Regional Environmental Change (2025) 25:95
https://doi.org/10.1007/s10113-025-02429-2

ORIGINAL ARTICLE

Economic viability of urban greening as a climate change adaptation measure in cool-climate cities

Juuso Suomi[1] · **Matti Hyyrynen**[2] · **Janina Käyhkö**[3] · **Jukka Käyhkö**[1] · **Sirkku Juhola**[3]

Received: 5 December 2024 / Accepted: 13 June 2025 / Published online: 5 July 2025

Abstract

This study explores whether urban greening through tree planting is an economically viable climate change adaptation measure in Northern Europe's climate. The analysis was conducted by modelling how increased tree canopy cover affects the urban heat island (UHI) effect and, in turn, reduces heatwave-related mortality among vulnerable populations. Using modelling data from 2022 to 2100 for three Finnish cities—Helsinki, Turku, and Oulu—the results suggest that, in some cases, tree planting can be an economically viable adaptation measure to reduce heat-related deaths. This requires that greening is applied in the most densely populated areas of the city. Among the three cities, greening proves most economically viable in Helsinki, which has the highest population density of the three study cities. Conversely, it is not an economically viable adaptation option in Oulu, the study's northernmost and least densely populated city. The effectiveness of greening in economic terms varies depending on the city, the specific climate change scenario, and the intensity of the greening effort. As a result, the net present value (NPV) of tree planting may be either positive or negative. Therefore, any greening initiative should be carefully evaluated within its local context.

Keywords Climate change adaptation · Canopy cover · Urban heat island · Economic viability · Vulnerability · Heatwave

Introduction

Some of the most urgent adaptation needs in cities relate to managing extreme temperatures. The majority of the global population now lives in urban areas, and this proportion is expected to continue rising (UN 2018). Cities form their specific local climate, whose one feature is the urban heat island (UHI) phenomenon (Cleugh and Oke 1986; Cotton and Pielke 1995; Cheval et al. 2024; Srivastava et al. 2024). UHI contributes to increased cooling demand and exacerbates heat stress in urban environments compared to their surroundings (Taha 1997; Santamouris 2014). Already in the past and current climatic conditions, heatwaves have been shown to increase health risks and mortality in Finland (Russo et al. 2015; Ruuhela et al. 2018). During heatwaves, indoor temperatures rise and often remain elevated throughout the night (Chen et al. 2025), leading to prolonged exposure that can last for several days or even weeks. This continuous exposure can result in significant public health impacts and substantial health-related costs (Beugin et al. 2023; Kiarsi et al. 2023). For instance, the prolonged heatwave of 2003 caused over 70,000 premature deaths across Europe (Robine et al. 2008).

Communicated by George Zittis

✉ Juuso Suomi
juuso.suomi@utu.fi

Matti Hyyrynen
matti.hyyrynen@luke.fi

Janina Käyhkö
janina.kayhko@helsinki.fi

Jukka Käyhkö
jukka.kayhko@utu.fi

Sirkku Juhola
sirkku.juhola@helsinki.fi

[1] Section of Geography, Department of Geography and Geology, University of Turku, FI-20014 TURUN YLIOPISTO Turku, Finland

[2] Natural Resources Institute Finland (Luke), Latokartanonkaari 9, FI-00790 Helsinki, Finland

[3] Ecosystems and Environment Research Programme, Faculty of Biological and Environmental Sciences, University of Helsinki, FI-00014 Helsinki, Finland

Also, in cold-climate countries in northern Europe, where heatwaves have not historically been seen as major health threats, these events significantly increase mortality among vulnerable groups, such as the elderly and those with chronic illnesses (Kollanus et al. 2021). In Finland, each major heatwave in recent decades (2003, 2010, 2014, and 2018) has resulted in an estimated 200 to 400 excess deaths (Kollanus and Lanki 2014; Toikkanen 2019). With rising global temperatures and ageing populations, heat-related health impacts are expected to increase worldwide (Huang et al. 2015; Gasparrini et al. 2017; Guo et al. 2018). Beyond increased mortality, rising daily temperature causes an excess risk of various diseases, as evidenced by a rise in respiratory hospital admissions. Common heat-related diseases include asthma, pneumonia, myocardial infarction, cerebrovascular diseases, and a range of pre-existing chronic health conditions, including endocrine, genitourinary, and nervous system diseases, and mental health disorders (Fouillet et al. 2006; Haines et al. 2006; Sohail et al. 2020).

In cities, health risks are typically mitigated by various cooling measures such as indoor air conditioning and district cooling. These measures also effectively reduce mortality in high-latitude cities (Hyyrynen et al. 2025). The overall temperature conditions in cities, including the UHI effect, can be managed by increasing green infrastructure (Balany et al. 2020; Knight et al. 2021; Manso et al. 2021; Apritasari et al. 2022; Cornu et al. 2024; Taylor et al. 2024). However, under certain conditions, which remain understudied, green infrastructure can have unintended effects. For example, green roofs and walls may increase indoor air temperatures in the heating season due to the insulation effect, or retain indoor heat during the cooling season by their heat-trapping effect (Apritasari et al. 2022; Susca et al. 2022). Trees may also trap heat under certain conditions, raising local air temperatures (Gunawardena et al. 2017).

Beyond their impact on heat, urban greening solutions can have multiple other benefits including greenhouse gas mitigation, improved air quality, increased flood resilience, and enhanced well-being, and they are broadly accepted (Silvennoinen et al. 2017; Ai et al. 2023; Jabbar et al. 2022; Sari et al. 2023), which makes them attractive to municipalities. While nature-based solutions and greening strategies have gained popularity, their effectiveness in reducing heat-related health impacts is still not fully understood due to their complexity (Straka & Sodoudi 2019; Graça et al. 2022).

For example, Kim et al. (2018) found that in high-rise urban areas in the USA, green roofs had only a modest effect on mitigating UHI whereas increased coverage of grass and trees was more effective, especially in hot climates. Quantitatively, Sadeghi et al. (2022) report that urban trees can reduce peak ambient temperature by 0.1–4 °C (averaging 1.5 °C), whereas the respective effect of green roofs is 0–3 °C (averaging 0.6 °C). The selection of tree species is crucial to maximizing cooling benefits (Lanza and Stone 2016). Based on a case study of Sydney, Sadeghi et al. (2022) also demonstrated that using multiple greening measures together is more effective than implementing any single measure. One positive side effect of this cooling is a reduction in heatwave-related health risks. For example, Sadeghi et al. (2022) estimated that planting 2 million trees across a 200 km^2 area and installing 474 km^2 of moderately irrigated green roofs in Sydney could prevent approximately 11.7 premature deaths per day during a heatwave.

Research on adaptation impact modelling has emerged only recently and there are yet few examples of integrated analyses on specific adaptation measure impacts on climate risk (see, e.g. Oswald et al. 2020). So far, research on realistic adaptation options, their potential, and impacts has been principally qualitative (see, e.g. Baker et al. 2012) (e.g. adaptation pathways, scenarios) or simply pointing out associated challenges (McClure and Baker 2018). The endeavours in developing adaptation indicators to guide and monitor adaptation policies nationally and globally are thus lacking appropriate methodologies, particularly in terms of what is cost-effective as a policy. Cost–benefit analysis (CBA), a systematic method for comparing the costs and benefits of a project, is particularly useful in urban planning due to the scale, duration, and complexity of these initiatives.

We address the question of whether greening of a city by tree planting is an economically viable climate adaptation measure for Northern European cities. To our knowledge, a similar research setting has not been previously conducted in high-latitude urban environments. We present a novel integrated modelling approach that assesses adaptation impacts both at the city level and in the most densely populated urban areas. We focus on one climate change adaptation measure—increasing the tree canopy cover by tree planting—to decrease the UHI and to reduce the mortality of vulnerable people in three Finnish cities during a heatwave until the end of the twenty-first century. This approach presents a novel take on adaptation by modelling the costs and mortality in different policy and climate scenarios through the following research questions:

1. What are the key differences in the economic viability of various tree planting strategies between the three coastal Finnish cities—Helsinki, Turku, and Oulu?
2. How does economic viability compare between two greening strategies; one applied across the entire city master plan area (untargeted), and one focused only on the most densely populated areas (targeted)?
3. How does the intensity of greening influence economic viability?
4. How does the economic viability of greening depend on the rate of future warming, as presented by different cli-

mate scenarios (Representative Concentration Pathways, RCPs)?

Materials and methods

We followed a five-step process to model the development of heat-related risk in Finland through the end of the twenty-first century. We developed projections for (1) the annual number of heatwaves, (2) the population in vulnerable age groups (65–74 and ≥ 75 years), (3) baseline mortality, and (4) mortality under an adaptation policy. Finally (5), we calculated the costs and benefits of the adaptation policy in terms of the economic value of saved lives. The adaptation policy we assessed involved increasing urban green infrastructure through tree planting. Tree canopy cover mitigates the urban heat island (UHI) effect, which in turn reduces heat-related health risks and mortality. Our target cities—Helsinki, Turku, and Oulu—are among Finland's six largest, together housing about 20% of the national population (Table 1, Fig. 1). The cities differ in population density: Helsinki is high-density, Turku is medium-density, and Oulu is low-density (Statistics Finland 2023; Kuntaliitto 2024). We focused only on the two oldest age groups, as statistically significant increases in heatwave-related mortality have been observed exclusively in these age groups (Kollanus et al. 2021).

