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The Finnish Climate Change Panel

DEVELOPING FINLAND'S ADAPTATION POLICY USING RISK MODELLING AND EFFECTIVENESS MONITORING OF ADAPTATION MEASURES

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The Finnish Climate Change Panel promotes climate dialogue between science and policymaking. The Panel provides climate policymaking recommendations for the Finnish Government and reinforces interdisciplinarity in the climate sciences. Reports and statements prepared by the Panel are compiled on scientific grounds.

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SUMMARY

Climate change is progressing rapidly, and its impacts are already visible in Finland. Adaptation to climate change and preparedness for the risks must be advanced, despite the uncertainty about the scale of impacts and directions of change in the future. The challenge is to identify specific goals, measures, and policy tools to promote adaptation under conditions of uncertainty. The climate risk framework of the Intergovernmental Panel on Climate Change (IPCC) can provide a systematic basis for modelling the effectiveness and scale of adaptation policy measures.

The aim of this report is to demonstrate how adaptation policy can be based on systematic risk modelling and enhance the monitoring of policy effectiveness by using relevant indicators. The report examines the impacts of a warming climate on the production of public goods, such as health, ecosystems, and information on climate change. The risk framework analysis is utilised to assess adaptation that ensures the health of both humans and ecosystems as temperatures rise and heatwaves become more common.

Regarding human health, the report presents an analysis of how premature deaths caused by heatwaves can be reduced by increasing mechanical cooling in residential buildings and by increasing green areas to mitigate the urban heat island effect. Helsinki, Turku, and Oulu were chosen for analysis to account for regional variations. The results indicate that the coverage of cooling systems in the housing stock should be increased to nearly 100% in Helsinki and Turku, while cooling should be targeted to selected areas in the northernmost case city Oulu. In terms of green areas, geographically targeted greening produces net positive benefits in all cities, with the greatest impact in Helsinki.

Ecosystem health is examined in this report with an example of the deterioration of the ecological state of a river and its prevention. Climate change also raises water temperatures, which weakens the ecological condition of rivers. Rising water temperatures can be mitigated by establishing tree-covered buffer zones along riverbanks, creating new green infrastructure that society supports. The analysis highlights the need to extend adaptation policy to ecological habitats and ecosystem services.

As well as modelling, information needs related to adaptation and indicators suitable for monitoring the effectiveness of adaptation policy are discussed in the report based on findings from scientific literature. The Finnish National Climate Change Adaptation Plan 2030 specifies adaptation goals and measures, as well as responsibilities for them. The Adaptation Plan also identifies methods for monitoring, but indicators of effectiveness have not yet been defined. There are differences in consistency and risk assessments in sector-specific adaptation strategies.

For the success of national adaptation policy, in addition to implementing the plans, the effectiveness of adaptation efforts must be monitored. To support effectiveness monitoring, identifying indicators for the considered measure selection is necessary. The use of indicators requires that the national adaptation plan uses the risk assessment to identify the risks to which adaptation measures are targeted at, and where possible, their subcomponents. Once the effectiveness of the selected measures has been assessed, indicators can be used to form an overall assessment of the success and challenges of adaptation policy.

The development of an indicator-based monitoring system is currently limited due to knowledge gaps in the effectiveness of adaptation measures. Despite these gaps, adaptation plans must be developed by defining goals at different levels and refining them as knowledge is gained. Long-term monitoring of environmental changes is also necessary to better plan and adapt adaptation policy as climate change progresses.

TIIVISTELMÄ

Ilmastonmuutos etenee nopeasti ja sen vaikutukset näkyvät Suomessa jo nyt. Ilmastonmuutokseen sopeutumista ja riskeihin varautumista on edistettävä, vaikka vaikutusten voimakkuuteen ja kehityssuuntiin tulevaisuudessa liittyy epävarmuutta. Haasteena on löytää epävarmuuden oloissa selkeät tavoitteet, toimenpiteet ja ohjauskeinot, joilla sopeutumista edistetään. Hallitustenvälisen ilmastonmuutospaneelin (IPCC) ilmastoriskiviitekehys tarjoaa systemaattisen perustan mallintaa sopeutumispolitiikan toimenpiteiden vaikuttavuutta ja mitoitusta.

Tämän raportin tavoitteena on havainnollistaa, kuinka sopeutumispolitiikkaa voidaan perustaa systemaattiseen riskimallinnukseen ja politiikan vaikuttavuuden seurantaa tehostaa siihen soveltuvien indikaattorien avulla. Raportti tarkastelee ilmaston lämpenemisen vaikutuksia julkishyödykkeiden tuotantoon. Julkishyödykkeitä ovat esimerkiksi maanpuolustus, terveys, ekosysteemien tila ja ilmastonmuutosta koskeva tieto. Riskiviitekehys-tarkasteluun valitaan ihmisten ja ekosysteemien terveyden turvaaminen, kun lämpötila nousee ja helleaallot yleistyvät.

Ihmisten terveyden osalta analysoidaan, kuinka helleaaltojen aiheuttamia ennenaikaisia kuolemia vähennetään joko lisäämällä asuntojen koneellista viilennystä tai kasvattamalla latvuspeitteisyyttä kaupunkien lämpösaarekkeiden vaikutusten vähentämiseksi. Tarkasteluun valittiin Helsinki, Turku ja Oulu, jotta alueelliset erot tulisivat huomioiduiksi. Tulosten mukaan Helsingissä ja Turussa viilennyksen kattavuus asuntokannasta tulisi kasvattaa liki sataan prosenttiin ja Oulussa viilennys tulisi kohdentaa valituille alueille. Kasvipeitteisyyden osalta alueellisesti kohdennettu viherryttäminen tuottaa positiivista nettohyötyä kaikissa kaupungeissa, eniten Helsingissä.

Ekosysteemien terveyttä tarkasteltiin valitsemalla esimerkiksi joen ekologisen tilan heikkeneminen ja sen ehkäisy. Ilmaston lämpeneminen nostaa myös veden lämpötilaa, mikä heikentää joen ekologista tilaa. Lämpötilan nousua voidaan lieventää perustamalla puustoisia suojakaistoja jokien varsille. Näin syntyy uutta vihreää infrastruktuuria, jota yhteiskunnan on tarpeen tukea. Tarkastelu korostaa sopeutumispolitiikan ulottamista elinympäristöihin ja ekosysteemipalveluihin.

Mallinnuksen lisäksi raportissa tarkastellaan tutkimuskirjallisuuden avulla sopeutumiseen liittyviä tietotarpeita ja sopeutumispolitiikan vaikuttavuuden seurantaan soveltuvia indikaattoreita. Suomen kansallisessa ilmastonmuutokseen sopeutumissuunnitelmassa (KISS2030) eritellään sopeutumisen tavoitteet ja toimet sekä niiden vastuutahot. Suunnitelmassa on myös tunnistettu seurantakeinoja, mutta vaikuttavuuden indikaattoreita ei ole toistaiseksi määritelty. Hallinnon- ja toimialakohtaisten sopeutumisstrategioiden välillä on puolestaan eroja johdonmukaisuudessa sekä riskikartoituksissa.

