et al.* 2022). Indicators assessed existing pedestrian infrastructure (e.g. amount and quality of paths) and bicycle paths (e.g. kilometres of bike paths per 100,000 population), as well as use of active transport modes (e.g. foot traffic patterns, percentage mode share for commuters) (Pinheiro and Luís 2020, Sharifi *et al.* 2021, Yin *et al.* 2021, Salvalai *et al.* 2022, Wei *et al.* 2023). Public transport spatial indicators measured accessibility and availability of public transport (e.g. kilometres of different public transport per 100,000 people) as well as the percentage of commuters using public transport (Pineo *et al.* 2018, UN-Habitat 2020, 2022, Lee *et al.* 2023). Public transport is important for healthy, climate resilient cities as it reduces transport emissions relative to private motor vehicles, provides opportunities for physical activity to and from stations or stops, and supports equity of access to essential infrastructure and services (World health Organization 2025). Motor vehicle traffic contributes to greenhouse gas emissions and traffic hazards (Giles-Corti *et al.* 2016), with indicators measuring access and density of roads, traffic levels and noise (Badaloni *et al.* 2023, Donzelli and Linzalone 2023). Transport policy indicators focused on the diversity and affordability of the transport network and effective transport operation and maintenance (ARUP 2014).

Land use

Indicators measured a range of land uses, beyond the specific types of land uses covered in other categories outlined above. Quantitative and/or spatial indicators measured various land use aspects that impact on exposure and responses to climate change-related hazards such as urban heat, pollution and flood. These included the built-up area (e.g. Normalized Difference Built-Up Index (NDBI), percentage built-up area (Ellena *et al.* 2020, Gonzalez-Trevizo *et al.* 2021)), amounts of unused land, grey space and open space (Weber *et al.* 2015, Nice *et al.* 2022, Çağlak and Murat 2023), and area and rate of urbanisation (Sera *et al.* 2019, Cheng *et al.* 2021, Li *et al.* 2022).

Three metrics were most specifically related to urban health and climate resilience. First, 'the rural-urban gradient' (Gonzalez-Trevizo *et al.* 2021) which was used to examine 'the influence of human disturbances on ecological, social and coupled natural-human systems' (Kaminski *et al.* 2021, p. 2937). Second, 'urban landscape metrics' (Gonzalez-Trevizo *et al.* 2021) quantified a variety of urban patterns (Bhatti *et al.* 2018) and have been extensively used to examine the connection between land uses and heating/cooling effects in urban areas. Third, 'safe hazard shelters versus expected public demand' (Figueiredo *et al.* 2018) which is one of the few composite indicators that connects land use planning to climate change-related hazard preparedness. Land use policy indicators measure the enforcement of land use zoning, the use of urban design to maximise ecosystem services and the extent to which land use plans have been developed using local hazard risk assessment (UNDRR 2017, Figueiredo *et al.* 2018, UN-Habitat 2022).

Infrastructure resilience

Infrastructure resilience indicators were all extracted from the grey literature, indicating a lack of emphasis on this area in the reviewed academic literature. Robust, responsive and adaptive infrastructure is an integral part of urban resilience (Meerow *et al.* 2016). The functional disruption of infrastructure can lead to widespread social and economic impacts, and affects human health by limiting access to essential services (Pant *et al.* 2016). The identified quantitative indicators included the loss factor (i.e. customer service days at risk of loss) for various critical infrastructure assets: electrical energy, gas, road, rail, airport, communication, water and sanitation (UNDRR 2017). Other quantitative indicators measured the cost of lost communication and transport services (UNDRR 2017). The infrastructure resilience category also included policy indicators measuring the availability of robust, secure, flexible and reliable infrastructure, and application of appropriate codes, standards and their enforcement for infrastructure resilience (ARUP 2014, UNDRR 2017).

Population vulnerability

Population vulnerability indicators measured demographic, health, social, economic and environmental characteristics of urban populations that influence exposure and vulnerability to climate change-related hazards and associated health impacts. They included population density, percentage of the population that is elderly or requiring recuperation, mortality, over-exposed population, social sensitivity, percentage of population at the risk of displacement, number of homeless people, and percentage of households living in fuel poverty (Arifwidodo and Chandrasiri 2020, Ellena *et al.* 2020).

Policy-specific indicators

Policies and their translation into interventions can support the creation of urban environments, systems and services that reduce the health impacts of climate change. In addition to the general resilience policy indicators discussed above, we identified a range of other governance-related indicators that assess policy processes, strategies, actions, implementation, resourcing and enforcement related to healthy, climate resilient cities. These indicators form a distinct policy-specific group, with indicators spanning three domains.

Policymaking and planning processes

Indicators in this domain assessed whether hazard and risk assessments were factored in during strategy development, and whether decisions were evaluated based on their resilience benefits or limitations (ARUP 2014, UNDRR 2017, UN-Habitat 2020). There were also indicators directed at disaster response and recovery planning including the clarification of private and public sectors' roles in disaster response, effectiveness of emergency response services, existence of post event recovery and economic reboot plans, and the role of stakeholders in Build Back Better plans (UNDRR 2017). Three indicators specifically emphasized health considerations, through measuring efforts to minimize the health impacts of climate change. These indicators were: the integration of health in climate change policies, engagement with health departments in planning and the robustness of health systems (ARUP 2014, Kleiman *et al.* 2022, Hoeben *et al.* 2023). Other indicators measured whether planning approaches were interdisciplinary and participatory, to ensure that health, climate and built environment actors work closely together and policies align to create healthy, climate resilient cities (Bannan *et al.* 2022, Kleiman *et al.* 2022).

Identifying and monitoring risks

This domain focused on identifying, understanding and monitoring current and future climate change- related risks. Relevant indicators included hazard and multi-hazard mapping, asset identification, vulnerability and exposure mapping, scenario planning, risk assessments, multi-hazard early warning, and monitoring and forecasting systems (ARUP 2014, UN-Habitat 2020, Yin *et al.* 2021).

These policy indicators did not focus on any specific climate change-related hazard and were geared towards the risk framework that is adopted by international agencies such as United Nations offices. In this framework, risk is often considered as a function of hazards, vulnerability, exposure and capacity in a given context, which can be calculated for economic, physical, social, cultural and environmental assets (UN General Assembly 2016, UNDRR 2019).

Resources

Resources indicators focused on budgets and financial resources for climate change adaptation and mitigation, data integration across climate change and health, availability of a single integrated set of resilience data for practitioners, and measurement of spare capacity as a key quality of resilient urban systems (ARUP 2014, UNDRR 2017, Kleiman *et al.* 2022, Lowe *et al.* 2024).