Daily average temperature scenarios were obtained from the Finnish Meteorological Institute's PLUMES (Pathways linking uncertainties in model projections of climate and its effects) project (Finnish Meteorological Institute 2019, 2024). The project concentrated on improving the key uncertainties in climate change impact, adaptation, and vulnerability analysis in the agriculture and human health sectors in Finland. The daily average temperature dataset used in this study includes observed daily averages from 1981 to 2010 and modelled daily projections from 2011 to 2100, interpolated on a 10-km grid using topographic and hydrological features. It covers four periods: 1981–2010 (observed only), and three future intervals (2011–2040, 2041–2070, 2071–2100) with increasing warming depending on greenhouse gas (GHG) scenarios. From 1981 to 2010, the temperatures associated with different GHG scenarios remain identical. From 2011 to 2040, the conditions mimic the previous 30 years' weather, albeit with generally elevated temperatures compared to the observational data from that period. This pattern continues in the subsequent periods of 2041–2070 and 2071–2100, with the degree of warming intensifying in accordance with the anticipated climate change, particularly in warmer climate scenarios. The climate projections represented the ensemble mean of 13 downscaled CMIP5 models, and for each city, a data on 10-km grid cell that represents the city centre was used. The downscaling was implemented with a delta change method (see M2 in Räisänen and Räty 2013). The respective 10-km resolution dataset is not available from CMIP6 models that suggest slightly higher summer temperatures in Finland compared to the CMIP5 models. This difference was not considered significant enough to alter our conclusions based on CMIP5 models (Ruosteenoja and Jylhä 2021).

We defined heatwaves based on Kollanus et al. (2021): at least four consecutive days with average temperatures exceeding the 90th percentile of May–August 2000–2014. Recognizing that future climate scenarios are inherently stochastic, we followed Hyyrynen et al. (2025) by fitting a linear trend to the 2022–2100 simulated temperature data. This provided annual heatwave frequency estimates for each city and climate scenario, which served as the lambda parameter for a non-homogeneous Poisson distribution, from which the number of annual heatwave occurrences was drawn in 10,000 Monte Carlo simulations.

Tree planting was selected as the adaptation policy based on prior studies and consultations with the target cities' officials. The cooling effect of greening was quantified using a multiple linear regression model. This model was calibrated with temperature data from 70 TURCLIM local climate observation network (TURCLIM 2024) observation sites in Turku, using explanatory variables related to land cover, topography, and water proximity. The model was trained on a 1-week heatwave period with an average temperature of 23.4 °C, which is 5.9 °C above the July 1991–2020 average (Jokinen et al. 2021), reflecting typical conditions of

Table 1 Basic information of the case cities Helsinki, Turku, and Oulu

City	Location (lat/long)*	Population**	Population density (persons/km^2)***	Land area/total area (km^2)****
Helsinki	60.17° N/24.94° E	664,028	3097	214.42/715.48
Turku	60.45° N/22.27° E	197,900	806	245.63/306.36
Oulu	65.02° N/25.47° E	211,848	71	2972.44/3817.74

*Coordinates of the city centre

**31.12.2022, Statistics Finland

***Population/land area

****1.1.2023, National Land Survey of Finland (2023)

Fig. 1 Locations and aerial views of the case cities, Helsinki (top right), Turku (bottom left), Oulu (bottom right). Copyrights of the aerial images: Jussi Hellsten/Helsinki Partners; Turun kaupunki, Suomen Ilmakuva; Oulun kaupunki/Lentokuva Vallas Oy

concern for health-based UHI mitigation. Although UHI is often strongest at night, average daily temperature was used to represent total heat exposure as it reflects the thermal conditions and potential heat stress throughout the day. Prior studies confirm that average temperature correlates with mortality (Kollanus et al. 2021; Ruuhela et al. 2021). According to our model, a 20 percentage point increase in tree canopy cover would reduce daily UHI by about 1 °C.

We estimated mortality risk in the vulnerable age groups using observed increases in heatwave-related mortality: 6.7% (95% CI = 2.9–10.8%) for ages 65–74, and 12.8% (95% CI = 9.8–15.9%) for ages ≥ 75 (Kollanus et al. 2021). Following Hyyrynen et al. (2025), we converted these relative increases into absolute risks using annual mortality statistics from Statistics Finland. Statistics Finland's (2021) database provides historical data on the population in vulnerable age groups from 2004 to 2021, along with projections for 2022 to 2040. To extend these trends to the year 2100, we employed ARIMA models to generate forecasts. For each age group in every city, we applied a series of ARIMA models, evaluated them using the Akaike Information Criterion (AIC) as introduced by Akaike (1974), selected the best-fitting model, and used it to project population growth in the vulnerable age groups up to 2100.

In this study, the threshold temperature of the 90th percentile during May–August that divides the days for potential heatwave days and for normal non-heatwave days was determined for all target cities separately based on their daily average temperatures of May–August 2002–2018. The threshold temperature was 20.7 °C for Helsinki, 20.6 °C for Turku, and 19.3 °C for Oulu, respectively. The threshold temperatures for Helsinki and Turku corroborate with the threshold temperatures used for southern and southwestern Finland (20.9 °C and 20.0 °C, respectively) by Kollanus et al. (2021), whereas the threshold temperature of Oulu corroborates with those for the Western and inland Finland and Northern Finland (19.5 °C and 18.7 °C). Using these thresholds, we identified 209 potential heatwave days. Of these, 135 in Helsinki and Turku, and 109 in Oulu met the 4 consecutive day criterion. To demonstrate the impact of cooling on heatwave days, a 1 °C drop in daily average temperature would reduce the number of heatwave days by 30.4% (135 → 94) in the case of the Turku example above. In our study, the impact of greening on heatwave-related

Table 2 Low and high greening potential areas for each case study city determined based on the master plans

City	Low greening potential area (km^2)*	High greening potential area (km^2)*
Helsinki	126.52	114.43
Turku	97.80	125.49
Oulu	2784.54	257.06

*The numerical values presented in this table are according to the city plans, which do not exactly correspond with the real land areas (cf. Table 1). Such mismatches include, e.g. shorelines and islands, and various areas not included in the master plan. Especially in the case of Helsinki, large shore areas, effectively covered by water on the data scale, cause an overestimate in the greening potential area

Table 3 The three greening options with different intensity levels used in the master plan-based approach

City	Intensity option 1 (L, H, A)	Intensity option 2 (L, H, A)	Intensity option 3 (L, H, A)
Helsinki	10, 20, 14.75	15, 30, 22.12	20, 40, 29.50
Turku	10, 20, 15.62	15, 30, 23.43	20, 40, 31.24
Oulu	10, 20, 10.85	15, 30, 16.27	20, 40, 21.69

The values represent the percentage point increase in tree canopy cover. *L* low greening potential area, *H* high greening potential area, *A* average greening potential

mortality is estimated by this diminished amount of heatwave days, but in practice our adaptation policy reduces the heat burden also during the days on which the threshold temperature is not exceeded as a consequence of the adaptation policy.

We implemented our adaptation policy using two approaches: a master plan–based approach (referred to as ‘untargeted’) and a population density–based approach (referred to as ‘targeted’). In the untargeted approach, we evaluated the realistic potential to increase tree canopy cover in various areas identified in the cities’ master plans. The feasibility of this approach was discussed with land use planning experts from the case study cities. Each city was first divided into areas of either high or low greening potential. For both categories, we applied three different levels of greening intensity (see Tables 2 and 3). Since the master plans and urban structures of the target cities differ, the classification into high and low greening potential areas was tailored to each city. In Helsinki and Turku, high-potential areas include those designated for green and recreational uses and related land functions; all other areas were classified as low potential. In Oulu, four urban development zones—city centre, city corridors, city zone, and expansion zone—were classified as high greening potential areas, with all remaining areas considered low potential areas. The greening intensity levels were determined based on the expected effectiveness and practical feasibility of the measures.

In the targeted greening measure, the focus was on the most densely populated continuous 9 km^2 area in each city, identified using population data from the end of 2021 (Statistics Finland 2021) (Fig. 2). The population densities in these areas—calculated using only land area—were 10,861, 6223, and 3870 persons per km^2 for Helsinki, Turku, and Oulu, respectively. This approach was based solely on population density; the physical suitability of the land for increasing tree canopy cover was not evaluated. Within the targeted areas, four uniform greening intensity levels were considered: 10, 20, 30, and 40 percentage point increases in tree canopy cover. Each intensity level was applied evenly across the entire 9 km^2 area. To estimate the number of vulnerable individuals affected by the greening, we used the proportion of the population living in the targeted areas relative to the total city population as a scaling factor. This assumes that the share of vulnerable age groups in the targeted areas is proportional to their share in the overall city population.

Cost estimates for tree planting, maintenance, and removal were based on the KAM ‘19 guide (Tajakka 2019), validated by a Turku tree expert. According to the guide’s fixed costs for the rooting period, the cost of planting a single tree was estimated at €2384.02 for park trees and €3543.60 for street trees. For our analysis, we assumed half of the planted trees as park trees and half as street trees. We assumed an average tree canopy diameter of 9 m, equating to a canopy coverage area of 63.62 m^2 per tree. Based on this, a 10-percentage point increase in tree canopy cover within a 1 km^2 area would require the planting of approximately 1572 trees. Given that our analysis extends through the year 2100, we accounted for a scenario in which 50% of the planted trees would need to be removed and replanted during this period. The cost of removing a tree, estimated at €2942 per tree, was also derived from the KAM ‘19 guide. All cost estimates were adjusted to reflect 2025 price levels.

Our estimates of fatalities in the absence of adaptation, i.e. under the baseline scenario, were based on the IPCC’s framework for assessing climate risk (Ara Begum et al. 2022). We calculated the annual number of fatalities by multiplying the number of heatwaves by the population in each vulnerable age group and by the corresponding age group–specific mortality risk associated with heatwaves. This yielded the projected number of deaths under the baseline scenario. Using the same approach, we also estimated fatalities under each greening, or adaptation, scenario. In these cases, the only variable adjusted was the annual frequency of heatwaves, which was reduced based on the selected level of greening intensity.