Kansallisen sopeutumispolitiikan onnistumisen kannalta suunnitelmien toimeenpanon lisäksi tulee seurata sopeutumisen vaikuttavuutta. Vaikuttavuuden seuranta tarvitsee tuekseen hyvin valitut indikaattorit. Indikaattorien käyttö edellyttää, että kansallisessa sopeutumissuunnitelmassa tunnistetaan riskiarvioinnin perusteella, mihin riskeihin, ja mahdollisuuksien mukaan niiden osa-alueisiin, sopeutumistoimilla pyritään vaikuttamaan. Kun valittujen toimien vaikuttavuutta on arvioitu, indikaattorien avulla voidaan muodostaa kokonaisarvio sopeutumispolitiikan onnistumisesta ja haasteista.

Indikaattoriperusteisen seurantajärjestelmän kehittämistä rajoittavat toistaiseksi tietoaukot sopeutumistoimien vaikuttavuudesta. Tietoaukoista huolimatta sopeutumissuunnitelmia on tehtävä määrittelemällä eri tasoisia tavoitteita ja tarkentamalla niitä jatkuvan kehittämisen periaatteella tiedon karttuessa. Myös ympäristön tilan muutoksia tulee seurata pitkäaikaisseurannalla, jotta sopeutumispolitiikkaa voidaan paremmin suunnitella ja mukauttaa ilmastonmuutoksen edetessä.

SAMMANDRAG

Klimatförändringarna framskrider snabbt och deras effekter är redan synliga i Finland. Anpassningen till klimatförändringarna och riskberedskapen måste främjas, även om det råder osäkerhet om hur kraftiga effekterna kommer att bli och hur utvecklingen kommer att se ut i framtiden. I en osäker omvärld är det utmanande att hitta tydliga mål, åtgärder och styrmedel för att främja anpassningen. Den mellanstatliga panelen för klimatförändringar (IPCC) har utkommit med en referensram för klimatrisker som erbjuder en systematisk grund för att modellera anpassningsåtgärdernas genomslag och omfattning.

Syftet med denna rapport är att illustrera hur anpassningspolitiken kan grunda sig på systematisk riskmodellering och hur uppföljningen av det politiska genomslaget kan förbättras med hjälp av lämpliga indikatorer. Rapporten innehåller analyser om den globala uppvärmningens inverkan på produktionen av kollektiva nyttigheter. Bland annat totalförsvaret, hälsa, ekosystemens tillstånd och informationen om klimatförändringarna räknas till kollektiva nyttigheter. Riskerna analyserades utifrån en referensram om hur hälsan hos människor och ekosystem kan tryggas när temperaturen stiger och värmeböljor blir allt vanligare.

Människors hälsa inbegriper en analys om hur man kan minska antalet förtida dödsfall som orsakats av värmeböljor, antingen genom att öka den maskinella kylningen av bostäder eller genom att öka växttäcket för att minska effekterna av urbana värmeöar. Helsingfors, Åbo och Uleåborg togs med i analysen för att beakta regionala skillnader. Resultaten visar att kylningen i Helsingfors och Åbo bör utökas till nästan 100 procent av bostadsbeståndet, och att kylningen i Uleåborg bör koncentreras till vissa specifika områden. Lokala växttäcken ger positiva nettoeffekter i alla städer, framför allt i Helsingfors.

Ekosystemens hälsa analyserades genom att till exempel undersöka det försvagade ekologiska tillståndet i en älv och hur en sådan situation kan förebyggas. Den globala uppvärmningen höjer också vattentemperaturerna, vilket inverkar menligt på älvarnas ekologiska tillstånd. De stigande temperaturerna kan mildras genom att anlägga trädkantade buffertzoner längs älvar. Detta kommer att skapa ny grön infrastruktur som samhället behöver stödja. Analysen betonar vikten av att bredda anpassningspolitiken till livsmiljöer och ekosystemtjänster.

Utöver modelleringen utgår rapporten från forskningslitteratur för att klargöra informationsbehoven och de indikatorer som lämpar sig för att följa upp anpassningspolitikens genomslag. Anpassningsmålen och åtgärderna samt de ansvariga aktörerna specificeras i Finlands nationella plan för anpassning till klimatförändringar (NAP2030). I planen ingår också uppföljningsmetoder, men några indikatorer för att mäta genomslag har tills vidare inte fastställts. De förvaltnings- och sektorspecifika anpassningsstrategierna skiljer sig från varandra i fråga om konsekvens och kartläggning av risker.

För att den nationella anpassningspolitiken ska bli framgångsrik behöver både planernas verkställande och anpassningarnas genomslag följas upp. En uppföljning av genomslaget kräver stöd av väl utvalda indikatorer. Användningen av indikatorer förutsätter att de risker (och om möjligt de riskaspekter) som man syftar till att hantera genom anpassningsåtgärder har identifierats i den nationella anpassningsplanen med hjälp av en riskbedömning. När åtgärdernas genomslag har utvärderats, kan indikatorerna användas för en övergripande bedömning av anpassningspolitikens framgångar och utmaningar.

Utvecklingen av ett indikatorbaserat uppföljningssystem begränsas för närvarande av luckor i tillgängliga data om anpassningsåtgärdernas genomslag. Anpassningsplanerna måste utarbetas trots luckorna genom att fastställa mål på olika nivåer och förfina dem enligt principen om kontinuerlig utveckling i takt med att datamängden ökar. Förändringarna i omvärldens tillstånd kräver långsiktig uppföljning, för att anpassningspolitiken bättre ska kunna utformas och anpassas i takt med att klimatförändringarna framskrider.

1. INTRODUCTION

As climate change progresses, societies have increased needs for adapting to its effects. Climate change impacts are trajectories that progress in a trend-like manner or as sudden shifts, such as extreme weather events. Some of these shifts can prove irreversible (e.g., Armstrong et al. 2022). The multiplicity and uncertainty of climate change impacts render it difficult to create a clear and functional policy for advancing climate change adaptation. Nonetheless, adaptation policy and risk preparedness must be implemented despite these uncertainties. Adaptation policy allows society to improve its performance under gradually progressing changes and its response in sudden crises.