Discussion

Breadth of determinants and indicators

Building urban climate resilience in ways that maximise benefits for human health is an urgent global priority (United Nations 2018, 2023, United Nations Environment Programme & International Science Council 2024, van Daalen *et al.* 2024, Whitmee *et al.* 2024). To support these goals, it is imperative to understand priority determinants and use urban-scale indicators to measure and monitor progress. We found that there is a large body of literature on determinants and measurement of healthy and climate resilient urban environments. This literature arises from many disciplines and countries (mostly from higher income economies) internationally. Diverse quantitative, spatial and policy indicators of healthy and climate resilient cities have been developed and applied in research and practice, however, there does not seem to be an agreed upon indicator framework. Indicators identified in this review measured similar conditions or domains in different studies and across geographical locations. For example, we found 26 distinct temperature indicators and 35 indicators of air pollution, including 13 different indicators of airborne PM. The number and diversity of indicators, particularly the large number of quantitative and spatial indicators, may provide limited guidance to researchers, policy-makers and planners about optimal measures of healthy, climate resilient cities.

Nonetheless, the determinant categories and indicator framework identified through this scoping review provide some indication of policy and measurement priorities. There is some agreement in the reviewed literature about urban heat, air pollution and flood being key climate-related health hazards, and the importance of planning for quality urban green space, building quality, robustness and sustainability, access to a variety of amenities, active, low-carbon transport systems, and risk assessment and policymaking processes that actively promote urban climate resilience. These determinants highlight the multiple sectors involved, and the need for complex system thinking to create healthy, climate resilient cities (Pineo *et al.* 2020, Bustamante *et al.* 2021, ICS 2021, Luna Pinzon *et al.* 2022, Gatzweiler *et al.* 2023). This is consistent with the wider international literature on intersectoral opportunities and approaches to achieve health and resilience co-benefits from climate action in urban contexts (Rockefeller Foundation and Arup 2015, Whitmee *et al.* 2024). Indeed, some of the identified policy indicators specifically focus on collaboration and intersectoral cooperation, particularly the involvement of the health sector in decisions about urban planning responses to climate change (UNDRR 2017, Figueiredo *et al.* 2018, ARUP 2019, Bannan *et al.* 2022, Kleiman *et al.* 2022, Hoeben *et al.* 2023, Lee *et al.* 2023).

Consistent with urban health and liveability frameworks (Badland *et al.* 2014, Giles-Corti et al. 2020, 2022), the indicators and determinants identified in our review span policies and upstream built environment determinants through to climate-related hazard exposure. Our findings broadly aligned with Giles-Corti *et al.* (2022) framework of pathways through which city planning influences human and planetary health. Like our review, this framework encapsulates the importance of good and integrated governance, to support active transport, access to amenities, well-designed housing, and urban greening access. These in turn influence risk exposures such as air pollution, greenhouse gas emissions, and heat islands.

Indicator gaps

However, relative to Giles-Corti *et al.* (2022) framework, there were some potential gaps in the indicators identified. While our review found some indicators of ecosystem services provided by green spaces, there was a lack of indicators of biodiversity loss, biodiversity-sensitive design and nature-based solutions more broadly. We found some housing and building-related energy use and efficiency indicators, but there were no specific indicators identified for the transition to renewable energy use in buildings or transport. Cultural determinants of urban health and climate resilience were also not covered by the identified indicators.

Disaster mitigation and management should be an integral part of city planning, to prevent, prepare for, and adapt to the physical, social, economic and psychological impacts of disasters in complex and dynamic urban environments (Renn *et al.* 2018, Galasso *et al.* 2021, Giles-Corti *et al.* 2022). Many of the identified built environment indicators measured aspects of climate change mitigation and adaptation, and we also found policy indicators focused on hazard identification and monitoring. However, there were no policy indicators related to specific types of climate change-related hazards or disasters. Nor were there policy indicators identified that assess actions to reduce the health impacts of disasters (e.g. policies to limit development in risk-prone areas). Much of the literature on policy-specific indicators provided insufficient details on data sources or measurement methods, limiting the ability to accurately replicate these indicators.

Further, some climate change-related hazards such as urban heat, flood and air pollution appeared to have received more attention than others in the measurement and monitoring of healthy, climate resilient cities. Although similarly expected to increase in frequency and severity due to climate change (IPCC 2022), hazards such as bushfire/wildfire, extreme cold, storms, cyclones and hurricanes have garnered minimal focus in the literature at the intersect of health, built environment and climate resilience. These indicator gaps could be due to difficulties in measurement and data availability. However, relevant literature may come from a wide range of fields, so more targeted reviews of literature related to these hazards and other determinants may be needed to identify relevant indicators.

Informing policies and interventions

Indicators can inform effective urban governance and robust reporting and evaluation of progress towards healthy and climate resilient urban environments. The identified indicators could be used to reveal problems, inequities or emerging issues related to climate change-related hazard exposures, built environment characteristics, population vulnerability or urban governance arrangements. This can inform agenda-setting and formation of policies or interventions to solve pressing challenges (Whitehead *et al.* 2004, Lowe *et al.* 2018). Policy indicators can be used to evaluate whether policy-making processes, resource allocation and policy aims and actions could support healthy, climate resilient cities (Lowe *et al.* 2022). Many of the identified indicators would be suitable for measuring changes that result from implementation of specific policies, plans or interventions, including monitoring short- and longer-term impacts on health and evolutionary climate resilience and whether stated policy aims are being achieved (Lowe *et al.* 2018, Pineo *et al.* 2018). This, in turn, can inform data-driven adjustments to policies in response to unintended negative consequences.

While indicators can be powerful tools, a range of other research evidence (e.g. community perspectives; quantitative evidence or modelling of the impacts of built environments on health) is needed to inform policy and evaluate outcomes. Evidence alone is also unlikely to be sufficient for galvanising policy action (Taylor and Hurley 2016). The wider political, economic and social context, including policy narratives and the power of policy actors, will ultimately determine strategies to tackle health and climate resilience challenges in cities (Sabatier and Weible 2014, Lowe *et al.* 2019).

Measuring and monitoring evolutionary urban climate resilience

To achieve evolutionary urban climate resilience, urban systems need to exhibit adaptive and transformative capacity in addition to the ability to persist through, and recover from, climate change-related shocks and stresses (Lowe *et al.* 2023, 2024). These four characteristics of resilience – persistence, recovery, adaptive capacity and transformative capacity – can be pursued through urban policy and built environment interventions (Davidson *et al.* 2019), and measured through indicators and research. The identified climate hazard-specific indicators reflected a reactionary (i.e. persistence and recovery) stance to hazards, as they measure exposure and/or responses to hazards rather than reducing health impacts or mitigation of those hazards. The identified general resilience quantitative and spatial indicators were mostly cross-sectional measures of the status of built environment characteristics. These would need to be repeated at regular intervals (e.g. every 5 years) to be able to assist with monitoring adaptations and changes in the built environment over time. Nevertheless, some spatial indicators were more focused on adaptive and transformative capacity as they explicitly measured changes in determinants of healthy, climate resilient cities, such as percentage reduction of average PM concentrations (Diener and Mudu 2021); or change in tree cover (UN-Habitat 2022).

