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Developing adaptation outcome indicators to urban heat risks

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ABSTRACT

Climate scenarios predict that temperatures will rise and the subsequent heat periods that negatively impact human well-being will increasingly become common. The impact of heat in cities can be adapted to through urban planning, economic investments and other measures. The outcomes of adaptation should be monitored, for example, through indicators. However, adaptation outcome indicators are lacking research and development. We report a co-development process of adaptation outcome indicators that can be used to assess adaptation progress to urban heat risk. We use existing literature, a focus group discussion and a questionnaire to co-develop 16 indicators in the City of Helsinki, Finland. Developed indicators take into account key urban characteristics, including social vulnerability, state of the environment, infrastructure, green–blue infrastructure, economic resources, and knowledge and awareness. This study provides a framework for cities to develop their adaptation monitoring strategy and illustrates a novel empirical case study of derivation process of urban heat risk adaptation indicators.

1. Introduction

Climate change is likely to increase heat risk, which is harmful to people (IPCC, 2021). Due to the urban heat island (UHI) phenomenon, temperatures in urban areas are often higher than in surrounding areas, which amplifies the impact of heat on people's health (Klein Rosenthal et al., 2014). Heat causes significant harm in cities and adaptation measures are already necessary (Bradford et al. 2015). Adaptation refers to the process of adapting to the current or expected climate and its effects (IPCC 2014, 2021). The need for heat risk adaptation is likely to increase towards the end of the century (IPCC, 2021). The impact of the UHI phenomenon on temperatures has been underestimated due to the uncertainties of current projections (Zheng et al. 2021). According to the IPCC (2021), UHI and heat waves are expected to become more intense and common, which stresses the need for heat risk adaptation in urban areas.

People are vulnerable to extreme heat and heat waves in cities (Schoessow et al. 2022). Tuholske et al. (2021) estimate that exposure of the urban population to heat increased nearly 200% between 1983 and 2016, affecting 1.7 billion people globally. Recent action to manage heat and related health implications has increased as part of planned adaptation. A recent global review (n = 98 countries) suggests that adaptation to heat in high-income, developed countries is a health issue, particularly in urban areas, with most of the adaptation comprising autonomous coping strategies (Kotharkar and Ghosh, 2022; Turek-Hankins et al., 2021). Any societal response to heat must consider the most vulnerable groups of people and identify the factors that contribute to vulnerability. This

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consideration is necessary because socially vulnerable neighborhoods often experience a greater negative impact of heat (Wilhelmi and Hayden 2010) including higher mortality during heat waves (Norton et al. 2015).

Policy-making requires information on the progress and success of adaptation (Hanger et al. 2013). This information on progress necessitates setting standards for adaptation progress, and monitoring and evaluating measures accordingly, which often utilizes indicators (Jacob et al., 2022). However, approaches to measuring this progress are still developing. The most often used adaptation indicator types are processual indicators, which assess whether adaptation is implemented or not (Pringle & Leiter 2018). Processual indicators are used when the outcomes of adaptation are only visible in the long term. Additionally, they give a simplified view of adaptation that excludes relevant insights of the risk, progress and other important information that may be necessary for decision-making (Pringle & Leiter 2018; Chen et al. 2018, Berrang-Ford et al. 2019; Murieta et al., 2021). In contrast, outcome indicators measure the effects of adaptation measures on a given phenomenon. Outcome indicators often aim at harm reduction, which necessitates a risk-based approach (Donatti et al. 2020, Ford et al. 2013).

In general, policy outcome evaluation is more prescriptive than descriptive, and thus seeks to explain the factors of success and failure of adaptation (McConnell, 2010). This prescriptive feature is methodologically challenging, which may require basing the processes of monitoring and evaluating adaptation policy on processual success as an intermediate target for the outcome evaluation process (Stadelmann et al., 2015, Hinkel 2011, Dupuis & Biesbroek 2013). Indicators suitable for prescriptive use are rarely discussed, despite the recognition of the associated benefits (Dupuis & Biesbroek 2013; Ford et al. 2013). Ford et al. (2013) identified the strengths of outcome-based adaptation tracking as follows: i) quantification of adaptation progress and effectiveness ii) metric observation can happen over time iii) availability of standardized global datasets of hazards, losses and mortality across regions iv) legitimacy within policy evaluation community. At the local level, benefits of the development of outcome-based indicators are considered to relate to the participatory/collaborative science-practice approach (Arnott et al. 2016).

This study addresses the empirical gap to develop adaptation outcome indicators that account for the different elements of heat risk in urban context. In addition, it contributes to the literature on co-development of monitoring and evaluation systems. The objective of the study is to report a co-development process of adaptation outcome indicators that can be used to assess adaptation progress to urban heat risk. The case study focuses on the city of Helsinki, drawing on existing literature, a focus group discussion, and an online questionnaire to develop a set of 16 indicators for monitoring and evaluating adaptation across key urban characteristics. These characteristics are social vulnerability, state of the environment, infrastructure, green–blue infrastructure, economic resources and knowledge and awareness. Our research results show that monitoring and evaluation systems for urban adaptation should be co-developed to ensure their usability (Leitch et al., 2019). Furthermore, our research provides a framework for development of urban heat risk adaptation monitoring indicators in cities.

2. Background

2.1. Challenges to monitor adaptation through indicators

Defining adaptation indicators involves several challenges. Most importantly, adaptation needs are inevitably contextual and often dynamic and consequently there is a lack of universal and static indicators for adaptation (Christiansen et al., 2018). According to the European Environment Agency (EEA, 2012), a good indicator of adaptation is characterized by the following factors: relevant to decision-making and planning, linked to climate change or another problem, meritable, easily accessible, and scientifically well-reasoned. The acquisition of reliable information on adaptation progress through indicators requires focusing on a selected set of indicators rather than a single indicator (EEA, 2015).