We defined the benefits of the adaptation measures as the reduction in fatalities, i.e. lives saved, compared to the

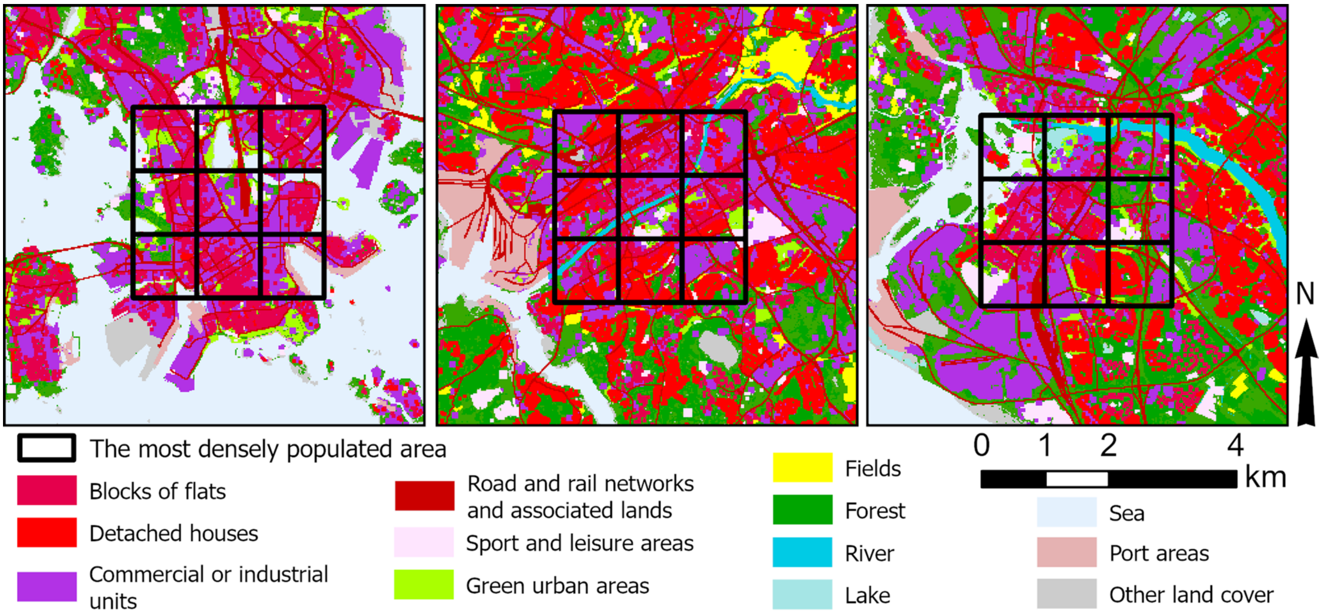

Fig. 2 The 3 × 3 km^2 areas with the highest population density in Helsinki (left), Turku (middle), and Oulu (right). The areas were used in modelling the targeted greening measure. Background map: CORINE (Coordination of Information on the Environment) Land Cover 2018, European Union Copernicus Land project. Reclassified

baseline scenario. The saved lives were then monetized to allow comparison with the associated costs, using the value of a statistical life (VSL). The VSL represents the monetary value placed on a uniform reduction in mortality risk across a population, equating to the prevention of one statistical death. It should not be interpreted as the amount an individual is willing to pay to save a specific life (Andersson and Treich 2011). Rather than being a fixed or absolute value derived from market data, the VSL reflects the trade-offs between money and risk that represent the preferences of a specific population sample (Viscusi and Aldy 2003). Economists estimate VSL using empirical data on real-world market decisions involving implicit trade-offs between money and risk (Viscusi and Aldy 2003). Governments can use VSL estimates as reference points when evaluating the benefits of policies aimed at reducing mortality risks.

According to a review by Hultkrantz and Svensson (2012), the average VSL estimate for Sweden is €3.7 million. However, Swedish authorities recommend a lower figure of €2.4 million per person, which we adopted in our analysis. Similarly, Kauppi and Kitti (2020), who assessed the willingness to pay for reduced health risks in traffic in Finland, estimated the VSL at €2.4 million—approximately €2.9 million in current (2025) value. This estimate is transferable to the health sector. Nonetheless, it is essential to recognize that transferring VSL estimates across contexts must account for variations in population preferences and valuations of life-saving measures (Viscusi and Aldy 2003). Moreover, VSL is inherently uncertain. Therefore, we conducted a sensitivity analysis to evaluate how our results respond to different VSL assumptions.

We also used the VSL to estimate health costs—also referred to as ‘health damage costs’ or ‘the health costs of inaction’. According to the World Health Organization (WHO 2013, page 6), these costs represent ‘the costs associated with climate change in the absence of planned adaptation or mitigation responses’. The purpose of assessing health costs in the context of climate change is to inform decision-makers about the consequences of inaction and to support advocacy efforts by emphasizing the significance of health impacts and the need to prevent or reduce them (WHO 2013). In our framework, this is most clearly captured by the value of health damage in the baseline scenario, i.e. the scenario in which no adaptation measures are implemented.

Using the estimated costs and benefits, we calculated the annual net benefits for each level of greening. To determine the overall economic viability of each adaptation policy, we computed the net present value (NPV) by summing the discounted annual net benefits over the entire planning horizon (2022–2100). A baseline discount rate of 3% was applied, and we also conducted a sensitivity analysis to examine how different discount rates affect the results (Basu and Ganiats 2016). To address uncertainties in future heatwave occurrences, we employed Monte Carlo (MC) simulations, which produced distributions of NPVs rather than single-point estimates. From these distributions, we calculated the expected NPV as the average outcome. These calculations were performed for each climate change adaptation (CCA) policy across the three climate scenarios RCP2.6, RCP4.5, and RCP8.5 (Moss et al. 2008) and for each city under study. A positive NPV indicates that a policy is economically viable, whereas a negative NPV suggests it should not be pursued based on economic grounds. Our framework closely aligns with that of Ryan and Stewart (2017), combining MC simulations and cost–benefit analysis to evaluate multiple CCA strategies. It explicitly incorporates the uncertainties and unknowns typically involved in climate adaptation planning. This is especially important given the substantial uncertainties surrounding climate-related risks, which make proactive adaptation challenging. Unlike many earlier studies that have focused on climate risks and adaptive capacity, our approach emphasizes the evaluation of the actual impacts of CCA policies, offering critical insights for policymakers.

Results

No greening

Model simulations with zero adaptation intensity, i.e. without any greening measures, show clear variation in the projected number of annual heatwaves across different RCP scenarios and cities (Fig. 3a–c). As climate change progresses towards the end of the century, the differences between RCPs become more pronounced. RCP8.5 results in a significantly higher number of heatwaves annually compared to RCP2.6 and RCP4.5, while the difference between RCP2.6 and RCP4.5 remains relatively modest.

The more substantial increase in heatwaves between RCP4.5 and RCP8.5, as opposed to the smaller difference between RCP2.6 and RCP4.5, can be attributed to how daily average temperatures shift relative to the heatwave threshold. Between RCP2.6 and RCP4.5, the threshold moves along the flatter part of the temperature distribution curve. However, between RCP4.5 and RCP8.5, the shift occurs on a steeper part of the curve, resulting in a larger increase in the frequency of days exceeding the threshold. The projected heatwave frequency increases quite similarly in Helsinki and Turku, whereas Oulu shows a noticeably smaller increase in heatwaves under RCP8.5 compared to the other two cities.

In the baseline situation, the costs of inaction were calculated by multiplying the number of fatalities in vulnerable age groups by the value of a statistical life (VSL). These costs are highest under the most severe climate scenario, RCP8.5, and lowest under the mildest, RCP2.6 (Fig. 3d–f). Among the cities, Helsinki bears the highest costs of inaction due to its larger share of vulnerable populations. Oulu has the lowest costs, corresponding with its lower projected frequency of heatwaves. In Turku and Oulu, the costs of inaction increase in a strictly convex manner over time, i.e.