Targets or benchmarks are needed to help guide adaptation and transformation of built environments (Lowe *et al.* 2022). In the reviewed literature, there was a lack of clarity on the desirable direction of change for most indicators, let alone clear targets or benchmarks. For example, indicators such as 'traffic levels' do not explicitly clarify whether and how much traffic should be reduced to promote health and climate resilience.

While quantitative and spatial indicators can measure policy implementation and impacts, policy indicators focus on measuring governance and decision-making processes. They are therefore oriented towards evaluating capacity for positive change and evolution, and align with the urban resilience literature which emphasises that resilience-building is more about processes than outcomes (Redman 2014, Kuhlicke *et al.* 2019). This further highlights the need to fill the identified policy indicator gaps in the climate hazard-specific and general resilience to climate hazards domains. For example, general resilience policy indicators can assess the existence and quality of policies related to transport system resilience, building design and access to amenities (Lowe *et al.* 2022), to inform targeted policy improvements.

Data and measurement considerations

A wide variety of data sources are required to generate the identified indicators. Quantitative and spatial indicators rely on remote sensing imagery, spatial data on the location of urban design and transport features, and street networks, and data on population characteristics. Composite spatial indicators (e.g. urban heat vulnerability) have advantages for measuring complex, multi-factorial domains of healthy, climate resilient cities, but may require a wider range of data inputs. Policy indicators require policy and process evaluation data, which is often not routinely collected (Lowe *et al.* 2022).

We identified existing indicators developed in, and applied to, a wide range of countries internationally, with many indicators (especially from the grey literature) having apparent international relevance. While a standard set of indicators would offer consistent and comparable measurement of cities internationally, not all indicators may be relevant or measurable in all countries or cities. When selecting indicators for research or practice in particular urban contexts, it is necessary to consider whether they are applicable to those cities, in terms of the specific climate change-related, built environment, sociodemographic, cultural or governance challenges they may be facing. Indicator selection also requires scoping data availability, quality and consistency across regions or internationally. Only then is it possible to determine whether an indicator can be measured for a particular city, the most appropriate scales (e.g. street, neighbourhood or whole metropolitan area) for measurement, and whether comparisons are possible within and between cities. Previous research has found that decision makers prefer indicators to be measurable at various scales, and able to show spatial inequities within cities, to help target interventions (Lowe *et al.* 2015). Using globally available open data wherever possible supports the principle of open science and international comparability (Boeing *et al.* 2022). Further research on potential methodological solutions in response to spatial challenges related to indicators is required (Solís *et al.* 2017).

Beyond data scoping, any attempt at creating indicators that can be used globally would require a highly iterative process including policy makers, stakeholders, identifying data sources and evaluating evidence (Pineo *et al.* 2018). Indicator methods would also need to be validated for cities of interest, or internationally. This can involve calculating and testing the accuracy of indicators for specific city contexts, using local expert knowledge (Badland *et al.* 2014, Liu *et al.* 2022). It can also be useful to validate indicators against other reference data sources. Consideration should be given to establishing associations between indicators and health and resilience outcomes, by linking indicators measured at an appropriate scale to outcome datasets. Regular reviews are required to ensure evidence of effectiveness, feasibility of measurement, data availability and programmatic relevance (Requejo *et al.* 2013).

There have been previous calls to marry indicators to existing urban policies, to simplify indicator selection (Badland *et al.* 2014). As a complement to relevant spatial indicators, policy indicators can evaluate the presence and quality of policies themselves. We found that, with a few exceptions, the policy indicators were derived from grey literature. There is a need for policy indicators to be more widely included in research studies, which would enable these indicators to be further tested, validated and refined.

Limitations and future research

Scoping reviews are broad in nature and there could potentially be gaps in the included literature. We tried to mitigate this risk by including research articles, review papers and grey literature. Although various keywords were included and different search queries were tested, the identified indicator gaps may be partly due to the keywords used for this review. In addition, only documents written in English were accessed, which may have limited inclusion of relevant indicators, especially related to lower-income countries whose populations are at higher risk of climate change impacts. While the selected literature covered a broad spectrum of domains and indicators, more targeted reviews of specific fields or climate change-related hazards, and inclusion of other languages could potentially yield additional relevant indicators. Future research could also refine or develop new indicators to address the indicator gaps we identified, as discussed above.

It was beyond the scope of this review to evaluate the feasibility or relevance of the identified indicators for specific urban contexts, as this requires detailed data scoping and testing (IPCC 2022). However, this is a necessary and planned next step in our research project.

This study has highlighted the relevance of indicators for measuring the health and climate resilience of urban areas. Future research could more fully explore the complexity and inter-relationships between the various determinants and indicators of urban health and climate resilience, and how these relationships can be built upon to leverage the goal of healthy and resilient cities.

Conclusion

The challenge of planning cities that contribute to human health in the face of climate change is well documented in the existing literature. Addressing this challenge requires a complex systems perspective, and transformative and evidence-based approaches to creating healthy, climate resilient cities. This scoping review contributes to understanding the key determinants and indicators of healthy and climate resilient urban areas, which could inform research and decision-making. We identified 12 main categories of determinants that have been measured in the literature, spanning climate hazard-specific, general resilience to climate hazards and policy-specific aspects. Although we uncovered a wide range of indicators, there was no agreed upon indicator framework in place to concurrently measure health and climate resilience. Multiple indicators were often used to measure similar concepts, providing limited guidance on optimal measures for research and practice. Our review identified the need for spatial and process-oriented policy indicators capable of measuring adaptive and transformative capacity, in alignment with evolutionary urban climate resilience. Informed by this review, our intention is to validate methods for internationally applicable open-source policy and spatial indicators of healthy, climate resilient cities, which can be used to guide policymaking and show inequities within and between cities. Our findings will also inform future research to develop a risk-based decision support system for delivering healthy, climate resilient cities.

Note

1. References for the indicators outlined in the Results are examples of the sources of the indicators. See the Appendix for a complete list of indicators and their references.

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References

Agathokleous, E., 2023. Light pollution driven by climate change. *Science*, 382 (6671), 655–655. doi:10.1126/science.adk7733.

Al-Obaidi, I., *et al.*, 2021. Assessing the impact of wind conditions on urban heat islands in large Australian cities. *Journal of ecological engineering*, 22 (11), 1–15. doi:10.12911/22998993/142967.

Alderman, K., Turner, L.R., and Tong, S., 2012. Floods and human health: a systematic review. *Environment international*, 47, 37–47. doi:10.1016/j.envint.2012.06.003.

Amoatey, P., *et al.*, 2025. Impact of extreme heat on health in Australia: a scoping review. *BMC public health*, 25 (1), 522. doi:10.1186/s12889-025-21677-9.

Arifwidodo, S.D. and Chandrasiri, O., 2020. Urban heat stress and human health in Bangkok, Thailand. *Environmental research*, 185, 109398. doi:10.1016/j.envres.2020.109398.