A major challenge for adaptation monitoring is the development of measurable indicators that are consistent with the current understanding of actual adaptation (vs. planned) (Ford & Berrang-Ford 2016, Ebi et al. 2018). One possible approach to adaptation monitoring is to use indicators that measure the adequacy of cities' decisions and programs and compare them with identified adaptation commitments, targets, and needs (Ford & Berrang-Ford 2016, Ebi et al. 2018). For example, to measure the progress of adaptation, it is important that monitoring methods go beyond the commonly used documentation of adaptation. However, the number of observed adaptation measures might not indicate progress towards a more successful adaptation in a city, i.e. reducing risks and vulnerability (Knill et al. 2012, Ford et al. 2013, Hupe et al. 2014, Dupuis & Biesbroek 2013, Massey et al. 2014). Another disadvantage of relying on process indicators concerns their reproduction of failures in planning. For example, the initial failure to fully incorporate risk-related information and knowledge into the adaptation plans (Murieta et al., 2021). It is especially important to understand how these policies account for current and future risks and subsequently evaluate their contribution to both reducing vulnerability and increasing adaptive capacity. Such assessment provides information on the performance of the process, evaluates its strengths and determines if adaptation contributes to maladaptation (Smit & Wandel 2006). To support adaptation decision-making, Murieta et al. (2021) stress the importance of a risk-based approach that includes appropriate methods and metrics. This approach could also help link adaptation planning and climate risk reduction and ensure that both policies are coherent and coordinated (Dow et al. 2013, Murieta et al., 2021).

We contribute to the discussion on adaptation indicators in subnational adaptation monitoring (Leiter, 2015) by developing an approach that uses outcome indicators of adaptation measures, thus connecting adaptation with the climate risk approach. This approach means identifying components of heat risk (i.e., hazard, vulnerability, and exposure), that subsequently enable the identification and quantification of the social and ecological system effects resulting from adaptation activities (Donatti et al. 2020). Accounting for risk components is important because the impacts of heat are connected and depend on factors related to the built environment, as well as to climate, institutions, society, and the economy (Ellena et al. 2020). Our developed list of indicators can be used to measure the adaptation outcomes, such as reduced impacts of heat on citizens (Donatti et al. 2020).

2.2. Outcome indicators for urban heat risk adaptation

Climate risk comprises three components: hazard, exposure, and vulnerability (IPCC, 2014). Hazard refers to biophysical events or trends, such as a heat wave or a gradual increase in average temperature, that can be detrimental to people, ecosystems, and other systems; for example, the built environment (IPCC, 2021). The UHI phenomenon converges with heat events and creates even more severe heat conditions in urban environments where urban structures exacerbate the impact of UHI (Carter et al. 2015; Martín and Paneque, 2022). Exposure refers to the location of exposed people or assets; vulnerability refers to the characteristics of an exposed unit that is often considered to include sensitivity and adaptive/coping capacity (IPCC, 2014). Options for adaptation to heat risk involve reducing vulnerability and exposure, improving sensitivity characteristics, and increasing adaptive/coping capacities, while hazard can be targeted with mitigation (Martín and Paneque, 2022). For example, reducing the exposure of heat stress in the urban environment may require adaptations to buildings and their surrounding landscapes (Carter et al. 2015).

Based on existing literature, we identify six urban physical, and socio-economic characteristics within which the impacts of the urban heat risk materialize, and through which the adaptation measures may be targeted (Fig. 1). These urban characteristics influence exposure and vulnerability in many ways; in the following paragraphs, we define the characteristics and discuss their importance and implications for urban heat risk adaptation.

2.2.1. State of the environment

The environmental state of a city strongly affects its manifestation of heat and the UHI phenomenon. Researchers have found that the effects of heat waves on people vary in different parts of the city (Buechley et al. 1972). People exacerbate local warming in cities by using more air conditioning on hot days, which increases heat emissions (O'Malley et al., 2015). The changes in a city's micro- and macro-climate caused by UHI are reflected in changes in winds, humidity, storms, floods, and local ecosystems (O'Malley et al., 2015). Humid conditions in urban areas exacerbate the effects of heat and increase mortality and discomfort (Smith et al. 2013; Zhao et al. 2018).

Urban population growth increases anthropogenic activities such as fossil fuel combustion, which in turn increases the concentrations of air pollutants such as sulfur dioxide (SO2), nitrogen dioxide (NO2), carbon monoxide (CO) and particulate matter (PM). These primary pollutants substantially contribute to the poor air quality of cities and can lead to health problems, particularly respiratory and pulmonary diseases (Ghanbari Ghozikali et al., 2016; Olmo et al., 2011, Khaniabadi et al. 2017). The presence of high concentrations of air pollutants can also influence the intensity of UHI in urban areas, both positively and negatively (Ngarambe et al. 2021; Ulpiani, 2021). Wind also affects the intensity of the phenomenon. The transfer of turbulent heat decreases in streets as wind speed decreases (Kleerekoper et al. 2012). Wind influences the temperature of cities as wind carries heat away from street canyons. Accounting for wind in urban planning and building wind corridors (Hsieh and Huang, 2016) could effectively cool city temperatures (Kleerekoper et al. 2012). The UHI that many cities experience is greater at night than daytime and the clearest difference is when the wind is weak.

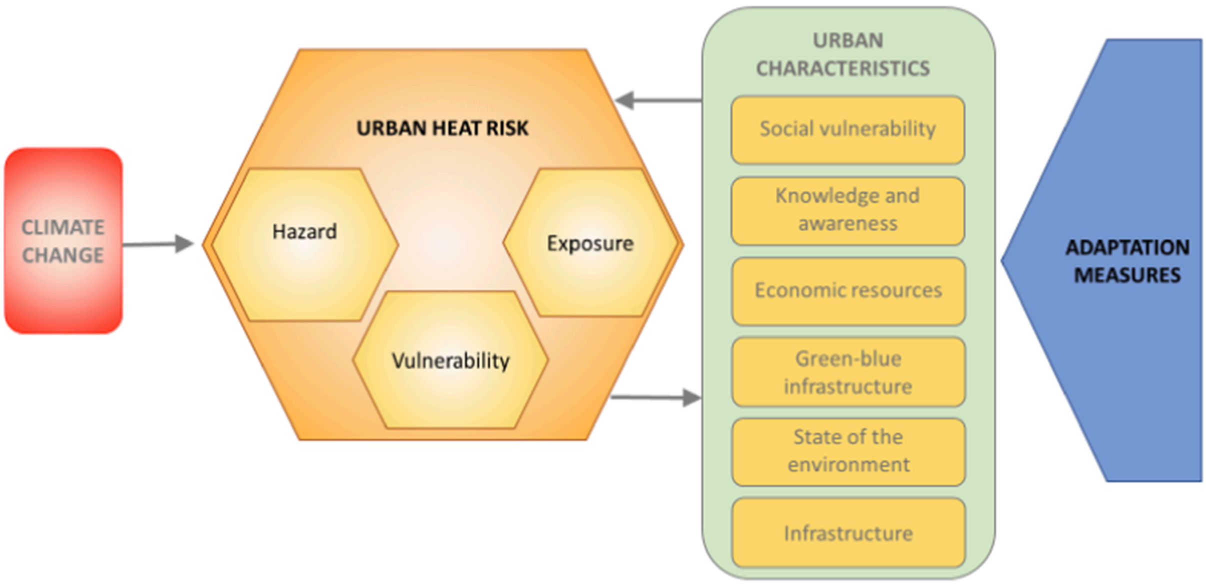

Fig. 1. Urban heat risk comprises hazard, vulnerability and exposure elements. *Urban heat risk is driven by climate change and influenced by the urban characteristics through which adaptation measures can target the elements of risk. The lowest arrow illustrates the impact on the urban characteristics.*