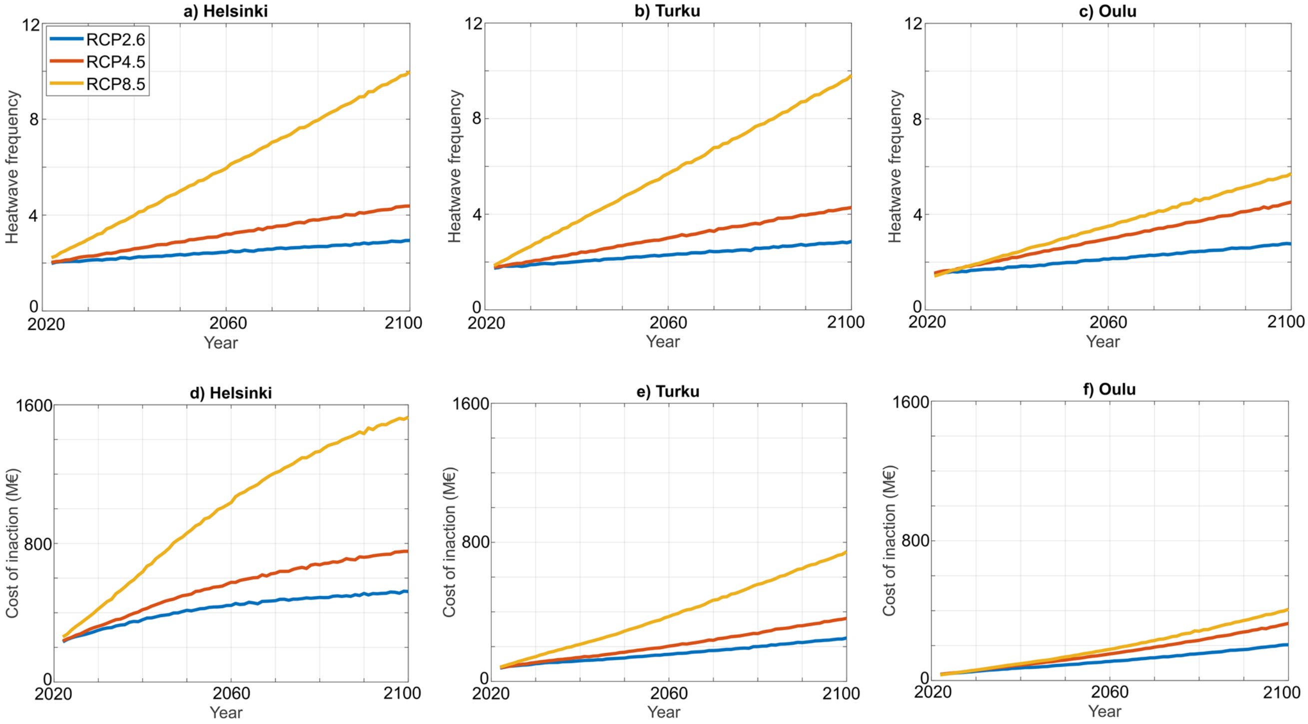

Fig. 3 Projections (2022–2100) of the heatwave frequency and the associated costs of inaction in Helsinki, Turku, and Oulu under climate scenarios RCP2.6 (RCP = Representative Concentration Pathways), RCP4.5, and RCP8.5

the rate of increase accelerates. In Helsinki, however, the increase is initially concave, meaning the rate of growth slows over time. This trend in Helsinki is driven by demographic changes and climate dynamics. Although both the number of heatwaves and the size of the vulnerable population initially rise, over time the size of the vulnerable population begins to decline due to ageing patterns, which moderates the increase in fatalities and thus slows the rise in associated costs. In contrast, in Turku and Oulu, the vulnerable population continues to grow steadily, and since heatwaves have a relatively smaller impact on population structure compared to Helsinki, the costs of inaction increase more sharply in a convex pattern.

Untargeted greening

In Helsinki, untargeted greening based on the master plan yields negative net present values (NPVs) under RCP2.6, but positive NPVs under RCP4.5 and RCP8.5 for the first and second greening intensity levels. However, at the third intensity level under RCP4.5, the NPV turns negative (Fig. 4a). In the most extensive greening scenario, the benefits exceed the costs only under the warmest climate scenario, RCP8.5.

In Turku and Oulu, master plan–based greening results in negative NPVs across all RCPs and greening intensity levels (Fig. 4b, c). In Turku, however, the NPV is close to zero for the lowest intensity level under RCP8.5, suggesting that greening is an almost recommendable adaptation policy. In contrast, Oulu consistently shows the lowest NPVs among the three cities, regardless of the climate scenario or greening intensity. This is primarily due to the lower population density and lower expected frequency of heatwaves in Oulu, making cooling-oriented adaptation less economically justifiable there. Overall, greening as an adaptation strategy proves economically viable only in Helsinki—and only under the more severe climate scenarios—when benefits are measured solely by the value of reduced mortality.

Targeted greening

When greening is targeted to the most densely populated area, in Helsinki, the NPVs are positive across all greening intensity levels and climate scenarios, indicating that this adaptation measure is economically viable (Fig. 5a). Under RCP4.5 and RCP8.5, the NPVs increase with the intensity of greening, while under RCP2.6, the NPVs

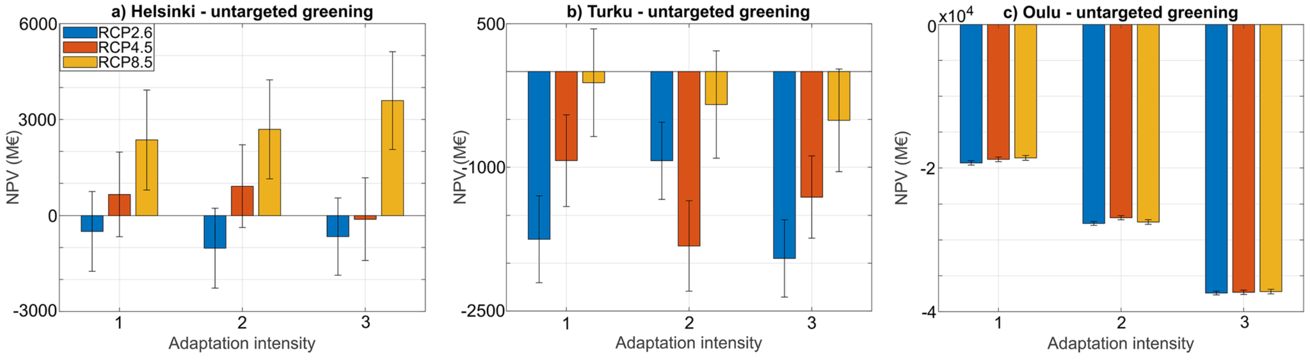

Fig. 4 The net present values (NPV) for the master plan–based untargeted greening in Helsinki, Turku, and Oulu for climate scenarios RCP2.6 (RCP = Representative Concentration Pathways), RCP4.5, and RCP8.5, and for three adaptation intensity levels

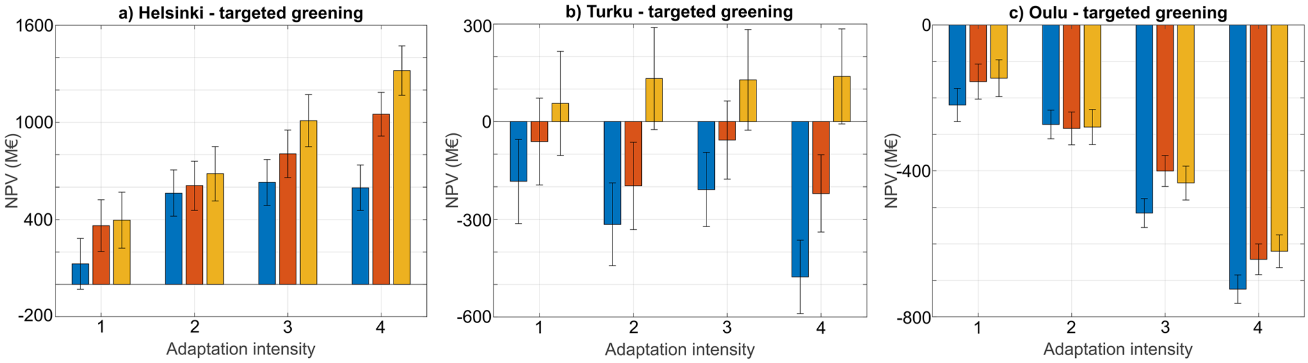

Fig. 5 The net present values (NPV) for the population density–based targeted greening in Helsinki, Turku, and Oulu for climate scenarios RCP2.6 (RCP = Representative Concentration Pathways), RCP4.5, and RCP8.5, and for four adaptation intensity levels

begin to decline after the third intensity level. This suggests that net benefits from greening only continue to grow with intensity under the warmer climate scenarios. Therefore, targeted greening clearly emerges as a recommendable strategy, with its net benefits increasing in warmer climate conditions.

In Turku, targeted greening is economically viable only under the warmest climate scenario, RCP8.5, where the NPV rises with the level of greening (Fig. 5b). In contrast, in Oulu, targeted greening results in negative NPVs across all RCPs and intensity levels. However, the losses are smaller than those associated with untargeted greening (Fig. 5c). Additionally, in Oulu, targeting results in more pronounced relative differences in NPVs across climate scenarios and greening intensities, compared to the untargeted approach.

Sensitivity analysis

Several parameters in the analysis are subject to uncertainty, including the discount rate, adaptation costs, the value of a statistical life (VSL), and the probability of mortality during heatwaves. To address these uncertainties, we conducted a sensitivity analysis to examine how variations in these parameters affect the results. Using Helsinki as an example, we evaluated the impact of each parameter on NPVs across different RCP scenarios at greening intensity level 2, under the targeted greening measure. The sensitivity analysis reveals that the discount rate and VSL significantly influence the NPVs (Fig. 6a, b). NPVs are substantially higher with a 1% discount rate, and the NPV consistently declines as the discount rate increases. For example, under untargeted greening with the highest adaptation intensity in RCP4.5, the NPV would shift from negative to positive if the discount