Society's challenge is to identify, under uncertainty, those clear goals, measures, and policy tools that will progress adaptation as much as possible. Conceptualizing adaptation policy is aided by clarifying the division of duties between public authority, i.e., the state and municipalities, and private actors. Public authority is foremost responsible for ensuring national safety, public health, and other public goods, such as advancing the state of living environments and adaptation-related knowledge production. On the other hand, private actors, enterprises, communities, and citizens have the best prerequisites for private adaptation in their own branches of activity, for example in industry or agriculture and forestry. Nevertheless, public authority must support private adaptation by decreasing the impacts of uncertainty to private decision-making, for instance by offering information on climate change progression and by aiding actors face financial risks. For support, adaptation policy requires both general principled objectives and concrete quantitative goals, the realization of which must be monitored.

The more policy outlines research-based quantitative goals, the easier monitoring policy effectiveness becomes. The Paris Climate Agreement, established in 2015, and national climate legislations bind states to report on adaptation measures. Since 2019, Finland has accordingly reported on the country's adaptation policy progress in both its annual, national-level climate report and in its National Energy and Climate Plan progress report, delivered to the European Commission once every two years in 2021 and 2023. To-date, these reports describe adaptation policy at a general level, despite the detailed guidelines issued by the European Union's Energy Union Governance Regulation (see EU 2020/1208, Annex 1[1]).

One of the objectives of the Finnish National Climate Change Adaptation Plan 2030 (hereafter Adaptation Plan 2030), published in 2023, is to implement systematic adaptation monitoring that supports the development of operations (Objective 24). The objectives set for adaptation policy and the indicators supplementing these objectives offer the possibility of both fine-tuning the adaptation policy objectives and systematizing climate change monitoring. One possible example is the objective of limiting the increase of heat-related deaths during heatwaves by advancing cooling coverage, either generally or by targeting vulnerable groups. Such an objective is a clear policy principle that is relatively easy to monitor.

The aim of this report is to show how science-based adaptation policy can be conceptualized through modelling and by the creative utilization of research data for achieving adaptation in relation to public goods. The report does not define the actions of public authority for advancing private adaptation in the production of so-called general commodities. In this context, adaptation policy requires increasing the knowledge of changing conditions and utilizing various ways to lessen the impacts of uncertainty. This is a complex task and has rarely been analysed in the literature.

[1] Commission Implementing Regulation (EU) 2020/1208, L278/1, Annex I: [https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R1208].

The definitions and goals of policy actions targeting public goods are analysed by referring to the theoretical framework for optimal adaptation formulated by the Intergovernmental Panel on Climate Change (IPCC 2014 (AR5), IPCC 2022 (AR6)). The analysis targets the roles of public authority and policy formulation. The health effects of heatwaves, the urban heat island effect, and the ecological state development of a case river under a warming climate are used as examples. It is possible to set quantifiable goals for the adaptation policies of the chosen cases, and to conceptualize the necessary actions and policy tools promoting them. The approach can also be applied to many other adaptation themes relating to public goods.

Once a policy has been defined, its progress must be monitored. Concurrently, it is necessary to remember that adaptation happens at several levels, and monitoring must therefore cover themes that are not part of public authority policy but whose follow-up is nevertheless important. In such cases, a national-level monitoring system, suggested by Klostermann et al. (2018), is applied for examining adaptation monitoring: 1) defining the system under follow-up, 2) defining the policy or identifying and choosing the applicable monitoring indicators, 3) identifying the parties in charge of monitoring and defining their responsibilities, and 4) defining the measures used for monitoring and assessment.

2. FRAMEWORKS FOR ADAPTATION POLICY AND ADAPTATION MONITORING

Modelling adaptation policies is a fairly novel process. Combining climate risk development with the choice and scales of the adaptation policies and incorporating all policy tools into one holistic analysis is a methodological challenge. To-date, only a few analyses have integrated climate risks (e.g., Holman et al. 2019, Oswald et al. 2020). Climate change monitoring also requires a systematic methodological approach. This chapter presents the theoretical frameworks used as the bases of policy analysis and monitoring.

2.1. Framework for defining adaptation policy

This report models adaptation policy using the latest IPCC risk framework (Ara Begum et al. 2022). Climate risk subcomponents — hazards, exposure, and vulnerability (adaptive capacity and sensitivity) — are defined in the IPCC Fifth Assessment Report (IPCC 2014). Figure 1 illustrates this approach. First, we define the baseline scenario of climate risk. This denotes climate risk development without planned adaptation, usually implemented by public authority. However, the baseline scenario includes private adaptation. The three initial subcomponents of risk describe the projections or scenarios of the baseline scenario, where adaptation policy is not implemented, yet autonomous private sector adaptation is included. For example, farmers perceive climate change-induced crop impacts through their individual activities. However, their adaptation level may remain too low relative to society’s needs, which is why public adaptation measures, i.e., adaptation policy, are required. The first risk component describes a hazard, i.e., a climate change-related physical phenomenon, such as heatwaves or the temperature development of a river. The next element of risk describes the consequences caused by exposure to the physical phenomenon. The third element describes the development of the exposed actor. Together, these three elements form the projections of the risk baseline scenario.