ARUP, 2014. *City resilience index- understanding and measuring city resilience*. New York: T. R. FOUNDATION & ARUP.

ARUP, 2019. *The city water resilience approach*. R. F. ARUP, SIWI, The Resilience Shift. Available from: https://www.arup.com/perspectives/publications/research/section/the-city-water-resilience-approach.

Badaloni, C., *et al.*, 2023. A spatial indicator of environmental and climatic vulnerability in Rome. *Environment international*, 176, 107970. doi:10.1016/j.envint.2023.107970.

Badland, H. and Pearce, J., 2019. Liveable for whom? Prospects of urban liveability to address health inequities. *Social science & medicine*, 232, 94–105. doi:10.1016/j.socscimed.2019.05.001.

Badland, H., *et al.*, 2014. Urban liveability: emerging lessons from Australia for exploring the potential for indicators to measure the social determinants of health. *Social science and medicine*, 111, 64–73. doi:10.1016/j.socscimed.2014.04.003.

Baldwin, J.W., *et al.*, 2023. Humidity's role in heat-related health outcomes: a heated debate. *Environmental health perspectives*, 131 (5), 55001. doi:10.1289/ehp11807.

Bannan, T.J., *et al.*, 2022. Monitoring and understanding urban transformation: a mixed method approach. *Frontiers in sustainable cities*, 3, 787484. doi:10.3389/frsc.2021.787484.

Bernetti, I., *et al.*, 2020. Climate change and urban well-being: a methodology based on Sen theory and imprecise probabilities. *Aestimum*, 2020, 57–80. doi:10.13128/aestim-8086.

Bhatti, S.S., Reis, J.P., and Silva, E.A., 2018. 1.14 - Spatial metrics: the static and dynamic perspectives. *In*: B. Huang, ed. *Comprehensive geographic information systems*. Elsevier, 181–196. doi:10.1016/B978-0-12-409548-9.09604-4.

Boeing, G., *et al.*, 2022. Using open data and open-source software to develop spatial indicators of urban design and transport features for achieving healthy and sustainable cities. *The Lancet global health*, 10 (6), e907–e918. doi:10.1016/s2214-109x(22)00072-9.

Bolte, G., *et al.*, 2023. Climate change and health equity: a public health perspective on climate justice. *Journal of health monitoring*, 8 (Suppl 6), 3–35. doi:10.25646/11772.

Boogaard, H., *et al.*, 2023. Long-term exposure to traffic-related air pollution and non-accidental mortality: a systematic review and meta-analysis. *Environment international*, 176, 107916. doi:10.1016/j.envint.2023.107916.

Braun, A., *et al.*, 2023. Relationship of urban heat with building density and green spaces – a remote sensing-based study across Vietnam's metropolitan areas. *Vietnam journal of science and technology*, 61 (1), 137–150. doi:10.15625/2525-2518/16435.

Bustamante, M., Vidueira, P., and Baker, L., 2021. Systems thinking and complexity science–informed evaluation frameworks: assessment of the economics of ecosystems and biodiversity for agriculture and food. *New directions for evaluation*, 2021 (170), 81–100. doi:10.1002/ev.20455

Çağlak, S. and Murat, T., 2023. Spatial distribution and future projections of thermal comfort conditions during the hot period of the year in Diyarbakır City, Southeastern Turkey. *Sustainability*, 15 (13), 10473. doi:10.3390/su151310473.

Cheng, W., *et al.*, 2021. Approaches for identifying heat-vulnerable populations and locations: a systematic review. *Science of the total environment*, 799, 149417. doi:10.1016/j.scitotenv.2021.149417.

Choi, H.M., *et al.*, 2022. Effect modification of greenness on the association between heat and mortality: a multi-city multi-country study. *EBioMedicine*, 84, 104251. doi:10.1016/j.ebiom.2022.104251.

Costello, A., *et al.*, 2009. Managing the health effects of climate change. *Lancet*, 373 (9676), 1693–1733. doi:10.1016/s0140-6736(09)60935-1.

Dao, P.U., *et al.*, 2024. The impacts of climate change on groundwater quality: a review. *Science of the total environment*, 912, 169241. doi:10.1016/j.scitotenv.2023.169241.

Davern, M., *et al.*, 2023. Liveability research creating real world impact: connecting urban planning and public health through the Australian Urban Observatory. *Cities & health*, 7 (5), 765–778. doi:10.1080/23748834.2023.2178091.

Davidson, K., *et al.*, 2019. The emerging addition of resilience as a component of sustainability in urban policy. *Cities*, 92, 1–9. doi:10.1016/j.cities.2019.03.012.

Diener, A. and Mudu, P., 2021. How can vegetation protect us from air pollution? A critical review on green spaces' mitigation abilities for air-borne particles from a public health perspective – with implications for urban planning. *Science of the total environment*, 796, 148605. doi:10.1016/j.scitotenv.2021.148605.

Donzelli, G. and Linzalone, N., 2023. Use of scientific evidence to inform environmental health policies and governance strategies at the local level. *Environmental science and policy*, 146, 171–184. doi:10.1016/j.envsci.2023.05.009.

Ebi, K.L., *et al.*, 2021. Hot weather and heat extremes: health risks. *Lancet*, 398 (10301), 698–708. doi:10.1016/S0140-6736(21)01208-3.

Eldesoky, A.H.M., Colaninno, N., and Morello, E., 2020. Mapping urban ventilation corridors and assessing their impact upon the cooling effect of greening solutions. *International archives of the photogrammetry, remote sensing and spatial information sciences - ISPRS archives*. Conference proceeding, Volume XLIII-B4-2020, 2020 | XXIV ISPRS Congress, Commission IV, online, Nice, France.

Ellena, M., Breil, M., and Soriani, S., 2020. The heat-health nexus in the urban context: a systematic literature review exploring the socio-economic vulnerabilities and built environment characteristics. *Urban climate*, 34, 100676. doi:10.1016/j.uclim.2020.100676.

Ellena, M., *et al.*, 2023. Micro-scale UHI risk assessment on the heat-health nexus within cities by looking at socio-economic factors and built environment characteristics: the Turin case study (Italy). *Urban climate*, 49, 101514. doi:10.1016/j.uclim.2023.101514.

European Environment Agency, 2019. *Soil, land and climate change*. European Environment Agency. Available from: https://www.eea.europa.eu/signals-archived/signals-2019-content-list/articles/soil-land-and-climate-change.

Ezeh, A., *et al.*, 2017. The history, geography, and sociology of slums and the health problems of people who live in slums. *Lancet*, 389 (10068), 547–558. doi:10.1016/S0140-6736(16)31650-6.

Ferguson, P., Wollersheim, L., and Lowe, M., 2020. Approaches to climate resilience. *In*: *The Palgrave handbook of climate resilient societies*. Springer International Publishing, 1–25. doi:10.1007/978-3-030-32811-5_97-1.

Figueiredo, L., Honiden, T., and Schumann, A., 2018. Indicators for resilient cities. OECD Regional Development Working Papers, No. 2018/02. Paris: OECD Publishing. doi:10.1787/6f1f6065-en.