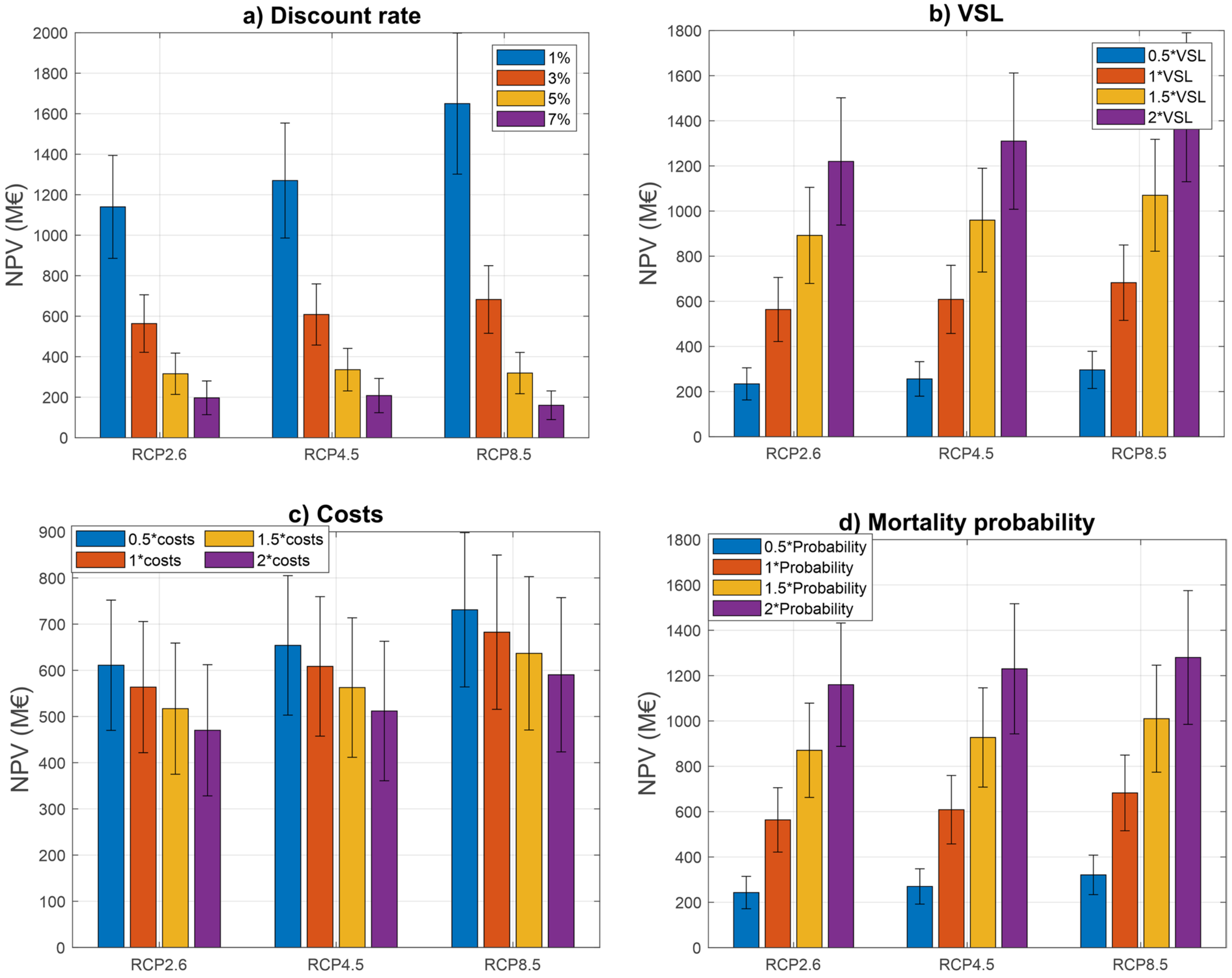

Fig. 6 Sensitivity of the results to the choice of discount rate, the value of saved lives (VSL), the adaptation costs (tree planting, maintenance and removal), and the probability of mortality

rate were reduced from 3 to 1%. This indicates that the choice of discount rate can directly affect the policy recommendation; determining whether greening is considered a cost-effective adaptation measure. Similarly, NPVs increase with higher VSL estimates. A sufficiently high VSL can turn a negative NPV into a positive one, highlighting the critical role of VSL assumptions in shaping policy conclusions. In contrast, adaptation costs have only a limited effect on NPVs, as most tree replacement costs occur far in the future and are therefore heavily discounted (Fig. 6c). The mortality probability during heatwaves also has a considerable impact on NPVs: the lower the probability of death, the smaller the benefit of adaptation, and consequently, the lower the NPV (Fig. 6d). Like the VSL and discount rate, changes in mortality probability can also reverse the sign of the NPV, underscoring its importance in determining the economic viability of greening as an adaptation strategy.

Discussion

In this study, we employed a novel approach to model the tree planting, maintenance and removal costs, and heatwave-related mortality under two climate change adaptation scenarios: targeted and untargeted greening. Our analysis indicates that increasing tree canopy cover through tree planting in the most densely populated area of Helsinki is economically viable across all three climate scenarios examined (RCP2.6, RCP4.5, and RCP8.5). This is because the economic value of reduced mortality outweighs the costs of planting and maintaining trees. However, when greening is applied across the entire city master plan area, its economic viability depends on both the climate scenario and the level of adaptation intensity. Under RCP2.6, greening is not economically viable at any intensity level, whereas under the most extreme scenario, RCP8.5, it proves viable regardless of intensity. In Turku, increasing tree canopy cover is an economically viable adaptation measure only when implemented for the most densely populated area under the RCP8.5 scenario. In Oulu, which is a smaller, more northern, and less densely populated city, increasing tree canopy cover is not an economically viable adaptation measure under any RCP scenario regardless of the implementation measure and intensity. Because heatwave definitions are based on city-specific threshold temperatures, the NPV differences between the cities are primarily explained by the differences in population density, both citywide and in densely populated areas. McDonald et al. (2024) found that in the USA, tree planting and maintenance costs often exceed the benefits derived from reduced mortality, morbidity, electricity use, and increased carbon sequestration except in areas with low existing tree cover. This aligns with our findings: even if greening is not economically viable citywide, targeted greening can be economically justified when benefits from reduced mortality are considered. In assessing the economic viability of the greening, it is good to notice that people are often willing to pay for adaptation infrastructure (Derkzen et al. 2017). Incorporating this willingness to pay for the greening infrastructure into the benefit side would yield higher NPVs and more favourable policy recommendations for greening. Similarly, including other benefits identified by McDonald et al. (2024) would further increase the NPVs of this study.

We used a rather moderate estimate for the value of statistical life (VSL), set at 2.9 M€. Hultkrantz and Svensson (2012) reviewed empirical studies and suggested an average of 3.7 M€, while Keller et al. (2021), in a review of 120 studies, reported a median midpoint estimate of 6.4 M€ for the health sector. Our sensitivity analysis showed that the outcomes are quite responsive to the VSL used; a higher VSL could shift NPVs from negative to positive, altering policy implications. Thus, our results may somewhat underestimate the cost-effectiveness of greening as an adaptation measure for reducing heat-related mortality. Moreover, we recognize that monetary metrics in the context of human life are controversial (Ackerman and Heinzerling 2004), and many aspects of health and well-being cannot easily be monetized. Nevertheless, using a standardized monetary metric facilitates the evaluation of different policies, thereby allowing policymakers to distribute resources more effectively. Monetizing non-marketed goods also enhances transparency and public understanding of policy prioritization (Andersson and Treich 2011). Still, it is important to remember that green infrastructure has numerous unquantified benefits such as recreation and aesthetic value that are not captured by using VSL alone. Consequently, the positive NPVs of this study can be considered conservative estimates.

One source of uncertainty in our methodology stems from the model-based estimate of UHI mitigation resulting from increased tree canopy. We estimate that a 10 percentage point increase in canopy cover would lower temperatures by slightly less than 0.5 °C. This is more than estimated by Iungman et al. (2023) for European cities at the city scale but less than the values reported by Marando et al. (2019) for the functional urban areas of European cities. However, our estimate aligns with Iungman et al. (2023) when considering that their value concerns the whole summer season, whereas ours concerns the heatwaves, during which spatial temperature differences are typically greater (see Suomi and Meretoja 2021).

Additional uncertainties relate to assumptions about the impact and evolution of UHI. Typically, UHI is strongest at night and weakest—or even negative—during the day. We assumed that the best way to capture diurnal variation and cumulative heat load is to use a heatwave as the reference period and to estimate greening's cooling effect based on daily average temperatures. Previous studies have validated average temperature as a good indicator of heat-related mortality (Näyhä 2007; Ruuhela et al. 2021; Ragettli et al. 2023). Different temperature metrics might have yielded different conclusions. Forecasts for UHI intensity under climate change are inconsistent; there is evidence of intensification (Sachindra et al. 2016) and, on the other hand, weakening (Scott et al. 2018). Wilby et al. (2003) and Sachindra et al. (2016) predict an intensification of UHI in the future, whereas Oleson et al. (2011) predict that summertime UHI will weaken slightly in the future supposing that a city does not grow, and it has an identical urban/rural atmospheric forcing. Overall, there is strong consensus on the predictions that heatwaves become more intense, and the UHI, for its part, increases heat burden (Dodman et al. 2022). For this study, we assumed constant baseline UHI intensity throughout the study period, which we consider as a realistic assumption, even if the city-specific areas dominated by UHI will probably grow because of urban growth.

Other sources of uncertainty include estimates of mortality probability, future interest rates, tree planting, maintenance and removal costs, the chosen VSL, the climate change scenarios used, and the dynamics of population and urban development. Sensitivity analysis illustrates how variations in the first four parameters influence NPVs. Using three RCP scenarios helps capture the range of possible warming trajectories and thus highlights the uncertainty inherent in climate modelling. Urban expansion, likely to increase areas with high UHI mitigation potential, is one probable aspect of future city development.

Beyond economic analysis, greening should also be evaluated from broader perspectives. Urban greenery has been linked to better mental and physical health (Ulmer et al. 2016; Barton and Rogerson 2017), better air quality (Ai et al. 2023), and better preparedness for urban floods (Silvennoinen et al. 2017). Monetizing these benefits would further raise NPVs and likely shift policy recommendations more in favour of greening. However, some of these associations have been questioned, and further research is needed (Nguyen et al. 2021; Venter et al. 2024). Potential disadvantages of greening or trees should also be acknowledged. Tree pollen may worsen allergies, pest infestations can lead to tree loss with associated health effects, and stressed trees may emit volatile organic compounds (VOC) that may enhance the formation of ozone and particulates in certain circumstances (Donovan et al. 2013, 2015; Salmond et al. 2016; Wolf et al. 2020). These complexities underline the importance of city-specific planning and implementation of greening measures.