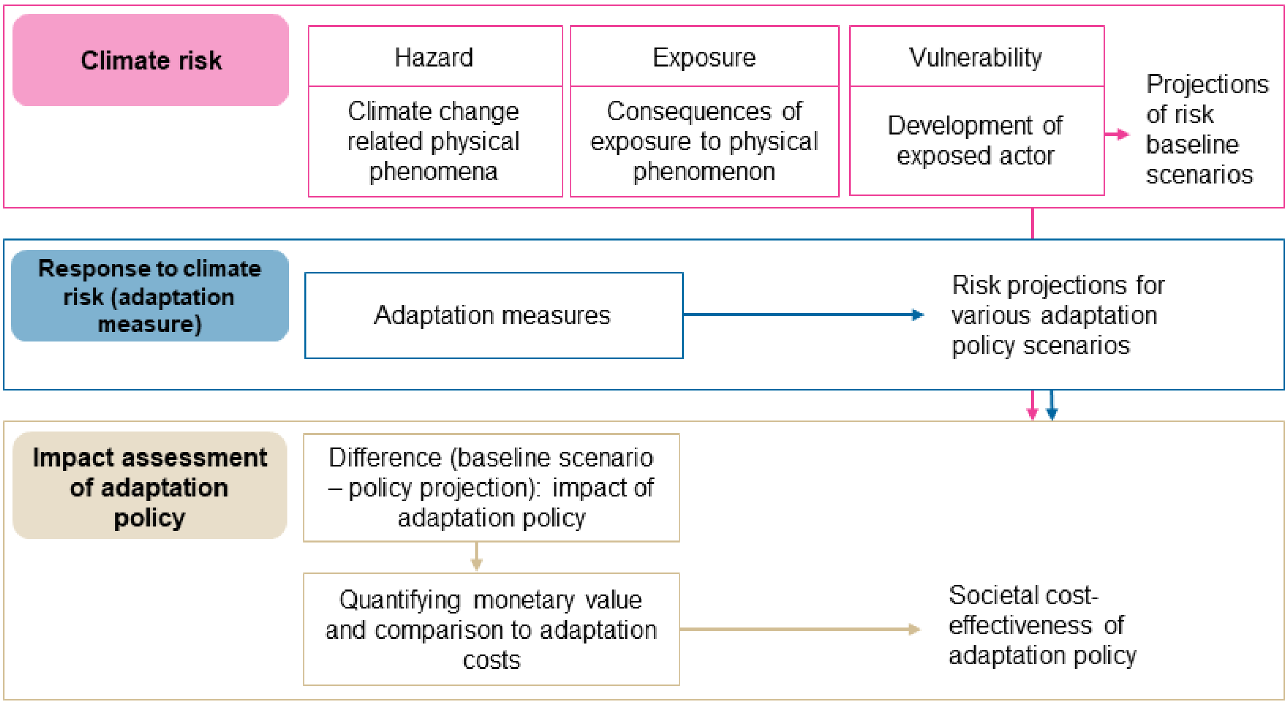

Figure 1. IPCC framework for assessing adaptation policy measures (based on Ara Begum et al. 2022).

A response signifies the planned (public) adaptation measures that influence a risk and must therefore be assessed as part of the risk framework (Simpson et al. 2021, Ara Begum et al. 2022). In a policy trajectory, public authority advances the implementation of adaptation policies. Combinations of adaptation measures form policy scenarios, which are described using policy trajectories. The difference between a risk baseline scenario and a policy trajectory describes the impact that an adaptation policy has on a risk. When possible, a monetary value can be defined for annual risk impacts, which provides the yearly benefits of adaptation. These can be compared to the annual expenses of adaptation measures. When the differences between benefits and expenses are discounted and summed over time, the net present value (NPV) of the adaptation policy is obtained. If the NPV is positive, advancing the adaptation policy becomes justified for society. The following chapter applies this approach to singular climate risks and adaptation measures in the adaptation policy scenarios.

The IPCC risk framework offers society a starting point for planning climate change adaptation in a way that maximizes societal wellbeing or minimizes its realized disadvantages in each situation. Policy formulation is carried out, accordingly to the IPCC risk framework, by defining and outlining a system, which is then assessed in terms of its adaptation. The system is appointed a clear adaptation goal based on the target set for the policy in question and on the assessed effectiveness of the chosen adaptation measures. The adaptation measures are proportioned with optimal adaptation so that the appointed goal is reached as effectively as possible. Comparing the baseline scenario in Figure 1 with the optimal adaptation policy allows defining those policy tools with which the adaptation measures are realizable at the desired level.

2.2. Frameworks for adaptation monitoring

Broadening the research for modelling adaptation effectiveness requires applying research that is used in other fields for studying policy effects and adaptation scenarios. Formulating and researching adaptation scenarios focuses on qualitative scenarios and on utilizing quantitative climate data and socioeconomic information, while impact assessments and policy scenarios receive less attention (Nalau and Cobb 2022). The municipal and regional levels use the shared socioeconomic pathways (SSP) method to envision the future while concurrently accounting for adaptation policy development. This may support local and regional adaptation policy (Reimann et al. 2021, Balk et al. 2022). Studies showcase promising examples of how vulnerability and exposure can be included in SSP projections (Binita et al. 2021, Landreau 2021, Marzi et al. 2021). *Ex ante*[2] cost-benefit analysis has to-date been rarely used to display successful adaptation policy (Nassopoulos et al. 2012, Ryan and Stuart 2017).

Once an adaptation policy has been defined, monitoring is used to examine how well the chosen adaptation measures are realized and how effective they are (Figure 2). It is useful to identify which types of indicators function best for realizing each measure and for monitoring measure effectiveness. Once the effectiveness of the chosen measures has been assessed, an overall evaluation can be formed of the adaptation policy's success and challenges.

Regarding monitoring, it is essential to understand that the effects of climate change are all-pervasive, and society does not necessarily define policies based on all possible impacts. For example, the adaptation policy for ecological changes and pressures is likely planned at a much slower pace than the policies regarding health impacts. Nonetheless, monitoring is also required for impacts that fall outside the scope of a given policy. In this case, defining the system, as shown in Figure 2, is significant when planning monitoring, to allow for defining automatic adaptation, adaptation measures, and their effectiveness and for planning their monitoring.

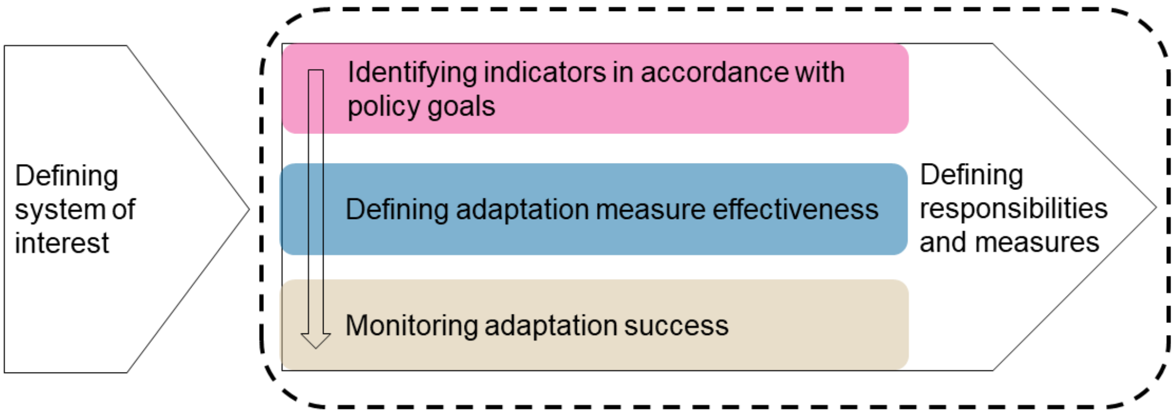

Figure 2. Application of developmental subcomponents in the Finnish National Climate Change Adaptation Plan 2030 (adapted from Klostermann et al. 2018).

[2] *Ex ante* = before an event, *Ex post* = retrospectively, after an event

3. OUTLINING ADAPTATION POLICY IN LIGHT OF THREE CASE STUDIES

We examine adaptation policy through three examples of public goods. Health issues, which are becoming increasingly important due to climate change, are examined through the prevention of premature deaths caused by heatwaves. Mortality due to heatwaves is limited either 1) by cooling apartments or 2) through targeted or zoning-based greening, i.e., by increasing green spaces. As an example of the impacts that rising temperatures have on ecosystems, 3) we use a case where the decline in the ecological condition of a river due to water temperature increases is controlled by establishing wooded buffer strips. Heat adaptation is examined using a Monte Carlo simulation of three climate scenarios[3] (RCP2.6, RCP4.5, RCP8.5 (Moss et al. 2008) in three cities (Helsinki, Oulu, Turku). The case river is a typical small river in southwestern Finland.