Folke, C., *et al.*, 2010. Resilience thinking integrating resilience, adaptability and transformability. *Ecology and society*, 15 (4). doi:10.5751/ES-03610-150420.

Foshag, K., *et al.*, 2020. Viability of public spaces in cities under increasing heat: a transdisciplinary approach. *Sustainable cities and society*, 59, 102215. doi:10.1016/j.scs.2020.102215.

Freitas, Â., Rodrigues, T.C., and Santana, P., 2020. Assessing urban health inequities through a multidimensional and participatory framework: evidence from the EURO-HEALTHY project. *Journal urban health*, 97 (6), 857–875. doi:10.1007/s11524-020-00471-5.

Fricke, L., Legg, R., and Kabisch, N., 2024. Impact of blue spaces on the urban microclimate in different climate zones, daytimes and seasons – a systematic review. *Urban forestry and urban greening*, 101, 128528. doi:10.1016/j.ufug.2024.128528.

Friel, S., *et al.*, 2011. Urban health inequities and the added pressure of climate change: an action-oriented research agenda. *Journal of urban health*, 88 (5), 886–895. doi:10.1007/s11524-011-9607-0.

Frumkin, H. and Haines, A., 2019. Global environmental change and noncommunicable disease risks. *Annual review of public health*, 40 (1), 261–282. doi:10.1146/annurev-publhealth-040218-043706.

Galasso, C., *et al.*, 2021. Editorial. Risk-based, pro-poor urban design and planning for tomorrow's cities. *International journal of disaster risk reduction*, 58, 102158. doi:10.1016/j.ijdrr.2021.102158.

Gatzweiler, F.W., *et al.*, 2023. Towards a new urban health science. *Urban Science*, 7 (1), 30. doi:10.3390/urbansci7010030.

GFDRR, 2020. *ThinkHazard!* Washington DC: Global Facility for Disaster Reduction and Recovery. Available from: https://understandrisk.org/tool/thinkhazard-online-resource-thor/.

Giles-Corti, B., Lowe, M., and Arundel, J., 2020. Achieving the SDGs: evaluating indicators to be used to benchmark and monitor progress towards creating healthy and sustainable cities. *Health policy*, 124 (6), 581–590. doi:10.1016/j.healthpol.2019.03.001.

Giles-Corti, B., *et al.*, 2016. City planning and population health: a global challenge. *Lancet*, 388 (10062), 2912–2924. doi:10.1016/S0140-6736(16)30066-6.

Giles-Corti, B., *et al.*, 2022. What next? Expanding our view of city planning and global health, and implementing and monitoring evidence-informed policy. *Lancet global health*, 10 (6), e919–e926. doi:10.1016/S2214-109X(22)00066-3.

Gonzalez-Trevizo, M.E., *et al.*, 2021. Research trends on environmental, energy and vulnerability impacts of urban heat islands: an overview. *Energy & buildings*, 246, Article 111051. doi:10.1016/j.enbuild.2021.111051.

Gössling, S., *et al.*, 2023. Weather, climate change, and transport: a review. *Natural hazards*, 118 (2), 1341–1360. doi:10.1007/s11069-023-06054-2.

Guo, A., *et al.*, 2023. Quantifying the impact of urban ventilation corridors on thermal environment in Chinese megacities. *Ecological indicators*, 156, 111072. doi:10.1016/j.ecolind.2023.111072.

Han, L., *et al.*, 2022. Urban ventilation corridors exacerbate air pollution in central urban areas: evidence from a Chinese city. *Sustainable cities and society*, 87, 104129. doi:10.1016/j.scs.2022.104129.

Hess, J.J., *et al.*, 2023. A novel climate and health decision support platform: approach, outputs, and policy considerations. *Environmental research*, 234, 116530. doi:10.1016/j.envres.2023.116530.

HLPF-UN, 20 Mar 2024. *Voluntary national reviews*. High-level political forum on sustainable development- United Nations. Available from: https://hlpf.un.org/vnrs.

Hoeben, A.D., Otto, I.M., and Chersich, M.F., 2023. Integrating public health in European climate change adaptation policy and planning. *Climate policy*, 23 (5), 609–622. doi:10.1080/14693062.2022.2143314.

Houghton, A. and Castillo-Salgado, C., 2020. Analysis of correlations between neighborhood-level vulnerability to climate change and protective green building design strategies: a spatial and ecological analysis. *Building & environment*, 168, Article 106523. doi:10.1016/j.buildenv.2019.106523.

Hunter, R.F., *et al.*, 2023. Advancing urban green and blue space contributions to public health. *Lancet public health*, 8 (9), e735–e742. doi:10.1016/S2468-2667(23)00156-1.

ICS, 2021. Urban health and wellbeing in the Anthropocene. *In*: *The urban health and wellbeing programme (UHWB)*. Xiamen, China: International Science Council.

IPCC, 2019. Summary for policymakers. In: P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley, eds. *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.* doi:10.1017/9781009157988.001 .

IPCC, 2022. *Climate change 2022: impacts, adaptation and vulnerability* (contribution of working group II to the sixth assessment report of the Intergovernmental Panel on Climate Change, issue. C. U. Press.

IPCC, 2023. Summary for policymakers. *In*: Core writing team, H. Lee, & J. Romero, eds. *Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the Intergovernmental Panel on Climate Change.* Vol. 2025. Geneva, Switzerland: IPCC, 1–34. doi:10.59327/IPCC/AR6-9789291691647.001.

IRDR, 2014. *Peril classification and hazard glossary (IRDR DATA publication no.1)*. Integrated Research on Disaster Risk.

Iungman, T., *et al.*, 2023. Cooling cities through urban green infrastructure: a health impact assessment of European cities. *Lancet*, 401 (10376), 577–589. doi:10.1016/s0140-6736(22)02585-5.

Iungman, T., *et al.*, 2024. The impact of urban configuration types on urban heat islands, air pollution, CO(2) emissions, and mortality in Europe: a data science approach. *The Lancet planetary health*, 8 (7), e489–e505. doi:10.1016/s2542-5196(24)00120-7.

Kabisch, N., Korn H, Stadler J, and Bonn A. 2017. Nature-based solutions to climate change adaptation in urban areas—linkages between science, policy and practice. *In*: N. Kabisch, H. Korn, J. Stadler, and A. Bonn, eds. *Nature-based solutions to climate change adaptation in urban areas: linkages between science, policy and practice.* Springer International Publishing, 1–11. doi:10.1007/978-3-319-56091-5_1.

Kaminski, A., *et al.*, 2021. Using landscape metrics to characterize towns along an urban-rural gradient. *Landscape ecology*, 36 (10), 2937–2956. doi:10.1007/s10980-021-01287-7.

Karan, S., Shweta, S., and Anusha, B.S., 2023. Light pollution and the impacts on biodiversity: the dark side of light. *Biodiversity*, 24 (4), 194–199. doi:10.1080/14888386.2023.2244920.