2.2.2. Green-blue infrastructure

Vegetation actively cools the environment through evapotranspiration, whereby leaves absorb solar radiation; this energy is converted into latent heat flux, lowering canopy temperature and surrounding area air temperature (Bowler et al., 2010; Rahman et al. 2017). Green infrastructure, urban forests, and trees can also lower air temperature by intercepting solar radiation, which overshadows the ground below and thus cools the surface (Bowler et al. 2010). Based on these processes, green areas can be several degrees cooler than closely built-up areas (ibid). The cooling effect can also extend to built-up areas close to green areas (Cohen et al., 2012; Feyisa et al., 2014; Zhang et al. 2017). The cooling capacity of vegetation is spread over an area of approximately 100–1000 m in an urban environment; however, this cooling is affected by the size of the vegetation area. Vegetation and green infrastructure, such as green roof and green wall systems cool cities temperatures. For example, evapotranspiration alone or together with shading can reduce peak summer temperatures by 1–5 °C (Laaidi et al., 2012; Pradhan et al., 2019). Covering roofs or facades with vegetation cools both outdoor and indoor temperatures and provides insulation during cold periods (Chun and Guldmann, 2018).

Water areas can also cool the temperature by 1–3° C through evaporation (Kleerekoper et al. 2012). A large body of water can absorb heat, which acts as a heat buffer; a moving body of water, such as a river, can transfer heat away from the area. This type of cooling effect varies by climate, distribution, geometry, time, and water body type (Gunawardena et al., 2017; Sun et al., 2012; Völker et al. 2013). In addition to the decrease in temperature caused by water evaporation, water is important in heat risk adaptation as it increases the quality of green structures by humidifying them during heat (Kleerekoper et al. 2012). The umbrella term for reservoirs, lakes, ponds, wetlands and rivers is blue infrastructure; such infrastructure can provide cooling benefits in urban areas (Gunawardena et al. 2017). Despite the cooling impact of blue infrastructure, it is used less than green infrastructure mainly due to its higher maintenance demands (ibid.).

2.2.3. Infrastructure

Urban heat risk involves significant harmful impacts on many infrastructure systems, the built environment and ecosystem services (Wang et al. 2021). Precise infrastructure design, therefore, can reduce the vulnerability of these infrastructures and mitigate the UHI phenomenon. For example, building density and building geometry are factors that affect both the amount of radiation in materials and the capture of the radiation of solar reflections between buildings and street surfaces (Kleerekoper et al. 2012). The thermal balance of cities is strongly affected by the exterior materials of buildings. On the one hand, these materials may absorb solar radiation, raising the ambient temperature (Santamouris et al. 2011). On the other hand, highly reflective materials can contribute to the energy efficiency of buildings by reducing the need for cooling and improving the microclimate of cities by lowering surface and air temperatures (Santamouris et al. 2011, 2012). Buildings can also develop wind corridors that can alleviate urban heat island phenomenon (Hsieh and Huang, 2016) and shading infrastructure can have cooling benefits (Dzyuban et al., 2022).

2.2.4. Social vulnerability

Social vulnerability is a measure of a population's sensitivity to hazards and its ability to respond to and recover from their effects (Cutter & Finch 2008). In other words, it is the inability of individuals, groups, or communities to adapt to potential external stressors (Füssel, 2012). Ethnicity, socio-economic class, health status, age and gender commonly define vulnerable populations (Cutter & Finch 2008). Cardiovascular diseases represent the most significant heat-stress-related health risk for sensitive groups such as older people and those with pre-existing medical conditions (Kivimäki et al. 2021; Kenney et al. 2014). The mortality of socially vulnerable residents during heat waves concerns other groups, most importantly people with mental health problems, children, and low-income single people. The homeless are particularly vulnerable to heat due to inadequate shelter (Bi et al. 2011, Gronlund et al. 2018, Kenney et al. 2014). Risks are particularly acute for those living in vulnerable areas, who may lack the necessary infrastructure, services, and adequate adaptability (Revi et al., 2014), such as access to health insurance, to ensure financial security in the face of climate risks (Knights & Vurdubakis 1993). Therefore, adaptation must consider the most vulnerable groups of people and identify the factors that contribute to their vulnerability.

2.2.5. Economic resources

Climate change is causing the urban economy to face new challenges that require the instruments already in use to become more adaptive for climate risks. This puts more pressure on city budgets and for additional adaptation resources (Kamal-Chaoui & Robert 2009), both in terms of public measures and autonomous adaptation by people living in cities (Johnson et al. 2021). Taxes, fees and grants are examples of existing financial instruments that can be developed to take better account of adaptation to climate risks (Kamal-Chaoui & Robert 2009).

Adaptation to UHI and the feasibility of adaptation options are still understudied, which complicates urban financial planning (Johnson et al., 2021). However, instruments such as a cost-benefit analysis can compare the economic viability of different adaptation scenarios (ibid). Central to UHI adaptation is green infrastructure, which is challenging for city administrations especially during tight financial periods due to the expense of implementing and maintaining such structures (Hansen et al. 2015, Kabisch et al., 2015).

The role of cities in assessing impact and addressing the root causes of vulnerability to climate risks (Ribot, 1995) is essential because socio-economically disadvantaged people are often most affected by heat stress and have a lower capacity to recover (Hallegatte et al., 2020). Therefore, cities must promote adaptation to heat-risk, as individuals cannot adapt to risk sufficiently. Such adaptation is possible, for example, by sustainable development budgeting in cities (Berg et al. 2019), taxation, or knowledge-building activities such as research or training (policy instruments) (Berrang-Ford et al. 2019).