3.1. Limiting heatwave-induced deaths through mechanical cooling

Increasingly more evidence is emerging concerning the health impacts of heat exposure. Studies based on Finnish data (Appendix 2c) connect heat exposure with manifold health problems. These include decreased stamina, sleep disturbances, and cardiovascular and respiratory symptoms (Näyhä et al. 2013), increased use of healthcare services, increased incidence of respiratory disorders, pneumonia, chronic obstructive pulmonary disease (COPD), and myocardial infarction (Sohail et al. 2020), increased risk of pathogenic microbial infections (Baker-Austin et al. 2016), and mortality (Ruuhela et al. 2017, Kollanus et al. 2021). Mortality during heatwaves has been studied considerably. For example, Kollanus and Lanki (2021) observed that non-accidental mortality increased in Finland by ten per cent (95% CI 7.7–12.1%) during heatwaves. Due to their prevalence, cardiovascular disorders are the most important heat-related cause of death in absolute terms (ibid.). Results from studies conducted among the Finnish population are in line with results from several international studies (Fouillet et al. 2008, Anderson and Bell 2009, Basagaña et al. 2011, Gasparrini and Armstrong 2011, Gasparrini et al. 2012, Gasparrini et al. 2015, de'Donato et al. 2015, Armstrong et al. 2017, Gasparrini et al. 2017, Ruuhela et al. 2017). The health effects of exposure to long-term temperature increases are currently less well-known than effects caused by exposure to short-term heatwaves.

Gasparrini et al. (2017) estimated that heat-related excess mortality will increase 1–4 per cent (CI 0.2–7.2%) by the end of the century if climate change limitation fails.

A study by the Finnish Institute for Health and Welfare showed that the national social and healthcare system are insufficiently prepared for challenges caused by hot weather (Ung-Lanki et al. 2017). The knowledge and competence that healthcare professionals have concerning extreme heat conditions are not comprehensively understood nor are the health impacts that extreme heat causes. The discontinued Kuumainfo [Heat information] website, Terveydenhuollon kylmä- ja kuumaopas [A healthcare guide to cold and heat] (Hassi et al. 2011, in Finnish), and Exceptional situations related to environmental health (STM 2014, in Finnish with English summary) are instructive documents aimed at various actor groups and providing guidance on extreme temperature exposure. However, precise understanding is lacking regarding how well the existing documents have reached their target groups and to what extent the message portrayed by these documents has been incorporated into organizational cultures.

[3] The RCP scenarios depict various climate trajectories from the greenhouse gas viewpoint. The numerical value in the scenario name illustrates how much radiative forcing (watts per square metre) has increased by 2100 compared to the pre-industrial age (Moss et al. 2008).

Research results are scarce concerning adaptation measures and their impacts on temperature increases and heatwaves. Adaptation impacts have been identified indirectly. For example, the impact of early-warning systems has been assessed directly by comparing mortality before and after system activation (Fouillet et al. 2008, Chiabai et al. 2018, Wu et al. 2020) and by comparing the scenarios of '*no adaptation'* (no adaptation measures are defined or incorporated) and '*full adaptation'* (adaptation measures are incorporated in model) (e.g., Diaz et al. 2019). However, measures for reducing risks and disadvantages can be identified in a risk-based manner. This report examines measures that can be influenced through national adaptation policy. Here, climate change mitigation policy is left outside of the examination, irrespective that a great deal of the direct health impacts due to temperature increases could be avoided in scenarios that include limitation strategies for curbing emissions and for slowing down global warming (Gasparrini et al. 2017).

Air conditioning (AC) is a self-evident solution for dealing with heatwaves and gradual temperature increases, as it reduces health hazards and mortality. Household air conditioning decreases high temperature-related mortality by 77 per cent (according to a meta-analysis of eight studies) (Bouchama et al. 2007, Kenny et al. 2010). A US study showed that air conditioning reduced heat-related deaths during 1960–2004 by as much as 86 per cent (Barreca et al. 2016).

We examined district cooling (DC) and installable air conditioners as adaptation measures for heatwaves. We assume that DC can reduce the heat-related mortality risk by 90 per cent (a resident is completely safe from a heatwave if they stay at home during the heatwave, as residential temperature can be freely regulated). This simplifying assumption, that nearly all mortality and morbidity are avoidable through adaptation, is typical in the absence of more precise knowledge (WHO 2013). Service provider information and expert consultations were used to estimate cooling equipment service age, apartment- and building-specific acquisition and installation expenses, and annual apartment- and building-specific energy consumption and prices (see Appendix 1).

Figure 3a–c illustrates the increase of heatwaves in forecasts and prediction models. Linear regression models fitted to the predictions of the Finnish Meteorological Institute offer yearly means for the Poisson distribution describing weather condition randomness, which, in turn, defines the number of annual heatwaves used in the Monte Carlo simulations. Clear differences exist between the climate scenarios. On the contrary, differences between the case cities are small, especially between Helsinki and Turku, as both are located in southern Finland and have similar climates. However, it must be noted that that these models do not account for the urban heat island effect (a coarser spatial resolution), which may increase temperatures during heatwaves. The intensity of the urban heat island effect is bound to the size and urban structure of the city in question.

Figure 3d–f presents vulnerability[4], which particularly links to older age groups and develops with time. Predictions show that in Turku the oldest age group (≥75-year-olds) is growing and the second oldest age group (65–74-year-olds) is decreasing throughout the time horizon, which indicates an ageing population. The oldest age group in Oulu is also increasing throughout the time horizon, whereas the second oldest age group remains more or less the same. Helsinki has a similar development trajectory as Oulu, with the exception that the oldest age group initially increases sharply, but later this growth levels out.

[4] This report uses high age as an indicator of vulnerability, as it is a well-known vulnerability factor in the literature and data for modelling the variable are readily available. The predictions used here originate from Statistics Finland until 2040, after which they have been extended using trends in the ARIMA models.