Kelly, F.J. and Fussell, J.C., 2015. Air pollution and public health: emerging hazards and improved understanding of risk. *Environmental geochemistry and health*, 37 (4), 631–649. doi:10.1007/s10653-015-9720-1.

Khanal, S., Ramadani, L., and Boeckmann, M., 2022. Health equity in climate change policies and public health policies related to climate change: protocol for a systematic review. *International journal of environmental research and public health*, 19 (15), 9126. doi:10.3390/ijerph19159126.

Kim, Y.J., *et al.*, 2023. Connecting public health with urban planning: allocating walkable cooling shelters considering older people. *Landscape & ecological engineering*, 19 (2), 257–269. doi:10.1007/s11355-023-00543-z.

Kleiman, G., *et al.*, 2022. Enhanced integration of health. *Frontiers in sustainable cities*, 4, 34672. doi:10.3389/frsc.2022.934672.

Klopfer, F. and Pfeiffer, A., 2023. Determining spatial disparities and similarities regarding heat exposure, green provision, and social structure of urban areas - a study on the city district level in the Ruhr area, Germany. *Heliyon*, 9 (6), e16185. doi:10.1016/j.heliyon.2023.e16185.

Kuhlicke, C., Kabisch, S., and Rink, D., 2019. Urban resilience and urban sustainability. *In*: A.A. Michael, A. Burayidi, J. Twigg, and C. Wamsler, eds. *The Routledge handbook of urban resilience*. London: Routledge.

Lee, E.Y., *et al.*, 2023. Physical activity in the era of climate change and COVID-19 pandemic: results from the South Korea's 2022 report card on physical activity for children and adolescents. *Journal of exercise science & fitness*, 21 (1), 26–33. doi:10.1016/j.jesf.2022.10.014.

Li, F., *et al.*, 2022. Understanding urban heat vulnerability assessment methods: a PRISMA review. *Energies*, 15 (19), 6998. doi:10.3390/en15196998.

Li, Y., Urich, P., and Yin, C., 2020. Systems approach for climate change impacts on urban health: conceptual framework, modelling and practice. *In*: R.B. Singh, B. Srinagesh, and S. Anand, eds. *Urban health risk and resilience in Asian cities*. Springer Singapore, 3–31. doi:10.1007/978-981-15-1205-6_1.

Liu, S., *et al.*, 2022. A generalized framework for measuring pedestrian accessibility around the world using open data. *Geographical analysis*, 54 (3), 559–582. doi:10.1111/gean.12290.

Lowe, M., Whitzman, C., and Giles-Corti, B., 2018. Health-promoting spatial planning: approaches for strengthening urban policy integration. *Planning theory & practice*, 19 (2), 180–197. doi:10.1080/14649357.2017.1407820.

Lowe, M., *et al.*, 2015. Planning healthy, liveable and sustainable cities: how can indicators inform policy? *Urban policy & research*, 33 (2), 131–144. doi:10.1080/08111146.2014.1002606.

Lowe, M., *et al.*, 2019. Evidence-informed planning for healthy liveable cities: how can policy frameworks be used to strengthen research translation? *Current environmental health reports*, 6 (3), 127–136. doi:10.1007/s40572-019-00236-6.

Lowe, M., *et al.*, 2021. *Urban resilience for local government: concepts, definitions and qualities*. T. U. O. Melbourne. Available from: https://sustainable.unimelb.edu.au/__data/assets/pdf_file/0012/3960399/MSSI_Issues_Paper_Urban-resilience-for-local-government_Concepts-definitions-and-qualities.pdf.

Lowe, M., *et al.*, 2022. City planning policies to support health and sustainability: an international comparison of policy indicators for 25 cities. *Lancet global health*, 10 (6), e882–e894. doi:10.1016/s2214-109x(22)00069-9.

Lowe, M., *et al.*, 2023. *Urban resilience and localised sustainable development goals- City of Melbourne and international case studies*. Melbourne, Australia: T. U. O. M. Melbourne Centre for Cities.

Lowe, M., *et al.*, 2024. A research-based, practice-relevant urban resilience framework for local government. *Local environment*, 29 (7), 886–901. doi:10.1080/13549839.2024.2318571.

Luna Pinzon, A., *et al.*, 2022. The ENCOMPASS framework: a practical guide for the evaluation of public health programmes in complex adaptive systems. *The international journal of behavioral nutrition and physical activity*, 19 (1), 33. doi:10.1186/s12966-022-01267-3.

Makvandi, M., *et al.*, 2023. Urban heat mitigation towards climate change adaptation: an eco-sustainable design strategy to improve environmental performance under rapid urbanization. *Atmosphere*, 14 (4), 638. doi:10.3390/atmos14040638.

Meerow, S. and Newell, J.P., 2019. Urban resilience for whom, what, when, where, and why? *Urban geography*, 40 (3), 309–329. doi:10.1080/02723638.2016.1206395.

Meerow, S., Newell, J.P., and Stults, M., 2016. Defining urban resilience: a review. *Landscape and urban planning*, 147, 38–49. doi:10.1016/j.landurbplan.2015.11.011.

Meerow, S. and Stults, M., 2016. Comparing conceptualizations of urban climate resilience in theory and practice. *Sustainability*, 8 (7), 701. doi:10.3390/su8070701.

Münzel, T., *et al.*, 2022. Environmental risk factors and cardiovascular diseases: a comprehensive expert review. *Cardiovascular research*, 118 (14), 2880–2902. doi:10.1093/cvr/cvab316.

Münzel, T., *et al.*, 2025. The links between soil and water pollution and cardiovascular disease. *Atherosclerosis*, 403, 119160. doi:10.1016/j.atherosclerosis.2025.119160.

Murage, P., *et al.*, 2020. What individual and neighbourhood-level factors increase the risk of heat-related mortality? A case-crossover study of over 185,000 deaths in London using high-resolution climate datasets. *Environment international*, 134, 105292. doi:10.1016/j.envint.2019.105292.

Mushtaha, E., *et al.*, 2021. A study of the impact of major urban heat island factors in a hot climate courtyard: the case of the University of Sharjah, UAE. *Sustainable cities and society*, 69, 102844. doi:10.1016/j.scs.2021.102844.

Neuman, W.L., 2011. *Social research methods: qualitative and quantitative approaches*. England and Associated Companies throughout the world: Pearson Education Limited. Available from: https://books.google.com.au/books?id=iHGncQAACAAJ.

Nice, K.A., *et al.*, 2022. Isolating the impacts of urban form and fabric from geography on urban heat and human thermal comfort. *Building & environment*, 224, 109502. doi:10.1016/j.buildenv.2022.109502.

Nieuwenhuijsen, M.J., 2020. Urban and transport planning pathways to carbon neutral, liveable and healthy cities; a review of the current evidence. *Environment international*, 140, 105661. doi:10.1016/j.envint.2020.105661.