2.2.6. Knowledge and awareness

As a tool, successful risk communication can help develop stakeholder trust, raise awareness and motivate people to prepare for climate risks (Moser, 2014). However, without trust between decision makers and people, clear communication, and relevant information, risk communication can fail (Abunyewah et al. 2018, Räsänen et al. 2017). Correct risk description strongly impacts motivation, environmental stressors, and the ability to act or adapt to climate change (Grothmann and Patt, 2005). Heatwaves occur differently; consequently, adaptation and coping measures vary greatly by sector. Heat preparedness plans and early warning systems can significantly reduce fatalities and other heat impacts (Casanueva et al. 2019, Watts et al. 2019). By introducing clear communication structures, responsibilities and instructions for heat events, adverse health effects can be minimized (WHO, 2008). Regarding such adverse health impacts, vulnerable people should be identified, approached, and provided with correct information, because they may not know their risk factors (Connelly et al. 2018).

3. Methods and materials

3.1. Study area

Our study area is the City of Helsinki, located in Southern Finland (60°10́N, 24°57́E). The overall population of the city is 660,000, with a population density of ca. 3000 per km^2. The city area includes densely and sparsely built residential areas, industrial and commercial areas, parks and forests, and some agricultural areas. Although Helsinki is located in the temperate zone with reasonably cool climate, heat waves during summer months are one of the key recognized climatic and weather hazards in the area (Pilli-Sihvola et al. 2018, Helsinki 2019). The adverse impacts of heat are in particular health-related, such as illnesses and deaths (Ruuhela et al. 2017, 2020, Sohail et al. 2020), and occasional drought periods (Pilli-Sihvola et al. 2018, Helsinki 2019). In the City adaptation plan, planned measures to decrease heat risk include temperature management in buildings, especially in hospitals and elderly homes, and development of blue and green infrastructure (Helsinki, 2019). However, the development of adaptation indicators to heat-related risk has not been a priority. Currently the Helsinki Metropolitan area uses the following adaptation indicators relevant to heat risks: annual mean temperature, number of hot days, number of green roofs, and social vulnerability to heat (HSY, 2022).

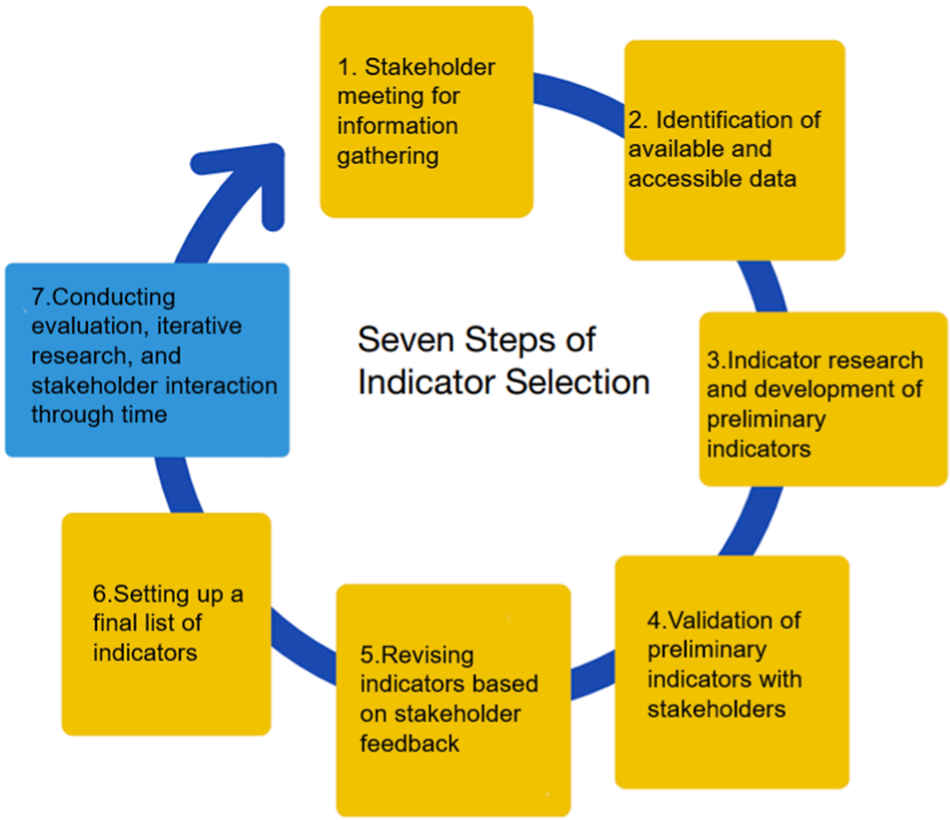

Fig. 2. The seven steps of the selection process for indicators and monitoring (NPCC, 2015). The steps in yellow were those implemented in this study.

3.2. Research approach

We chose an indicator-based approach, as indicators can be used to assess and monitor the effectiveness and usefulness of adaptation measures; indicators can also help to systematically assess adaptation projects and increase their comparability (Kabisch et al. 2016). We used the Seven Steps to the Selection Process of Indicators and Monitoring framework (NPCC, 2015) (Fig. 2) as an iterative tool, using the premise that what cannot be measured cannot be controlled.

This research uses a framework developed by NPCC (2015) (Fig. 2) for the indicator selection process. The framework was chosen because the process is clearly described, iterative, enables co-development and is repeatable for possible future needs. The framework is not location-bound, so it can be used in any city. The process itself does not monitor the adaptation, but when all the steps have been implemented, an indicator system has been created that can be used to monitor the adaptation, allowing for iterative development of indicators for adaptation monitoring. We apply the first six steps of the framework to report a co-development process of adaptation outcome indicators.

3.3. Methods

Steps 1–3: Compilation of preliminary indicators. To develop the indicators, we searched for articles in the Web of Science and Google Scholar databases using the following search commands related to urban heat risk, adaptation and monitoring: urban heat island, social vulnerability, adaptation, heat island indicator, climate change adaptation, along with combinations of these search commands. We refined the articles found in the search for those addressing the urban heat risk elements (hazard, vulnerability, exposure). Our subsequent discussions with the City of Helsinki's expert on adaptation of climate change concerned the key issues concerning both adapting to heat risk in Helsinki and the available data to monitor the adaptation progress. Table 2 illustrates the preliminary list of indicators we developed to reflect the six characteristics presented above (Fig. 1).