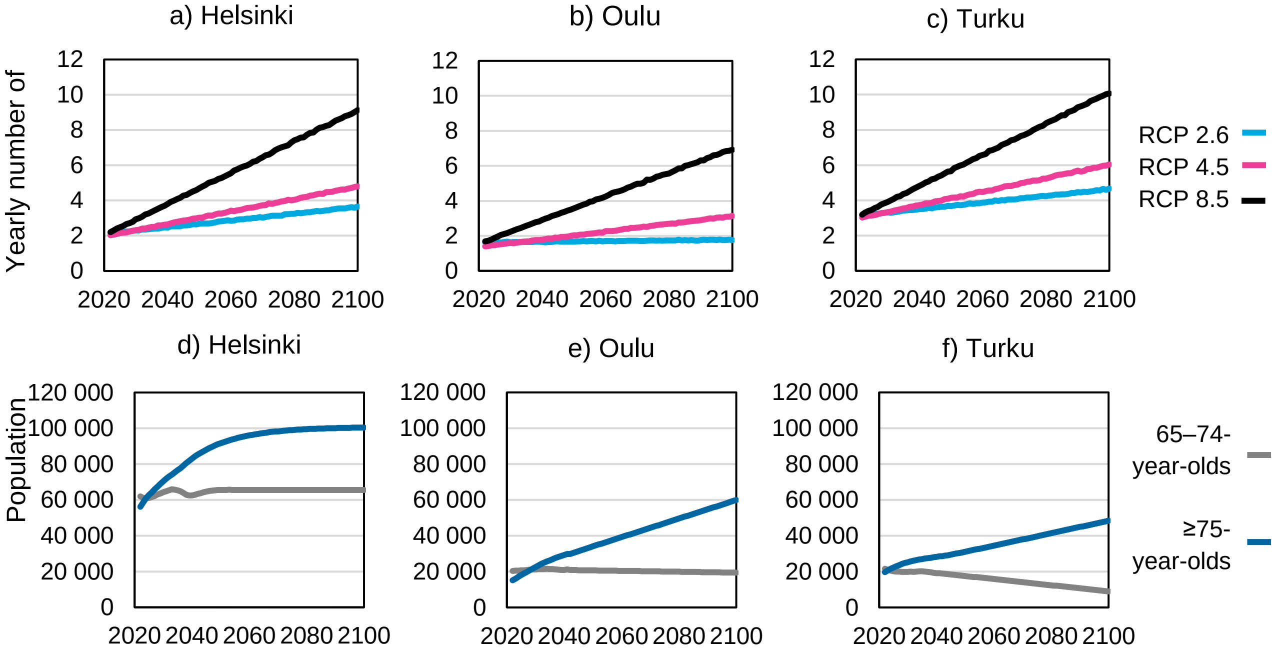

Figure 3. Increase in heatwave incidence (a–c) in three climate scenarios and the development of vulnerable age groups (d–f) in Helsinki, Turku, and Oulu.

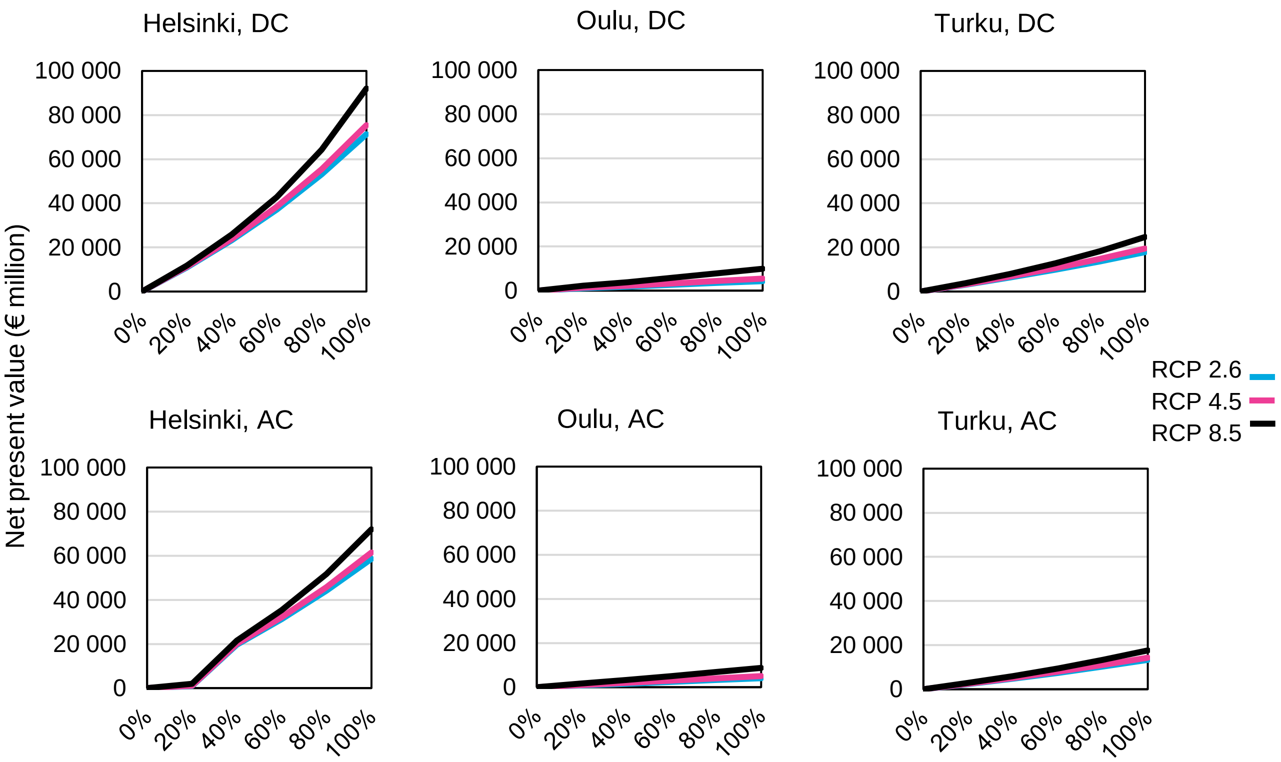

Figure 4. Net present value of district cooling (DC) and installable air conditioners (AC) in the cities of Helsinki, Oulu, and Turku as a function of the share of vulnerable population with access to cooling.

Figure 4 presents the net benefits of adaptation measures at various levels of adaptation. Here, the level of adaptation denotes the share of the vulnerable population that has access to cooling. The benefit is prevented death, and the costs are the investment and operating expenses over the time horizon, with expenses discounted to present value, i.e., by calculating the NPV of adaptation. Positive NPVs indicate that adaptation through cooling is recommendable. Irrespective of climate scenario, city, or cooling method, the NPV increases as a function of the share of the vulnerable population with access to cooling. The rise in net benefits shows that *complete adaptation is the best policy* for society, as it avoids all excess deaths related to heatwaves. The high estimate for human life value (2.4 million €) influences this result. Figure 4 also shows that the net benefit of adaptation is greater the warmer the climate scenario.

The conclusion of this examination is *a recommendation to gradually provide cooling to the entire vulnerable population*. For this, public authority must compile a plan together with heating plants and real estate properties for increasing cooling coverage in cities. Cooling is expected to progress in a market-based manner. Public authority should set minimum demands for temperature conditions in new construction and in subject-to-licence reconstruction. The requirements for preventing indoor overheating, i.e., hazardously high temperatures, should be reviewed through current research. Cooling should also be advanced in the current housing stock. Pipeline and plumbing renovations offer a good opportunity for advancing building-specific cooling outside of the cooling network. Society should offer knowledge-based guidance and positive incentives for advancing cooling.