Orru, H., Ebi, K.L., and Forsberg, B., 2017. The interplay of climate change and air pollution on health. *Current environmental health reports*, 4 (4), 504–513. doi:10.1007/s40572-017-0168-6.

Pant, R., Hall, J.W., and Blainey, S.P., 2016. Vulnerability assessment framework for interdependent critical infrastructures: case-study for Great Britain's rail network. *European journal of transport and infrastructure research*, 16 (1). doi:10.18757/ejtir.2016.16.1.3120.

Pascal, M., *et al.*, 2021. Greening is a promising but likely insufficient adaptation strategy to limit the health impacts of extreme heat. *Environment international*, 151, 106441. doi:10.1016/j.envint.2021.106441.

Peng, S. and Maing, M., 2021. Influential factors of age-friendly neighborhood open space under high-density high-rise housing context in hot weather: a case study of public housing in Hong Kong. *Cities*, 115, 103231. doi:10.1016/j.cities.2021.103231.

Pineo, H., *et al.*, 2018. Promoting a healthy cities agenda through indicators: development of a global urban environment and health index. *Cities & health*, 2 (1), 27–45. doi:10.1080/23748834.2018.1429180.

Pineo, H., *et al.*, 2018. Urban health indicator tools of the physical environment: a systematic review. *Journal of urban health*, 95 (5), 613–646. doi:10.1007/s11524-018-0228-8.

Pineo, H., Zimmermann, N., and Davies, M., 2020. Integrating health into the complex urban planning policy and decision-making context: a systems thinking analysis. *Palgrave communications*, 6 (1), 21. doi:10.1057/s41599-020-0398-3.

Pinheiro, M.D. and Luís, N.C., 2020. COVID-19 could leverage a sustainable built environment. *Sustainability (Switzerland)*, 12 (14), 5863. doi:10.3390/su12145863.

Pinho-Gomes, A.-C., *et al.*, 2023. Air pollution and climate change. *The Lancet planetary health*, 7 (9), e727–e728. doi:10.1016/s2542-5196(23)00189-4.

PRISMA, 2018. *Prisma for scoping reviews (PRISMA-ScR)*. Retrieved July 15.

Prudent, N., Houghton, A., and Luber, G., 2016. Assessing climate change and health vulnerability at the local level: Travis County, Texas. *Disasters*, 40 (4), 740–752. doi:10.1111/disa.12177.

Prüss-Üstün, A., *et al.*, 2016. *Preventing disease through healthy environments: a global assessment of the burden of disease from environmental risks*. France: W. H. Organization. Preventing disease through healthy environments: a global assessment of the burden of disease from environmental risks (who.int).

Redman, C.L., 2014. Should sustainability and resilience be combined or remain distinct pursuits? *Ecology and society*, 19 (2). Available from: http://www.jstor.org/stable/26269581.

Renn, O., Klinke, A., and Schweizer, P.-J., 2018. Risk governance: application to urban challenges. *International journal of disaster risk science*, 9 (4), 434–444. doi:10.1007/s13753-018-0196-3.

Requejo, J.H., *et al.*, 2013. Measuring coverage in MNCH: challenges and opportunities in the selection of coverage indicators for global monitoring. *PLOS medicine*, 10 (5), e1001416. doi:10.1371/journal.pmed.1001416.

Rockefeller Foundation and Arup, 2015. *City resilience framework*. R. F. a. Arup.

Rothenberg, R., *et al.*, 2015. Urban health indicators and indices—current status. *BMC Public health*, 15 (1), 494. doi:10.1186/s12889-015-1827-x.

Sabatier, P.A. and Weible, C.M., 2014. *Theories of the policy process*. 3rd ed. Boulder, Colorado: Westview Press. Available from: http://site.ebrary.com/id/10901836.

Sallis, J.F., *et al.*, 2015. Co-benefits of designing communities for active living: an exploration of literature. *The international journal of behavioral nutrition and physical activity*, 12 (1), 30. doi:10.1186/s12966-015-0188-2.

Salvalai, G., *et al.*, 2022. Pedestrian single and multi-risk assessment to SLODs in urban built environment: a mesoscale approach. *Sustainability (Switzerland)*, 14 (18), 11233. doi:10.3390/su141811233.

Schmidt, K. and Walz, A., 2021. Ecosystem-based adaptation to climate change through residential urban green structures: co-benefits to thermal comfort, biodiversity, carbon storage and social interaction. *One ecosystem*, 6, e65706. doi:10.3897/oneeco.6.e65706.

Sera, F., *et al.*, 2019. How urban characteristics affect vulnerability to heat and cold: a multi-country analysis. *International journal of epidemiology*, 48 (4), 1101–1112. doi:10.1093/ije/dyz008.

Sharifi, A., *et al.*, 2021. A systematic review of the health co-benefits of urban climate change adaptation. *Sustainable cities and society*, 74, 103190. doi:10.1016/j.scs.2021.103190.

Simpson, N.P., *et al.*, 2021. A framework for complex climate change risk assessment. *One earth*, 4 (4), 489–501. doi:10.1016/j.oneear.2021.03.005.

Skevaki, C., *et al.*, 2024. Impact of climate change on immune responses and barrier defense. *The journal of allergy and clinical immunology*, 153 (5), 1194–1205. doi:10.1016/j.jaci.2024.01.016.

Slätmo, E., Nilsson, K., and Turunen, E., 2019. Implementing green infrastructure in spatial planning in Europe. *The land*, 8 (4), 62. doi:10.3390/land8040062.

Smith, N., *et al.*, 2021. Urban blue spaces and human health: a systematic review and meta-analysis of quantitative studies. *Cities*, 119, 103413. doi:10.1016/j.cities.2021.103413.

SMR, 2021. *Risk systemicity questionnaire*. San Sebastian: University of Navarra. Available from: https://smrproject.eu/tools/risk-systemicity-questionnaire/ .

Solís, P., Vanos, J.K., and Forbis, R.E., 2017. The decision-making/accountability spatial incongruence problem for research linking environmental science and policy. *Geographical review*, 107 (4), 680–704. doi:10.1111/gere.12240.

Southerland, V.A., *et al.*, 2022. Global urban temporal trends in fine particulate matter (PM(2·5)) and attributable health burdens: estimates from global datasets. *The Lancet planetary health*, 6 (2), e139–e146. doi:10.1016/s2542-5196(21)00350-8.

Speak, A.F. and Salbitano, F., 2022. Summer thermal comfort of pedestrians in diverse urban settings: a mobile study. *Building & environment*, 208, 108600. doi:10.1016/j.buildenv.2021.108600.

Taylor, E.J. and Hurley, J., 2016. "Not a lot of people read the stuff": Australian urban research in planning practice. *Urban policy & research*, 34 (2), 116–131. doi:10.1080/08111146.2014.994741.