Step 4–6: Evaluation of indicator list. The developed indicator list was evaluated with the help of a focus group discussion (Appendix B) and a questionnaire (Barbour, 2007). The selection criteria for participants (both focus group discussion and questionnaire respondents) were being an expert from the metropolitan area in the field of and adaptation and heat risk being related to their work. A workshop was held in January 2020 on adaptation to climate change in the City of Helsinki, which included this study's focus group discussion. The discussion involved a short introduction to the topic and the current monitoring of Helsinki's adaptation and its indicators. The introduction was followed by a 25-minute focus group discussion on the preliminary indicators to evaluate their challenges, usefulness, and feasibility in Helsinki, focus group discussion was also a good information source for participants' perceptions on the topic. The focus group participants were six experts working for the City of Helsinki. Experts were from the environmental, technical, and social and health sectors.

The focus group discussion was recorded, transcribed, and subsequently analyzed in ATLAS.ti. An abductive thematic analysis was applied where the transcripts were coded, reviewed, and regrouped according to relevant factors (Thompson 2022). Six codes (Table 1) were developed according to the content of the discussion that raised important heat risk adaptation means for Helsinki by the participants, and the subcategories were developed through reviewing the codes to inform which subject areas the codes contain. See appendix B for detailed description of the focus group discussion results.

The questionnaire was used to further evaluate the list of indicators, which was modified according to the focus group discussion, using the four-point Likert scale (from value 1, "useless" to 4, "really useful", and "I don't know". The questionnaire also had open-ended responses on how a single indicator could be developed or refined. This allowed us to map the experts' current priorities for adaptation to heat risk and UHI in the city, their possible lack of information on the topic and the areas they consider have room for improvement. Questionnaire had 10 respondents from the workshop (22 participants) that were not all participants of the focus group discussion. Respondents were from the environmental, technical, social and health sectors.

Based on the content of the response, the open-ended responses were arranged into the following four categories: *proposed correction, irrelevant, positive comment, and clarifying question.* We developed a final list of indicators based on the information in the questionnaire and identified the climate risk elements that each indicator targets based on literature.

Table 1
The coding scheme for analyzing the workshop discussions.

Code	Subcategories
State of the environment	Temperature, Air quality
Green infrastructure	Green roofs, City trees
Blue infrastructure	Stormwater solutions, Water areas
Green area	Green factor
Cooling	Cooling equipment, Ventilation, Sunshade
Social vulnerability	Elderly, Home care

Table 2
List of indicators and justifications for them.

Factors	Preliminary list of indicators	Justification	Indicator after the focus group discussion	Final list of indicators after the questionnaire	Component of risk affected by indicator
Social vulnerability	1. Number of residents with health insurance	Health insurance is needed to ensure financial security in the face of climate risks and their possible negative impact on health (Knights and Vurdubakis 1993).	*No changes suggested*	*Deleted*	–
	2. Number of elderly people at risk area	The elderly are most at risk during heat waves (Bi et al. 2011).	Number of people in need of home care in the risk area	Relative number of people in home care in the heat prone area	Vulnerability
	3. Regional distribution of social vulnerability and comparison of these areas with environmental factors	Regional social conditions affect the magnitude of climate risk and health impacts (Revi et al., 2014).	Regional distribution of social vulnerability	Territorial distribution of internal (e.g., age and health) and external (e.g., income level, education, housing) social vulnerability	Vulnerability Exposure
Infrastructure	4. Area of cool surfaces in the district	Highly reflective materials are cost-effective, environmentally friendly, and efficient types of passive technology. These materials contribute to the energy efficiency of buildings by reducing the need for cooling and improving the microclimate of cities by lowering surface and air temperatures (Santamouris et al. 2011, 2012).	*No changes suggested*	Area of cool surfaces in proportion to the number of residents in the district	Exposure
	5. Number of dwellings/ premises without a cooling device	High temperatures can cause significant problems in regulating body temperature, which can result in discomfort to a person and even pose a health risk (Kleerekoper et al. 2012). Therefore, it is important to monitor the indoor temperature as well.	*No changes suggested*	Relative amount of dwellings/ premises in the heat prone area that are in danger of exceeding the permitted temperature levels and do not have a cooling device	Exposure
	6. Number of dwellings/ premises with district cooling / possibility for district cooling	High temperatures can cause significant problems with body temperature regulation, which can result in human discomfort and even pose a health risk (Kleerekoper et al. 2012). It is therefore important to monitor the indoor temperature as well.	*No changes suggested*	Relative amount of dwellings/ premises with or without district cooling in the heat prone area	Exposure
Blue-green infrastructure	7. Number of green roofs in the district	Indoor temperature of the building decreases due to the insulating value of the green roof/wall (Chun and Guldmann, 2018).	*No changes suggested*	Relative amount of green roofs in the heat prone area	Exposure Hazard
	8. Number of green areas in the district	Vegetation and green infrastructure, such as green roofs and green wall systems cool cities temperatures. For an example, evapotranspiration alone or together with shading can reduce peak summer temperatures by 1–5 °C (Laaidi et al., 2012; Pradhan et al., 2019)	*No changes suggested*	Areas covered by vegetation in relation to the water-impermeable area in the district	Exposure Hazard
	9. Number of green walls in the district	Indoor temperature of buildings decreases due to the insulating value of the green roof/wall (Chun and Guldmann, 2018).	*No changes suggested*	Relative amount of green walls in the heat prone area	Exposure Hazard
	10. Number of water areas in the district	Water has an average cooling effect of 1–3° C and can cool the temperature through evaporation. A large body of water can absorb heat, which acts as a heat buffer; a moving body of water, such as a	*No changes suggested*	Relative amount of water areas in the heat prone area	Exposure

(*continued on next page*)

Table 2 (*continued*)

Factors	Preliminary list of indicators	Justification	Indicator after the focus group discussion	Final list of indicators after the questionnaire	Component of risk affected by indicator
		river, can transfer heat out of the area (Kleerekoper et al. 2012).			
	11. Number of trees in the district	Trees can lower air temperature by intercepting solar radiation (Bowler et al. 2010).	*No changes suggested*	Relative amount of trees in heat prone area	Exposure Hazard
State of environment	12. Nitrogen dioxide content in the district	The presence of high concentrations of air pollutants could also influence the manifestation and intensity of UHI in urban areas (Ngarambe et al., 2021, Ghanbari Ghozikali et al., 2016; Olmo et al., 2011; Khaniabadi et al. 2017)	*No changes suggested*	Concentrations of air pollution in the heat prone area during the summer	Exposure
	13. Temperature differences between districts	UHI increases the intensity and duration of a heat wave in an urban environment. The effects of heat waves on people have been shown to differ in different parts of the city (Buechley et al. 1972).	*No changes suggested*	Temperature differences between districts	Exposure
	14. Humidity and temperature in neighborhoods	High humidity increases heat stress (Smith et al. 2013; Zhao et al. 2018)	*No changes suggested*	Humidity and temperature in neighborhoods	Exposure
	15. Temperature of building roofs	The materials of the exterior of buildings are central to the thermal balance of cities. These materials absorb solar radiation, raising the ambient temperature (Santamouris et al. 2011).	*No changes suggested*	Temperature of building roofs	Exposure
Economic resources	16. City financial contribution to X	Cities should support sustainable development, such as adaptation to the challenges of climate change, through their budgeting (Berg et al. 2019).	*No changes suggested*	The city's annual investment and operating costs to prevent the UHI phenomenon	Exposure Vulnerability Hazard
Knowledge and awareness	17. Number of early warning systems	Vulnerability is also associated with a lack of risk communication; lack of appropriate information can lead to incorrect risk descriptions (Birkmann and Fernando, 2008).	*No changes suggested*	Proportion of residents reached by the early warning system	Vulnerability