Additionally, a separate plan should be compiled for offering cooling solutions to senior citizen housing, hospitals, and daycare centres across the country and recommendations for cooling private properties (single-family homes).

3.2. Limiting heatwave-induced deaths using zoning-based and targeted greening

Heatwave-related health hazards are also linked to city structure. Physical constructions that impact health hazards include the compactness of the built environment, the distribution of building types, air current-channelling street canyons, surface material quality, green structures, areas with canopy cover, and spatial cooling solutions (e.g., Salata et al. 2017, Arifwidodo and Chandrasiri 2020, Ellena et al. 2020, Venter et al. 2020). Intervening in urban framework planning and steering is justifiable for advancing health risk adaptation (Jurgilevich et al. 2023). Heat convection away from city areas can be increased by including the street canyon phenomenon, i.e., the wind-channelling effect of streets, as part of urban planning (Kleerekoper et al. 2012). Correspondingly, green structures can be used to increase the cooling effect by 1–7 °C in their immediate vicinity and more broadly (Cohen et al. 2012, Feyisa et al. 2014, Zhang et al. 2017, Alvi et al. 2022).

Urban land use has been shown to create urban heat islands (UHIs). These are areas where temperatures rise above those in surrounding areas, chiefly due to waste heat created through human actions (particularly during winter) and by the release of irradiation energy stored in urban structures and the smaller evaporation in urban areas compared to rural regions (particularly during summer). The higher temperatures caused by UHIs induce year-round health hazards at low latitudes and mainly summertime health hazards at high latitudes such as Finland. (Suomi and Käyhkö 2012, Ruuhela et al. 2021). Vegetation coverage both in and outside of cities decreases the UHI phenomenon (Miles and Esau 2020). An extensive study covering 452 localities in 24 countries, including the metropolitan region of Finland, showed that urban green space coverage decreases heat-related deaths (Choi et al. 2022). Cities with the most green spaces (the top one-third) had a heat-related mortality risk of 1.12 (95% CI 1.13–1.25), while this risk was markedly higher in cities with the least green spaces (the lowest one-third): 1.46 (CI 1.31–1.62). Increases to green structures and their cooling effect through urban planning and environmental and regional planning can therefore be considered an adaptation measure. Building construction guidelines and safety instructions should be updated, to increase climate change preparedness. More research on this topic is required (Esau et al. 2021).

In a situation with direct sunlight and high irradiation, the impact of green walls on daytime temperature averaged -2.4 °C (median, min. -2.0 °C, max. -2.8 °C) in cities belonging to the humid continental climate (Dfb) of the Köppen climate classification (e.g., southern Finland). The night-time cooling effect was less strong: -1.9 °C (min.-1.7 °C; max. -2.0 °C) (Susca et al. 2022). Green walls can therefore, in certain cases, have a cancelling effect on local UHI phenomena (ibid.). In continental climates, average daytime cooling levels measured in the immediate vicinity of greening solutions include: -0.8 °C under trees, -1.6 °C in urban forests, -0.8 °C in parks and gardens, and -0.6 °C on lawn areas. The cooling effect of parks and gardens has been observed to reach a 1.25-kilometre distance from the green space in question. (Knight et al. 2021). This effect gradually decreases as the distance increases.

Possible maladaptation should be avoided when constructing green spaces. Maladaptation generally means adaptation measures that cause unintended disadvantages (see e.g., Juhola and Käyhkö 2023, Juhola et al. 2016). For example, certain vector-transmitted diseases, such as Lyme borreliosis, may increase if adaptation measures enhance the suitable habitats and conditions of their vector species (Mathieu and Karmali 2016). The placement and occurrence in green spaces of important pollen allergy -causing plant groups, such as birches and mugwort (*Artemisia vulgaris*), should also be considered. Additionally, expanding the surface area covered by green spaces may increase heating needs during the heating season at Finnish latitudes (Santamouris 2014).

We examined the greening effect on city temperatures and mortality through the case study cities of Helsinki, Oulu, and Turku (Appendix 1). Based on discussions with Turku and Helsinki city representatives, canopy cover increases were chosen as the most feasible and effective greening measure for limiting the UHI effect; the representatives believed it to be the most feasible and sensible alternative. Additionally, an article by Sadeghi et al. (2022) showed that, based on earlier literature, planting trees decreases temperatures by 0.1 to 4 °C (mean 1.5 °C), while the cooling effect of green roofs is 0–3 °C (mean 0.6 °C). In other words, planting trees is a more efficient greening measure. Due to the shading effect, tree planting can also be considered to have a wider impact than planting lawn areas. The costs of increasing canopy coverage and tree removals were calculated for the observation period (2026–2100) using standard expenses for park and street trees (50%–50%) (Tajakka 2019). A regional greening implementation scheme was carried out in two ways in the cities of Helsinki, Oulu, and Turku: 1) a regionally broader scheme based on the cities' master plans, using the cities' zoned areas as focal regions, and 2) a population density -based plan targeted at the most densely habited nine-square-kilometre area of each city. Cost calculations for greening were computed using greening alternatives of various scales, where canopy coverage was increased by 10, 20, 30, and 40 percentage points compared to current canopy cover levels.

The effect of increasing canopy coverage on limiting the UHI phenomenon was examined by modelling a continuous thermal surface through a linear regression model, where temperature observations from the Turku local climate network (TURCLIM) acted as the dependable variables and soil cover (CLC 2018 and SLICES 2010) and terrestrial elevation (DEM data) as the explanatory variables (see Appendix 1). Although the UHI phenomenon is typically strongest at night, in this case mean 24-hour temperature was chosen as the temperature variable because it provides the most comprehensive picture of heat exposure. Previous studies conducted in Finland have observed mean temperature to describe the connection between heat exposure and mortality (Kollanus and Lanki 2021, Ruuhela et al. 2021). According to the regression model, increasing canopy coverage by ten percentage points would decrease a city's UHI by approximately 0.5 °C per 24 hours, while a 20 percentage point coverage increase would produce a circa 1°C temperature decrease.

Tree planting expenses were 2384.02 and 3543.60 euros for park and street trees, respectively. They correspond to the standard expenses provided in a guidebook for urban tree value determination (Tajakka 2019) for rooting times of equivalent tree species. Half of the planted trees were park trees, and the other half were street trees. Trees were considered to have nine-metre-wide crowns, and one crown covered 63.62 square metres. As an example: a ten percentage point increase in canopy coverage over a one-square-kilometre area requires planting 1572 trees. As the calculation time frame reaches until the end of 2100, the projections have been made for scenarios where 50 per cent and 100 per cent of the planted trees must be removed and replanted with new individuals during the observation period. Tree removal expenses were also defined according to a guidebook for urban tree value determination (Tajakka 2019), in which case the costs of removing one tree amount to 2942 euros.