Another consideration is the dual nature of UHI. In high-latitude regions during winter, UHI is principally seen as beneficial due to lower heating demand (Oke 1987; Taha 1997; Giridharan and Kolokotroni 2009). UHI areas may also offer more suitable habitats for certain animal species (Parris and Hazell 2005; Jochner et al. 2012) and provide a longer growing season for plants. From a health perspective, UHI may have mild benefits during spring, winter, and autumn (Huang et al. 2023). Due to these seasonal differences, the studies on the impacts of greening on UHI and health are focused on summer and warm conditions (Chun and Guldmann 2018). Increasing tree canopy cover has probably also the most significant UHI mitigation effect in summer, when solar radiation is the key driver of UHI. During other seasons, the microclimatological effect of greening is less clear and may vary depending, e.g. on the tree species. Should greening weaken the UHI during the cold season, this may lead to increased energy demand for heating, which is worth acknowledging in the assessment of pros and cons of greening (see, e.g. Santamouris 2014; Taleghani et al. 2014; Skelhorn et al. 2018). Especially in high latitudes in mid-winter, reduced radiative cooling due to tree canopy is, however, probably an energetically more relevant phenomenon than the combined effect of increased evapotranspiration and reduced solar heat storage due to the shadowing effect of trees, and consequently, trees may even strengthen the UHI in winter.

Although green infrastructure and nature-based solutions are generally favoured by the public (Badura et al. 2021), our findings highlight the need for a deeper understanding of greening as an adaptation measure (see also Matthews et al. 2015; Byrne et al. 2015). Differences between cities underscore the importance of local context in adaptation planning. Place-based approaches have been shown to enhance acceptance of adaptation measures (Groulx et al. 2014). Finally, city planning involves balancing multiple, sometimes conflicting, objectives. For example, greening efforts may compete with housing needs. Addressing these trade-offs requires collaboration among city stakeholders and transparent dialogue that includes citizens (Erlwein et al. 2023).

Conclusion

Based on our analysis—distinct in its focus on high-latitude cities and its novel approach to modelling adaptation—the economic viability of tree planting as an adaptation measure to reduce heat mortality risk is clearly highest in densely populated urban areas, when benefits are measured by the economic value of lives saved. In contrast, cities with low population density show lower or even negative viability. The differences in economic outcomes between cities appear to be more closely tied to population density than to climatic variations related to their latitude.

Additional factors influencing economic viability include the implementation strategy for greening and the future climate scenario. Untargeted greening based on the master plan is rarely an economically viable adaptation measure. However, in densely populated cities, economic viability improves under warmer climate scenarios. Targeted greening—focused on the most densely built areas—is economically viable across all climate scenarios in high-density city, and also in medium-density city under the warmest scenarios. The relationship between greening intensity and economic viability is less straightforward, except in low-density cities, where the viability is negatively correlated with greening intensity both in the master plan–based and targeted greening.

Ultimately, these findings underscore the complexity of evaluating adaptation costs and benefits over time, especially in the face of uncertain climate trajectories and evolving urban dynamics such as population ageing and densification. When planning strategies to address urban heat, tree planting can complement other adaptation measures and offer co-benefits, including enhanced biodiversity and improved human well-being. Thorough assessments of adaptation options are essential to inform decision-making in contexts where multiple, and often competing, priorities must be balanced.

Acknowledgements Antti Mäkelä from the Finnish Meteorological Institute provided the data on daily average temperature scenarios. The experts of the cities of Helsinki, Turku, and Oulu represented useful viewpoints and recommendations on the methodological choices of the work.

Funding Open Access funding provided by University of Turku (including Turku University Central Hospital). Funding for this research has been admitted by the Finnish Ministry of Environment via the Finnish Climate Change Panel's *SOIKE—Developing the indicators of adaptation* project, grant Nr. 329239. Finalizing of the research has also been funded by the Research Council of Finland via the project *Kestävät ilmastonmuutoksen hillintästrategiat energia-maankäyttö-materiaalit -systeemissä.* The Geography Section of the University of Turku has financially supported the establishment and maintenance of the TURCLIM weather observation network. The Urban Environment Division of the City of Turku has financially supported the maintenance of the TURCLIM weather observation network.

Data availability Data will be made available on request as widely as possible.

Declarations

Competing interests The authors declare no competing interests.

References

Ackerman F, Heinzerling L (2004) Priceless: on knowing the price of everything and the value of nothing. The New Press, New York

Ai H, Zhang X, Zhou Z (2023) The impact of greenspace on air pollution: empirical evidence from China. Ecol Indic 146:109881. https://doi.org/10.1016/j.ecolind.2023.109881

Akaike H (1974) A new look at the statistical model identification. IEEE Trans Automat Contr 19(6):716 –723. https://doi.org/10.1109/TAC.1974.1100705

Andersson H, Treich N (2011) Handbook in transport economics, Chapt. 'The value of a statistical life'. In: de Palma A, Lindsey R, Quinet E, Vickerman R (eds.). Edward Elgar, Cheltenham, pp 396–424

Apritasari YD, Triyadi S, Wonorahardjo S, Indraprahstra A (2022) Review on appropriateness of urban heat island mitigation technologies at several climates condition. IOP Conf Ser Earth Environ Sci 1058:012011. https://doi.org/10.1088/1755-1315/1058/1/012011

Ara Begum R, Lempert R, Ali E, Benjaminsen TA, Bernauer T et al. (2022) Point of departure and key concepts. In: Climate change 2022: impacts, adaptation and vulnerability. Cambridge University Press, Cambridge and New York, pp 121–196. https://doi.org/10.1017/9781009325844.003

Badura T, Lorencová EK, Ferrini S, Vačkářová D (2021) Public support for urban climate adaptation policy through nature-based solutions in Prague. Landsc Urban Plan 215:104215. https://doi.org/10.1016/j.landurbplan.2021.104215

Baker I, Peterson A, Brown G, McAlpine C (2012) Local government response to the impacts of climate change: an evaluation of local climate adaptation plans. Landsc Urban Plan 107(2):127–136. https://doi.org/10.1016/j.landurbplan.2012.05.009

Balany F, Ng AW, Muttil N, Muthukumaran S, Wong MS (2020) Green infrastructure as an urban heat island mitigation strategy—a review. Water 12(12):3577. https://doi.org/10.3390/w12123577

Barton J, Rogerson M (2017) The importance of greenspace for mental health. BJPsych Int 14(4):79–81. https://doi.org/10.1192/s2056474000002051

Basu A, Ganiats TG (2016) Discounting in cost-effectiveness analysis. In: Neumann PJ, et al. (eds). Cost-effectiveness in health and medicine. 2nd ed. Oxford Academic. https://doi.org/10.1093/acprof:oso/9780190492939.003.0010

Beugin D, Clark D, Miller S, Ness R, Pelai R, Wale J (2023) The case for adapting to extreme heat. Costs of the 2021 B.C. heat wave. Canadian Climate Institute. https://climateinstitute.ca/wp-content/uploads/2023/06/The-case-for-adapting-to-extremeheat-costs-of-the-BC-heat-wave.pdf. Accessed 4 Feb 2024

Byrne JA, Lo AY, Jianjun Y (2015) Residents' understanding of the role of green infrastructure for climate change adaptation in Hangzhou, China. Landsc Urban Plan 138:132–143. https://doi.org/10.1016/j.landurbplan.2015.02.013

Chen Z, O'Sullivan KC, Dohig RK, Pierse N, Jiang T et al (2025) Identifying summer energy poverty and public health risks in a temperate climate. Clim Risk Manag 48:100698. https://doi.org/10.1016/j.crm.2025.100698

Cheval S, Amihăesei V-A, Chitu Z, Dumitrescu A, Falcescu V et al (2024) A systematic review of urban heat island and heat waves research (1991–2022). Clim Risk Manag 44:100603. https://doi.org/10.1016/j.crm.2024.100603

Chun B, Guldmann J-M (2018) Impact of greening on the urban heat island: seasonal variations and mitigation strategies. Comput Environ Urban Syst 71:165–176. https://doi.org/10.1016/j.compenvurbsys.2018.05.006

Cleugh HA, Oke TR (1986) Suburban-rural energy balance comparisons in summer for Vancouver, BC. Boundary-Layer Meteorol 36:351–369. https://doi.org/10.1007/BF00118337

Cornu T, Marchal B, Renmans D (2024) How do urban green spaces influence heat-related mortality in elderly? A Realist Synthesis BMC Public Health 24:457. https://doi.org/10.1186/s12889-024-17973-5

Cotton WR, Pielke RA (1995) Human impacts on weather and climate. Cambridge University Press, Cambridge

Derkzen ML, Van Teeffelen AJ, Verburg PH (2017) Green infrastructure for urban climate adaptation: how do residents' views on climate impacts and green infrastructure shape adaptation preferences? Landsc Urban Plan 157:106–130. https://doi.org/10.1016/j.landurbplan.2016.05.027

Dodman D, Hayward B, Pelling M, Castan Broto V, Chow W, Chu E, Dawson R, Khirfan L, McPhearson T, Prakash A, Zheng Y, Ziervogel G (2022) Cities, settlements and key infrastructure. In: Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 907–1040. https://doi.org/10.1017/9781009325844.008