4. Results

4.1. Refining the preliminary list of indicators

We initially developed a preliminary list of 17 indicators and grouped them into six characteristics based on literature (section 2.2). Identified in the coding process were the six most important heat risk adaptation means for Helsinki that were determined during the discussion. They emphasized the importance of four factors of urban characteristics (social vulnerability, infrastructure, blue-green infrastructure, state of the environment) in relation to existing literature. Table 2 shows the five most useful indicators (#4, #10, #11, #13 and #16) that the city experts determined according to the survey responses. The highest number of "I do not know" responses (40 %) related to the indicator "nitrogen dioxide content in the district" as respondents lacked information about the effects of nitrogen dioxide on the UHI phenomenon. Only three indicators (#1, #5 and #17) were considered "useless" by some respondents. The open-ended responses mainly concerned the specification of an indicator, implying the need for indicators to be clearer and more operational in practice (Appendix A). Responses also helped to more precisely account for the needs and opportunities of the city's adaptation planning. Open-ended responses criticized two indicators (#1 and #5) and questioned their necessity. Responses had little fragmentation; respondents often considered the same indicators to be either useful or respondents were uncertain about the functioning of the indicator. Based on the survey results, we modified 11 indicators and removed 1 indicator ('Number of residents with health insurance'). Table 2 illustrates the final list. In addition, Table 2 shows the justification drawn from the literature, the modification of the indicator after the focus group discussion, the final list of completed indicators after the questionnaire, and the urban heat risk elements targeted by the indicator.

4.2. Indicators for measuring progress

Developed for the social vulnerability factor were two indicators (#2 and #3). Indicator #2 (Table 2), which concerns the relative number of residents particularly vulnerable to excess heat, focuses on the number of people in home care in the area. According to focus group participants, hospitals and service homes in the risk area need special consideration and should be the primary focus during heat periods. Many participants stated that people who are unable to move around independently at home are the most vulnerable group because they do not have immediate security or someone who constantly checks their well-being. Thus, monitoring the change in the relative population residing in home care in a particular area can be used to indicate the change in overall vulnerability of the area. As the home-care patients are not the only socially vulnerable group, we developed another indicator #3, which shows the risk areas that are particularly vulnerable to heat and UHI in relation to internal and external social vulnerability. The value of the indicator constitutes of the proportion of socially vulnerable areas (social vulnerability index in city of Helsinki) within the heat hazard prone areas in direct proportion. Thus, monitoring the change in the proportion of socially vulnerable people in heat prone areas can be used to indicate changes in vulnerability and exposure to heat as an element of the total social vulnerability of an area, together with indicator #2.

Three indicators (#4–6) were developed to identify the exposure to heat risk through infrastructure. Most participants addressed the issue of passive cooling and thought it to be inappropriate to have cooling devices in every building. Important to remember is future inventions for existing buildings, such as cooling technologies that promote adaptation to climate change and heat such as window protection, which are common in green construction (Chun and Guldmann, 2018) and can provide more solutions in the future. This emphasizes the importance of green infrastructure in adaptation. Group discussions confirmed the suitability of cool surfaces for monitoring adaptation**.** Thus, the change in the proportion of cool surface areas mitigating UHI in the risk area (#4) can be used to monitor the change in the exposure of the area in direct proportion. This indicator alone is insufficient to show the infrastructure related exposure. Contributing indicators #5 and #6 were developed to measure the change in the exposure level at the household scale with a relative amount of risk area dwellings that are most exposed to heat hazard and are neither prepared with cooling (#5) nor the availability of distance cooling in an area (#6). The value of these indicators is directly proportional to the exposure level of an area, that is, as the value decreases, the exposure to risk increases.

Five indicators (#7–11) were developed to measure the change in exposure through the change in the proportion of blue-green infrastructure coverage of an area. This change also mitigates climate change through increased carbon capture (green infrastructure) and thus indicates the change in hazard. Developed indicators account for broad green and blue areas (#8 and #10), and also smaller green structures (#7, #9 and #11) that support heat-risk adaptation. Together, these four indicators more comprehensively show blue-green infrastructure related exposure, along with any change in hazard. All participants stressed the need for more green spaces and blue areas, and more attention paid to monitoring. The value of the indicator refers to the relative amount of blue-green infrastructure in the heat prone area; this value has an indirect proportional relation to the exposure and hazard elements of the blue-green infrastructure related risk. The fewer blue-green structures existing in the city in relation to the area, the lower the value of the indicator. As the indicator value decreases, the hazard exacerbates, and the exposure of people to the heat hazard increases.

Developed for the state of the environment factor were four indicators (#12–15). These indicators show which areas are at risk of more severe exposure to heat (indicators #12 and #15), and which are most exposed to the UHI that is related to temperature differences between districts (#13). Indicator #15 also shows which buildings are most exposed to UHI, and their temperatures. Focus group discussion participants stressed the need to start temperature monitoring in Helsinki. Temperature has not been sufficiently systematically measured, which is a significant deficit for heat hazard and UHI monitoring. The higher the temperature, humidity, and the proportion of nitrogen dioxide in the air, the lower the value of the indicator. The decline in value causes an increase in exposure to heat risk.

The indicator (#16) that was developed for the economic resources factor shows the city's annual financial contribution to UHI adaptation. This contribution can reduce all the heat risk components, as it can be directed to different types of measures. Thus, monitoring the change in the amount a city's UHI adaptation budget can be used as an overall indicator of the heat risk adaptation progress that is related to economic resources in direct proportion. A low budget lowers the value of the indicator and negatively affects all three components of risk.