Técher, M., Ait Haddou, H., and Aguejdad, R., 2023. Urban heat island's vulnerability assessment by integrating urban planning policies: a case study of Montpellier Méditerranée metropolitan area, France. *Sustainability (Switzerland)*, 15 (3), 1820. doi:10.3390/su15031820.

Thompson, R., *et al.*, 2023. Ambient temperature and mental health: a systematic review and meta-analysis. *The lancet planetary health*, 7 (7), e580–e589. doi:10.1016/S2542-5196(23)00104-3.

UN General Assembly, 2015. *Resolution adopted by the General Assembly: transforming our world: the 2030 agenda for sustainable development A/RES/70/1*. Available from: https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf.

UN General Assembly, 2016. *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction*. United Nations Office for Disaster Risk Reduction. Available from: https://www.undrr.org/publication/report-open-ended-intergovernmental-expert-working-group-indicators-and-terminology.

UN-Habitat, 2020. *Nua monitoring framework and related indicators. Draft version*. United Nations Human Settlements Programme. Available from: (https://www.urbanagendaplatform.org/data_analytics.

UN-Habitat, 2022. *Global urban monitoring framework*. Available from: https://unhabitat.org/the-global-urban-monitoring-framework.

UNDRR, 2017. *Disaster resilience scorecard for cities*. Geneva: United Nations Disaster Risk Reduction. Available from: https://www.unisdr.org/campaign/resilientcities/toolkit/article/disaster-resilience-scorecard-for-cities.html.

UNDRR, 2019. *Global assessment report on disaster risk reduction*. United Nations Office for Disaster Risk Reduction.

UNDRR, 2020. *Hazard definition and classification review: technical report*. Sendai Framework: UNDRR.

UNFCCC, 2024. *Defining and understanding transformational adaptation at different spatial scales and sectors, and assessing progress in planning and implementing transformational adaptation approaches at the global level* FCCC/TP/2024/8. United Nations Frameowrk Convention on Climate Change. Available from: https://unfccc.int/sites/default/files/resource/tp2024_08.pdf .

United Nations, 2015. *Indicators and a monitoring framework for the sustainable development goals: launching a data revolution for the SDGs*. New York: United Nations. Available from: https://sdgs.un.org/publications/indicators-andmonitoring-framework-sustainable-development-goals-17958 .

United Nations, 2018. *Resolution adopted by the General Assembly (A/RES/71/313): Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development*. United Nations.

United Nations, 2023. *COP28 UAE declaration on climate and health*. United Nations.

United Nations Environment Programme & International Science Council, 2024. *Navigating new horizons: a global foresight report on planetary health and human wellbeing*. Available from: https://wedocs.unep.org/20.500.11822/45890 .

United Nations Specialised Conferences, 2005. *Hyogo framework for action 2005-2015: building the resilience of nations and communities to disasters (A/CONF.206/6)*. United Nations. Available from: https://www.refworld.org/reference/confdoc/un/2005/en/20145 .

van Daalen, K.R., *et al.*, 2024. The 2024 Europe report of the Lancet Countdown on health and climate change: unprecedented warming demands unprecedented action. *Lancet public health*, 9 (7), e495–e522. doi:10.1016/s2468-2667(24)00055-0.

Van De Walle, J., *et al.*, 2022. Lack of vegetation exacerbates exposure to dangerous heat in dense settlements in a tropical African city. *Environmental research letters*, 17 (2), 024004. doi:10.1088/1748-9326/ac47c3.

Wang, L., 2023. Mediating effect of heat waves between ecosystem services and heat-related mortality of characteristic populations: evidence from Jiangsu Province, China. *International journal of environmental research and public health*, 20 (3), 2750. doi:10.3390/ijerph20032750.

Wardekker, A., *et al.*, 2020. A diagnostic tool for supporting policymaking on urban resilience. *Cities*, 101, 102691. doi:10.1016/j.cities.2020.102691.

Watts, N., *et al.*, 2015. Health and climate change: policy responses to protect public health. *Lancet*, 386 (10006), 1861–1914. doi:10.1016/S0140-6736(15)60854-6.

Watts, N., *et al.*, 2021. The 2020 report of the Lancet Countdown on health and climate change: responding to converging crises. *Lancet*, 397 (10269), 129–170. doi:10.1016/S0140-6736(20)32290-X.

Weber, S., *et al.*, 2015. Policy-relevant indicators for mapping the vulnerability of urban populations to extreme heat events: a case study of Philadelphia. *Applied geography*, 63, 231–243. doi:10.1016/j.apgeog.2015.07.006.

Wei, X., *et al.*, 2023. Integrating planar and vertical environmental features for modelling land surface temperature based on street view images and land cover data. *Building & environment*, 235, 110231. doi:10.1016/j.buildenv.2023.110231.

Whitehead, M., *et al.*, 2004. Evidence for public health policy on inequalities: 2: assembling the evidence jigsaw. *Journal of epidemiology and community health*, 58 (10), 817–821. doi:10.1136/jech.2003.015297.

Whitmee, S., *et al.*, 2024. Pathways to a healthy net-zero future: report of the Lancet Pathfinder Commission. *Lancet*, 403 (10421), 67–110. doi:10.1016/s0140-6736(23)02466-2.

WHO, 2010. *Urban HEART: Urban Health Equity Assessment and Response Tool*. J. World Health Organization & WHO Centre for Health Development (Kobe, Ed.). World Health Organization.

WHO, 2022. *Review of indicator frameworks supporting urban planning for resilience and health: third report on protecting environments and health by building urban resilience*. Available from: https://apps.who.int/iris/handle/10665/355763.

Wilkinson, C., 2011. Social-ecological resilience: insights and issues for planning theory. *Planning theory*, 11 (2), 148–169. doi:10.1177/1473095211426274.

Willis, K., 2010. Chapter 14: analysing qualitative data. *In*: M. Walter, ed. *Social research methods*. South Melbourne, Victoria: Oxford University Press.

World Health Organization, 2021. *Cop26 special report on climate change and health: the health argument for climate action*. World Health Organization. Available from: https://iris.who.int/handle/10665/346168.

World Health Organization, 2022. *Urban planning for resilience and health: key messages – summary report on protecting environments and health by building urban resilience*. Available from: https://apps.who.int/iris/handle/10665/355760.

World Health Organization, 2025. *World report on social determinants of health equity*. W. H. Organization.

Xu, T., *et al.*, 2023. A quantitative evaluation model of outdoor dynamic thermal comfort and adaptation: a year-long longitudinal field study. *Building & environment*, 237, 110308. doi:10.1016/j.buildenv.2023.110308.

Yin, Y., *et al.*, 2021. Dtex: a dynamic urban thermal exposure index based on human mobility patterns. *Environment international*, 155, Article 106573. doi:10.1016/j.envint.2021.106573.

Zhang, K. and Chui, T.F.M., 2019. Linking hydrological and bioecological benefits of green infrastructures across spatial scales – a literature review. *Science of the total environment*, 646, 1219–1231. doi:10.1016/j.scitotenv.2018.07.355.