Donovan GH, Butry DT, Michael YL, Prestemon JP, Liebhold AM et al (2013) The relationship between trees and human health. Am J Prev Med 44:139–145. https://doi.org/10.1016/j.amepre.2012.09.066

Donovan GH, Michael YL, Gatziolis D, Prestemon JP, Whitsel EA (2015) Is tree loss associated with cardiovascular-disease risk in the Women's Health Initiative? A natural experiment. Health Place 36:1–7. https://doi.org/10.1016/j.healthplace.2015.08.007

Erlwein S, Meister J, Wamsler C, Pauleit S (2023) Governance of densification and climate change adaptation: how can conflicting demands for housing and greening in cities be reconciled? Land Use Policy 128:106593. https://doi.org/10.1016/j.landusepol.2023.106593

Finnish Meteorological Institute (2019) Pathways linking uncertainties in model projections of climate and its effects (PLUMES). https://en.ilmatieteenlaitos.fi/plumes. Accessed 25 May 2025

Finnish Meteorological Institute (2024) Daily mean temperature predictions, 1981–2100. CSC - IT Center for Science Ltd. http://urn.fi/urn:nbn:fi:csc-kata20180918114340806244. Accessed 26 June 2024

Fouillet A, Rey G, Laurent F, Pavillon G, Bellec S et al (2006) Excess mortality related to the August 2003 heat wave in France. Int Arch Occup Environ Health 80(1):16–24. https://doi.org/10.1007/s00420-006-0089-4

Gasparrini A, Guo Y, Sera F, Vicero-Cabrera AM, Huber V et al (2017) Projections of temperature-related excess mortality under climate change scenarios. Lancet Planet Health 1(9):e360–e367. https://doi.org/10.1016/S2542-5196(17)30156-0

Giridharan R, Kolokotroni M (2009) Urban heat island characteristics in London during winter. Sol Energy 83(9):1668–1682. https://doi.org/10.1016/j.solener.2009.06.007

Graça M, Cruz S, Monteiro A, Neset TS (2022) Designing urban green spaces for climate adaptation: a critical review of research outputs. Urban Clim 42:101126. https://doi.org/10.1016/j.uclim.2022.101126

Groulx M, Lewis J, Lemieux C, Dawson J (2014) Place-based climate change adaptation: a critical case study of climate change messaging and collective action in Churchill, Manitoba. Landsc Urban Plan 132:136–147. https://doi.org/10.1016/j.landurbplan.2014.09.002

Gunawardena KR, Wells MJ, Kershaw T (2017) Utilising green and bluespace to mitigate urban heat island intensity. Sci Total Environ 584:1040–1055. https://doi.org/10.1016/j.scitotenv.2017.01.158

Guo Y, Gasparrini A, Li S, Sera F, Videco-Cabrera AM et al (2018) Quantifying excess deaths related to heatwaves under climate change scenarios: a multi-country time series modelling study. PLoS Med 15(7):e1002629. https://doi.org/10.1371/journal.pmed.1002629

Haines A, Kovats RS, Campbell-Lendrum D, Corvalan C (2006) Climate change and human health: impacts, vulnerability, and mitigation. Lancet 367(9528):2101–2109. https://doi.org/10.1016/S0140-6736(06)68933-2

Huang WTK, Masselot P, Bou-Zeid E, Fatichi S, Paschalis S et al (2023) Economic valuation of temperature-related mortality attributed to urban heat islands in European cities. Nat Commun 14:7438. https://doi.org/10.1038/s41467-023-43135-z

Huang Z, Lin H, Liu Y, Zhou M, Liu T et al (2015) Individual-level and community-level effect modifiers of the temperature-mortality relationship in 66 Chinese communities. BMJ Open 5(9):e009172. https://doi.org/10.1136/bmjopen-2015-009172

Hultkrantz L, Svensson M (2012) The value of a statistical life in Sweden: a review of the empirical literature. Health Policy 108(2–3):302–310. https://doi.org/10.1016/j.healthpol.2012.09.007

Hyyrynen M, Ollikainen M, Käyhkö J, Suomi J, Lintunen J et al (2025) Cooling is a cost-efficient way to adapt to heatwaves even in high-latitude cities. Clim Chang 178:96. https://doi.org/10.1007/s10584-025-03913-8

Iungman T, Cirach M, Marando F, Barboza EP, Khomenko S et al (2023) Cooling cities through urban green infrastructure: a health impact assessment of European cities. Lancet 401(10376):577–589. https://doi.org/10.1016/S0140-6736(22)02585-5

Jabbar M, Yusoff MM, Shafie A (2022) Assessing the role of urban green spaces for human well-being: a systematic review. GeoJournal 87:4405–4423. https://doi.org/10.1007/s10708-021-10474-7

Jochner SC, Sparks TH, Estrella N, Menzel A (2012) The influence of altitude and urbanisation on trends and mean dates in phenology (1980–2009). Int J Biometeorol 56(2):387–394. https://doi.org/10.1007/s00484-011-0444-3

Jokinen P, Pirinen P, Kaukoranta J, Kangas A, Alenius P et al (2021) Tilastoja Suomen ilmastosta ja merestä 1991–2020. Ilmatieteen laitoksen raportteja 2021:8. https://helda.helsinki.fi/items/d7ce3a4f-bf47-4453-be76-2a0de738c59a

Keller E, Newman JE, Ortmann A, Jorm LR, Chambers GM (2021) How much is a human life worth? A Systematic Review Value Health 24(10):1531–1541. https://doi.org/10.1016/j.jval.2021.04.003

Kiarsi M, Amiresmaili M, Mahmoodi MR, Farahmandia H, Nakhaee N et al (2023) Heat waves and adaptation: a global systematic review. J Therm Biol 116:103588. https://doi.org/10.1016/j.jtherbio.2023.103588

Kim H, Gu D, Kim HY (2018) Effects of urban heat island mitigation in various climate zones in the United States. Sustain Cities Soc 41:841–852. https://doi.org/10.1016/j.scs.2018.06.021

Kauppi K, Kitti M (2020) Suomalaisten halukkuus maksaa tieliikenteen henkilövahinkojen vähentämisestä. Traficomin tutkimuksia ja selvityksiä 20/2020. https://urn.fi/URN:NBN:fi-fe2021042823136

Kollanus V, Lanki T (2014) Helteet ovat terveysriski Suomessakin. Ilmansuojelulehti 2/2014:6–8. https://urn.fi/URN:NBN:fi-fe201502231696. Accessed 9 June 2024

Kollanus V, Tiittanen P, Lanki T (2021) Mortality risk related to heatwaves in Finland – factors affecting vulnerability. Environ Res 201:111503. https://doi.org/10.1016/j.envres.2021.111503

Knight T, Price S, Bowler D, Hookway A, King S et al (2021) How effective is greening of urban areas in reducing human exposure to ground-level ozone concentrations, UV exposure, and the urban heat island effect? An updated systematic review. Environ Evid 10:12. https://doi.org/10.1186/s13750-021-00226-y

Kuntaliitto (2024) Kuntien pinta-alat ja asukastiheydet. https://www.kuntaliitto.fi/kuntaliitto/tietotuotteet-ja-palvelut/kaupunkien-ja-kuntien-lukumaarat-ja-vaestotiedot/kuntien-pinta-alat-ja-asukastiheydet. Accessed 28 June 2024

Lanza K, Stone B Jr (2016) Climate adaptation in cities: what trees are suitable for urban heat management? Landsc Urban Plan 153:74–82. https://doi.org/10.1016/j.landurbplan.2015.12.002

Manso M, Teotónio I, Silva CM, Cruz CO (2021) Green roof and green wall benefits and costs: a review of the quantitative evidence. Renew Sustain Energy Rev 135:110111. https://doi.org/10.1016/j.rser.2020.110111

Marando F, Salvatori E, Sebastiani A, Fusaro L, Manes F (2019) Regulating ecosystem services and green infrastructure: assessment of urban heat island effect mitigation in the municipality of Rome, Italy. Ecol Model 392(24):92–102. https://doi.org/10.1016/j.ecolmodel.2018.11.011

Matthews T, Lo AY, Byrne JA (2015) Reconceptualizing green infrastructure for climate change adaptation: barriers to adoption and drivers for uptake by spatial planners. Landsc Urban Plan 138:155–163. https://doi.org/10.1016/j.landurbplan.2015.02.010

McClure L, Baker D (2018) How do planners deal with barriers to climate change adaptation? A case study in Queensland, Australia. Landsc Urban Plan 173:81–88. https://doi.org/10.1016/j.landurbplan.2018.01.012

McDonald RI, Biswas T, Chakraborty TC, Kroeger T, Cook-Patton SC et al (2024) Current inequality and future potential of US urban tree cover for reducing heat-related health impacts. NPJ Urban Sustain 4:18. https://doi.org/10.1038/s42949-024-00150-3

Moss R, Babiker W, Brinkman S, Calvo E, Carter T et al (2008) Towards new scenarios for the analysis of emissions: climate change, impacts, and response strategies. Intergovernmental Panel on Climate Change Secretariat (IPCC). Geneva, Switzerland

National Land Survey of Finland (2023) Pinta-alat kunnittain 1.1.2023 (Areas of the municipalities). National Land Survey of Finland. https://www.maanmittauslaitos.fi/tietoa-maanmittauslaitoksesta/organisaatio/tilastot. Accessed 18 Oct 2023

Nguyen PY, Astell-Burt T, Rahimi-Ardabili H, Feng X (2021) Green space quality and health: a systematic review. Int J Environ Res Public Health 18(21):11028. https://doi.org/10.3390/ijerph182111028