The indicator (#17) was developed for vulnerability to heat risk in relation to the knowledge and awareness factor. This indicator measures the proportion of residents reached by the early warning systems and it tells how many residents in the risk area can mitigate the harms of the heat by anticipation. The value of the indicator is calculated in relation to the number of people who are reached by the early warning system. The fewer people the warning system reaches, the lower the indicator value, which increases the vulnerability to risk.

5. Discussion

We developed 16 monitoring indicators for adaptation to heat risk in cities. The indicators represent the key outcomes of heat risk adaptation in accordance with the different components of climate risk (hazard, vulnerability, exposure), which is considered crucial in understanding the success of adaptation (Murieta et al., 2021). Additionally, outcome indicators are suitable for evaluation and are a good gauge of the success of adaptation (Ebi et al. 2018). The strength of the developed outcome indicators is that they deal with every component of risk. Outcome indicators will also be important in the future when cities want to assess the success of adaptation. The effectiveness and successfulness of adaptation is increasingly being discussed (Owen 2020, Singh et al., 2022) and outcome indicators can support the development of this effectiveness/successfulness research.

This study confirms that topics considered important in literature, such as the importance of green spaces, were also perceived as important means of adaptation in the discussion and survey responses. Versatile means of adaptation to heat risk contribute to the well-being and public health of the urban environment and its citizens. Blue-green infrastructure helps to solve many other challenges than just the heat risk and UHI phenomenon; for example, well-designed blue-green infrastructure can mitigate noise pollution, air pollution and stormwater problems (Li et al., 2019; Nieuwenhuijsen, 2021; Tomson et al., 2021).

Our indicators illustrate the outcomes of adaptation that can be observed in relation to hazard, exposure, and vulnerability, and the possibility of reducing the climate risk arising from heat and UHI phenomenon. For example, the indicator “proportion of residents reached by the early warning system” informs how many residents in the risk area have the opportunity to alleviate the harms of heat by anticipation. Our study brings a twofold contribution to the field of adaptation to heat risk in cities: firstly, regarding the focus on outcome indicators and secondly, regarding the co-development process of the indicators themselves.

First, monitoring cities’ adaptation measures can contribute to the success of adaptation, reduce the impact of climate risks, increase knowledge dissemination and positive competition between cities for adaptation (Surminski 2013, Chen et al. 2018). Adaptation monitoring also facilitates documenting best practices, enabling their early adoption, promoting collaboration between different actors (Ford et al. 2011), and allowing the sharing of information about what works, where, and why (Berrang-Ford et al. 2019). Our focus on outcome indicators allowed us to explore how adaptation measures may be working in relation to the climate risk. This exploration goes beyond merely documenting whether a measure has been implemented as planned; instead, it facilitates an understanding of how the measure has affected the risk in question. The measuring process could be further developed by establishing numerical baseline for indicators and a regular monitoring interval; the baseline could be tested and evaluated after different periods of time to assess its performance. The indicators should also be periodically revised in relation to any implemented changes in adaptation policy and measures.

Our indicators can be used to monitor the decrease/increase of harm in three risk factors. Developing indicators for key urban characteristics facilitates monitoring progress on adaptation. The indicators developed in this study are possible to be combined with already existing indicators in Helsinki and they may be applicable in other cities as well. However, the use of a framework, such as the NPCC’s steps towards indicator selection, may allow for case specific indicators to be chosen. In this way, the feasibility of the indicators can be ensured in the target city. This research gives tools for cities to develop their adaptation monitoring strategy and co-development process. Future research could focus on types of outcome indicators that are more locally relevant and concern issues that are relevant to the daily lives of city stakeholders. We consider the indicators applicable to both large- and medium-sized urban areas if the adaptation monitoring system is based on the identification of a city’s characteristics, climate, and future climate scenarios. The indicators cannot yet be compared because Helsinki does not have a numerical baseline and long-term monitoring is needed to develop this baseline. To further evaluate the indicators developed in this study, indicators should be put into practice and create values for them. After this, two or more cities should introduce the same indicator development process and compare both the process and the usefulness of indicators over time.

In addition to advancing the field in terms of the outcome indicators related to adaptation, the co-development approach supports the advancement of adaptation in cities. Here, we implemented the approach developed by the NPCC to show how an iterative process can advance adaptation development, planning, evaluation and monitoring. This study found that a good information source for participants’ perceptions is the focus group discussion method. Group discussions allowed us to establish a collective expert view of the UHI phenomenon as part of the climate-change-induced heat risk in Helsinki and the main associated concerns (Wilson, 1997). By supplementing the focus group discussion results with an electronic questionnaire, we gained in-depth information that helps us to understand the issues requiring development in the City of Helsinki. Merely conducting a survey would not have resulted in comprehensive information, as questionnaire have limitations (Wilson, 1997). The most significant limitations of this study include the short duration of the focus group discussion; with more time, the indicators could have been discussed in more depth. Moreover, a larger number of participants and a wider sample including other stakeholder groups, such as residents, may have provided additional information about the region’s adaptation needs and capacities. Two experts were representing their own field related to urban heat risk in Helsinki. The same problem limits the results of the survey. A larger group of respondents could have contributed to a more critical examination of the indicators. Indicators could have been developed further and clarified how their operation would work in practice, how they would be measured and in what timeframe.

6. Conclusion

This study used literature, focus group discussion and an electronic questionnaire to develop 16 indicators for monitoring the outcomes of adaptation to heat risk. These indicators comprehensively addressed adaptation across six urban characteristics (state of environment, social vulnerability, urban infrastructure, economic resources and knowledge and awareness), while accounting for the three components of climate risk. This study shows how risk knowledge can be integrated into adaptation policy outcome monitoring, and thus moves towards a more advanced assessment of adaptation. The importance of systematic and comparable adaptation strategies is widely acknowledged (see, for example NPCC, 2015). Important for a city to develop its adaptation monitoring is the documentation of decisions and programs to explore sufficient coverage. Decisions and programs should be compared to identified adaptation commitments, targets and needs.