Näyhä S (2007) Heat mortality in Finland in the 2000s. Int J Circumpolar Health 66(5):418–424. https://doi.org/10.3402/ijch.v66i5.18313

Oke TR (1987) Boundary layer climates, 2nd edn. Routledge, London

Oleson KW, Bonan GB, Feddema J, Jackson T (2011) An examination of urban heat island characteristics in a global climate model. Int J Climatol 31:1848–1865. https://doi.org/10.1002/joc.2201

Oswald SM, Hollosi B, Žuvela-Aloise M, See L, Giggenberger, et al (2020) Using urban climate modelling and improved land use classifications to support climate change adaptation in urban environments: a case study for the city of Klagenfurt, Austria. Urban Clim 31:100582. https://doi.org/10.1016/j.uclim.2020.100582

Parris KM, Hazell DL (2005) Biotic effects of climate change in urban environments: the case of the grey-headed flying-fox (*Pteropus poliocephalus*) in Melbourne, Australia. Biol Conserv 124(2):267–276. https://doi.org/10.1016/j.biocon.2005.01.035

Ragettli MS, Saucy A, Flückiger B, Vienneau D, de Hoogh K et al (2023) Explorative assessment of the temperature-mortality association to support health-based heat-warning thresholds: a national case-crossover study in Switzerland. Int J Environ Res Public Health 20(6):4958. https://doi.org/10.3390/ijerph20064958

Robine J, Cheung SLK, Le Roy S, Van Oyen H, Criffiths C et al (2008) Death toll exceeded 70,000 in Europe during the summer of 2003. C R Biol 331(2):171–178. https://doi.org/10.1016/j.crvi.2007.12.001

Ruosteenoja K, Jylhä K (2021) Projected climate change in Finland during the 21st century calculated from CMIP6 model simulations. Geophysica 56(1):39–69

Russo S, Sillmann J, Fischer EF (2015) Top ten European heatwaves since 1950 and their occurrence in the coming decades. Environ Res Lett 10:124003. https://doi.org/10.1088/1748-9326/10/12/124003

Ruuhela R, Hyvärinen O, Jylhä K (2018) Regional assessment of temperature-related mortality in Finland. Int J Environ Res Public Health 15(3):406. https://doi.org/10.3390/ijerph15030406

Ruuhela R, Votsis A, Kukkonen J, Jylhä K, Kankaanpää S et al (2021) Temperature-related mortality in Helsinki compared to its surrounding region over two decades, with special emphasis on intensive heatwaves. Atmosphere 12(1):46. https://doi.org/10.3390/atmos12010046

Ryan PC, Stewart MG (2017) Cost-benefit analysis of climate change adaptation for power pole networks. Clim Change 143(3):519–533. https://doi.org/10.1007/s10584-017-2000-6

Räisänen J, Räty O (2013) Projections of daily mean temperature variability in the future: cross-validation tests with ENSEMBLES regional climate simulations. Clim Dyn 41:1553–1568. https://doi.org/10.1007/s00382-012-1515-9

Sachindra DA, Ng AWM, Muthukumaran S, Perera BJC (2016) Impact of climate change on urban heat island effect and extreme temperatures: a case-study. Q J R Meteorol Soc 142(694):172–186. https://doi.org/10.1002/qj.2642

Sadeghi M, Chaston T, Hanigan I, de Dear R, Santamouris R et al (2022) The health benefits of greening strategies to cool urban environments — a heat health impact method. Build Environ 207(Part B):108546. https://doi.org/10.1016/j.buildenv.2021.108546

Salmond JA, Tadaki M, Vardoulakis S, Arbuthnott K, Coutts A et al (2016) Health and climate-related ecosystem services provided by street trees in the urban environment. Environ Health 15(Suppl 1):S36. https://doi.org/10.1186/s12940-016-0103-6

Santamouris M (2014) On the energy impact of urban heat island and global warming on buildings. Energy Build 82:100–113. https://doi.org/10.1016/j.enbuild.2014.07.022

Sari R, Soytas U, Kanoglu-Ozkan DG, Sivrikaya A (2023) Improving the climate resilience of European cities via socially acceptable nature-based solutions. NPJ Urban Sustain 3:9. https://doi.org/10.1038/s42949-023-00090-4

Scott AA, Waugh DW, Zaitchik BF (2018) Reduced Urban Heat Island intensity under warmer conditions. Environ Res Lett 13(6):1. https://doi.org/10.1088/1748-9326/aabd6c

Silvennoinen S, Taka M, Yli-Pelkonen V, Koivusalo H, Ollikainen M et al (2017) Monetary value of urban green space as an ecosystem service provider: a case study of urban runoff management in Finland. Ecosyst Serv 28(Part A):17–27. https://doi.org/10.1016/j.ecoser.2017.09.013

Skelhorn CP, Lindley S, Levermore G (2018) Urban greening and the UHI: seasonal trade-offs in heating and cooling energy consumption in Manchester, UK. Urban Clim 23:173–187. https://doi.org/10.1016/j.uclim.2017.02.010

Sohail H, Kollanus V, Tiittanen P, Schneider A, Lanki T (2020) Heat, heatwaves, and cardiorespiratory hospital admissions in Helsinki, Finland. Int J Environ Res Public Health 17(21):7892. https://doi.org/10.3390/ijerph17217892

Srivastava VT, Sharma A, Jadon SS (2024) A review of the formation, mitigation strategies from 50 years of global urban heat island studies. Environ Dev Sustain. https://doi.org/10.1007/s10668-024-04966-y

Statistics Finland (2021) Population grid data 2021, 1 km x 1 km. CSC – IT Center for Science. http://urn.fi/urn:nbn:fi:att:976bffd6-bcb4-4f05-a109-54645f64c9f9. Accessed 14 Jun 2022

Statistics Finland (2023) Kuntien avainluvut 2022 (Key statistics of the municipalities). Statistics Finland. https://pxdata.stat.fi/PxWeb/pxweb/fi/Kuntien_avainluvut/. Accessed 14 Aug 2023

Straka M, Sodoudi S (2019) Evaluating climate change adaptation strategies and scenarios of enhanced vertical and horizontal compactness at urban scale (a case study for Berlin). Landsc Urban Plan 183:68–78. https://doi.org/10.1016/j.landurbplan.2018.11.006

Suomi J, Meretoja M (2021) Trends and irregular variation of spatial temperature differences in the high-latitude coastal city of Turku, Finland. Clim Res 84:41–57. https://doi.org/10.3354/cr01649

Susca T, Zanghirella F, Colasuonno L, Del Fatto V (2022) Effect of green wall installation on urban heat island and building energy use: a climate-informed systematic literature review. Renew Sustain Energy Rev 159:112100. https://doi.org/10.1016/j.rser.2022.112100

Taha H (1997) Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. Energy Build 25(2):99–103. https://doi.org/10.1016/S0378-7788(96)00999-1

Tajakka H (ed) (2019) Kaupunkipuiden arvonmääritysmalli KAM '19 -OPAS. Viherympäristöliiton julkaisu nro 66. https://www.vyl.fi/ohjeet/kasvillisuuden-arvonmaaritys. Accessed 16.5.2023

Taleghani M, Tenpierik M, van den Dobbelsteen A, Sailor DJ (2014) Heat mitigation strategies in winter and summer: field measurements in temperate climates. Build and Environ 81:309–319. https://doi.org/10.1016/j.buildenv.2014.07.010

Taylor J, Simpson C, Brousse O, Viitanen A-K, Heaviside C (2024) The potential of urban trees to reduce heat-related mortality in London. Environ Res Lett 19(5):054004. https://doi.org/10.1088/1748-9326/ad3a7e

Toikkanen (2019) Viime kesän helteet lisäsivät ikääntyneiden kuolleisuutta. Lääkärilehti. https://www.laakarilehti.fi/ajassa/ajankohtaista/viime-kesan-helteet-lisasivat-ikaantyneiden-kuolleisuutta/. Accessed 7 Jul 2024

TURCLIM (2024) Turku urban climate research group. Geography section, University of Turku, Finland. https://sites.utu.fi/turclim/. Accessed 19 May 2024

Ulmer JM, Wolf KL, Backman DR, Tretheway RL, Blain CJA et al (2016) Multiple health benefits of urban tree canopy: the mounting evidence for a green prescription. Health Place 42:54–62. https://doi.org/10.1016/j.healthplace.2016.08.011

UN (2018) 8% of the world population projected to live in urban areas by 2050, says UN. United Nations Department of Economic and Social Affairs. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html. Accessed 6 Apr 2023

Venter ZS, Hassani A, Stange E, Schneider P, Castell N (2024) Reassessing the role of urban green space in air pollution control. Proc Natl Acad Sci U.S.A. 121(6):e2306200121 https://doi.org/10.1073/pnas.2306200121

Viscusi WK, Aldy JE (2003) The value of a statistical life: a critical review of market estimates throughout the world. J Risk Uncertain 27:5–76. https://doi.org/10.1023/A:1025598106257

WHO (2013) Climate change and health—WHO tool to estimate health and adaptation costs. World Health Organization. https://www.who.int/europe/tools-and-toolkits/climate-change-and-health---who-tool-to-estimate-health-and-adaptation-costs. Accessed 12 Mar 2024

Wilby RL (2003) Past and projected trends in London's urban heat island. Weather 58:251–260. https://doi.org/10.1256/wea.183.02

Wolf KL, Lam ST, McKeen JK, Richardson GRA, van den Bosch M, et al. (2020) Urban trees and human health: a scoping review. Int J Environ Res Public Health 17(12):4371. https://doi.org/10.3390/ijerph17124371