The development of indicators in this study does not in itself directly contribute to achieving the desired level of adaptation; nevertheless, the study represents an important step in the process of developing adaptation monitoring and co-development of it. This study raises further questions for research and practice, for example, concerning city-specific design needs for a monitoring framework, and the possibility and potential meaningfulness of developing a framework that could be used in all cities in a given country. These types of consolidated approaches would allow for a better comparison of adaptation developments between cities. The concrete benefits of the indicators should be practically tested, a set of indicators should be introduced, and the development of adaptation should be consistent and monitored over an agreed period of time. These steps would enable us to determine the existence of a change in adaptation during a particular period.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Questionnaire open-ended answers

COMMENTED INDICATOR	OPEN-ENDED ANSWERS
1. Number of residents with health insurance	A situation whereby vulnerability is described by the number of private insurances was not seen as desirable. The indicator was considered irrelevant. The responses confirmed that the indicator was not useful.
2. Number of people in need of home care in the risk area	Respondents asked for a more precise definition of those in need of home care. They also suggested modifying the spelling of the indicator so that it would be more exact and leave no room for interpretation of who is “in need of home care”. The responses also considered whether this could be reflected in the health care resources of each region and whether there is a high-resource or low-resource health care service in a region that relies on home care.
3. Regional distribution of social vulnerability	Responses highlighted that social vulnerability includes both external and internal vulnerabilities. The indicator should reflect both of these aspects, i.e., the indicator should be considered through different groupings. Internal vulnerability includes health and external income levels, education, and housing. The indicator was also found very useful and helpful in planning and targeting when presented as spatial data.
4. Area of cool surfaces in the district	Respondents considered whether the area of cool surfaces could be interpreted from map data or aerial photographs. Both quantity and providing sufficiently large cool surfaces as spatial data were considered important. The area of cool surfaces should be somehow proportional to the size of the area or the number of inhabitants.
5. Number of dwellings / premises without a cooling device	The lack of cooling systems does not necessarily mean that the dwelling or premises is problematic in heat conditions. Cooling systems consume energy and can also exacerbate the UHI phenomenon locally; therefore, these systems are unfeasible regarding sustainable development goals. A better indicator of exposure concerns dwellings or premises where the indoor temperature exceeds 32° C (or 28° C) and when the outdoor temperature exceeds 25° C. Respondents claimed that the primary aim should be the prevention of premises from heating up passively.
6. Number of dwellings / premises with district cooling / possibility to it	The indicator should be restricted to determining the number of premises with district cooling in the district cooling area. However, centralized cooling was considered a more sensible solution than stand-alone equipment.
7. Number of green roofs in the district	Respondents perceived the development of the number of green roofs a very important and useful indicator. Additionally, respondents believed that studying the number of green surfaces in neighborhoods would be interesting.
8. Number of green areas in the district	Respondents found the term “green area” unclear; therefore, needed is new wording such as “area covered by vegetation”, which could be presented regarding built-up or impermeable areas; thus, spatial data would be used accordingly. Determining the extent of the area could involve comparing individual trees to park areas. The indicator could also include a few size classes.
9. Number of green walls in the district	The monitoring of green walls divided many respondents’ opinions. Some considered the issue quite marginal and unnecessary. However, many respondents considered monitoring green walls useful and urgent, and that it should also be presented as spatial data. Respondents also suggested including this indicator in green roofs, as a separate examination may not add value.
10. Number of water areas in the district	Waters should be classified and defined. Depth and surface area must also be considered.

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(*continued*)

COMMENTED INDICATOR	OPEN-ENDED ANSWERS
11. Number of trees in the district	The number of trees should be proportional to the area of the district to allow both comparison with other districts and analysis of the stormwater flood / UHI phenomenon. Also considered useful was to develop an index that accounts for tree size.
12. Nitrogen dioxide content in the district	The combined effect of air quality and the UHI phenomenon can be much greater than the effect of warming alone. Nitrogen dioxide is only one air pollutant, the most significant being particulate matter, especially fine particles (PM 2.5). Ozone is also important, although the concentrations are low in Finland.
13. Temperature differences between districts	This indicator did not receive open answers. The indicator was found to be really useful (70 %), useful (20 %) and slightly useful (10 %) on the Likert scale. The indicator is intended to be clear and easy to implement; therefore, writing further questions or criticisms may have been considered unnecessary.
14. Humidity and temperature in neighbourhoods	Respondents noted that humidity and temperature could be their own indicators; however, their combined effect is significant.
15. Temperature of building roofs	According to some respondents, roof temperature could be included in the UHI modeling; however, other respondents stated that the issue is not significant in Finland except in individual sites where the thermal insulation of the roofs is very weak.
16. City financial contribution to x	Based on the responses, this indicator reflected how seriously the matter is considered in the city. The city's annual investment and operating costs to adapt the UHI phenomenon can be calculated. Development in environmental accounting is needed.
17. Number of early warning systems	Respondents did not wish for a large number of early warning systems; instead, they wished that the indicator could monitor how many inhabitants a particular system reaches.

Appendix B

Results of the focus group discussion

FACTOR	RESULTS OF THE FOCUS GROUP DISCUSSION
Social Vulnerability	According to the participants, the UHI phenomenon is strongest in the city center. Although the vulnerability map suggests that social vulnerability is lowest in the city center, hospitals in the area need consideration. If the area has service homes or hospitals, they should be the primary focus. Many participants stated that people who are unable to move independently at home are the most relevant group because they do not have immediate security. The number of elderly people in the risk area is a very general indicator; however, not all elderly people are tied to their own home. There are also other people in home care than the elderly.
Infrastructure	The majority of participants stated that it is inappropriate to have cooling systems everywhere and that the meaning of cooling systems should be clarified. A consultancy study on cooling options for senior centers is being commissioned in Helsinki, as mechanical cooling will not necessarily be needed. One participant said the city will address the appropriate level of ventilation or window protection.
Blue-green infrastructure	Participants considered increasing green roofs in Helsinki, although their construction has been very slow. Zoning often has green roof recommendations; however, these are rarely implemented. Green roofs are considered a risk structure in the construction industry; consequently, the industry prefers green areas, water areas and trees. A few participants stated that more information was needed on green roofs. One participant also suggested monitoring green roofs that had existed for many years to demonstrate how well they have worked. One participant claimed that Espoo needed temperature and climate development alongside the stormwater program. Much has been done and considered; however, more comprehensive planning has been done to prevent or prepare for flood situations. This cooling and ecological role of water in the urban environment should also be considered more broadly. All participants felt that there was much room for improvement. None of the participants in the discussion considered as problematic green areas and their monitoring. More areas would be needed to better monitoring; however, one participant highlighted the lack of money as an obstacle. Instead of being increased, green spaces are being reduced due to accelerated construction. According to the participants, green areas and their monitoring require more attention. One participant told of an attempt to increase the number of green areas with the help of the green index and that efforts have been made to get green areas on the private plots.
State of the environment	The participants hoped that temperature monitoring using several measuring points could begin in Helsinki and Espoo, as has happened in Turku, Finland.

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