When adaptation is carried out using *zoning-based* city greening and modelled using three greening levels and three climate scenarios (RCP2.6, RCP4.5, AND RCP8.5), the net benefit for all greening levels in all climate scenarios is only positive in Helsinki (Figure 5). The corresponding net benefit for all greening levels is negative in Oulu. In Turku, the net benefit in climate scenario RCP2.6 is negative for all greening levels, whereas the benefit is positive for all greening levels in scenario RCP8.5.

When greening is *targeted* to the most densely populated areas of each city using four greening levels and three climate scenarios, the clearest change compared to zoning-based greening is seen in Oulu, where the NPV of the net benefit becomes positive in scenario RCP8.5 for all four greening levels, and even the three largest greening levels turn positive in the RCP4.5 scenario (Figure 5). In all examined cases, the net benefits gained by Helsinki are markedly greater compared to the other cities.

The policy recommendation based on this examination is clear for Helsinki and Turku: both cities should implement further greening as an adaptation measure. Oulu should consider targeted greening regionally within the city.

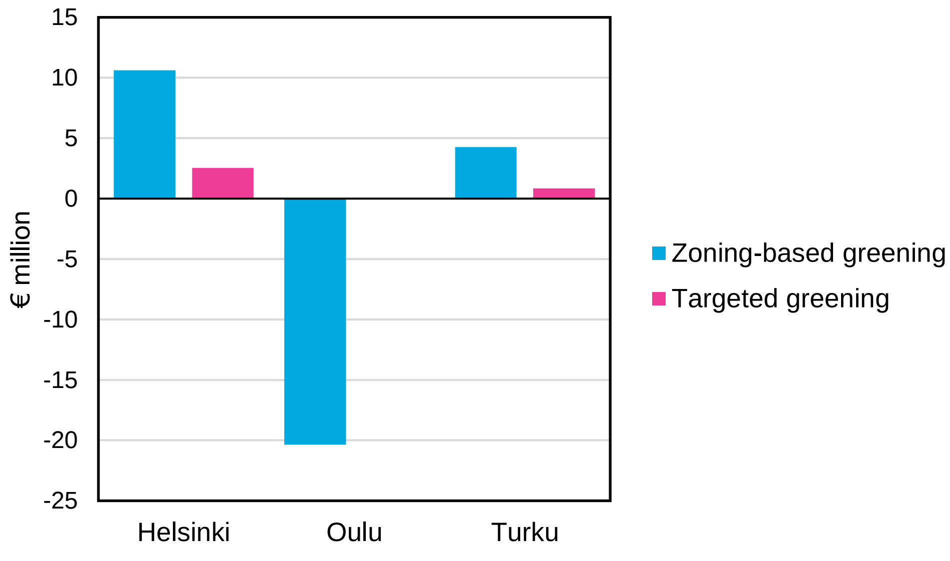

Figure 5. The average net present values of zoning-based and targeted greening in the cities of Helsinki, Oulu, and Turku (when all greening levels and climate scenarios are aggregated).

3.3. Using wooded buffer strips to limit the decline in a river's ecological state caused by water temperature increases

Increasing temperatures also cause harm and stress to nature. For example, water ecosystems are sensitive to temperature changes. Adaptation policy expands to also include living environments and species and to predicting changes in these factors. Examining the ecological state of a river offers an example of the adaptation difficulties faced by the production of a public commodity related to nature. The increase in summer daytime mean temperature raises river temperatures, which weakens their ecological state and reduces the opportunities for their recreational use (Whitehead et al. 2009, Estrela-Segrelles et al. 2023, Fuso et al. 2023).

When we examine water quality, the policy trajectory observes the impact of a precipitation increase on nutrient leaching by optimizing buffer strip width, and river temperature increases are curbed by planting trees in surrounding or bordering buffer strips. The baseline scenario includes private adaptation, i.e., we assume that private farmers account for climate change-induced crop increases when making fertilization decisions. We can assume that farmers do not account for river temperature increase -induced declines in the ecological state of rivers or the rise in nutrient leaching caused by elevated precipitation. We also assume that, in the baseline scenario, society defines a buffer strip width that prevents nutrient leaching along rivers and considers the maximum fertilization limits as defined by the Nitrogen Directive but does not acknowledge the impact of temperature on the ecological state of waters.

Economic optimization uses several simplifying assumptions, which are used to rid the process of certain details that are of little significance to the analysis. This is due to spatial-dynamic problems, i.e., problems combining place and time, being extremely complex to solve. We do not examine any specific river, but rather use a model river (a medium-sized river in southern Finland). For this reason, factors, such as water clarity, turbidity, and colour, river bottom type, contact with groundwater, river shape (depth, width), season (e.g., the elevation angle of the Sun, phenology), or tree type, do not influence the analysis. We use three locations on the river: upstream, midstream, and downstream. The model time frame extends to year 2100. We assume that the mean summertime (June–August) temperature development until 2100 denotes an air temperature rise of approximately two degrees Celsius in RCP2.6, a three-degree rise in RCP4.5, and a six-degree rise in RCP8.5. One year is used as the analysis time step. We assume that a one Celsius degree increase in air temperature raises the summertime mean water temperature by 0.7 °C (El-Jabi et al. 2014), in which case the water temperature rises accordingly with the realized climate scenario (Morrill et al. 2005, Yu et al. 2021).

We examined shade-increasing wooded shoreline zones that reduce direct warming caused by sunlight as a measure for alleviating temperature increases in lotic waters (Bowler et al. 2012, Turunen et al. 2021). According to Turunen et al. (2021), wooded shoreline zones can decrease water temperature by 0.7 °C. Additionally, planting trees along river shores increases the value of the ecological index, depending on what part of the river is being examined. The increase in ecological index value means that the value of the ecological benefits gained from a river increase, i.e., the increase has a direct positive effect on human wellbeing. To allow for tree planting, we assume that a buffer zone limiting nutrient leaching must be at least three metres in width. In our calculations, the impact increasing the ecological index of trees is at its weakest downstream, where the river is at its widest. The connection between river water temperature and ecological condition is also influenced by the location in the river's longitudinal profile, as river width typically increases downstream. An ecological index is used to assess river ecological state in the European Union, and this index is influenced by several factors. An ecological index can also be changed into monetary value and included in economic analyses (Nelson 1999, Yu et al. 2009, Becker et al. 2021). Agricultural nutrient leaching will increase with climate change, particularly due to winter rains, reductions in ground frost, and repeated snowmelt (Meier et al. 2022). These effects weaken the quality of river ecosystem services, thereby decreasing societal wellbeing.

Climate change causes several risks to agriculture, and farmers use various strategies for adaptation. Climate change may induce crop increases, and farmers account for this by increasing nitrogen fertilization levels (Käyhkö 2019, Neset et al. 2019, Wiréhn et al. 2020). The steering measure palette for agricultural environmental impacts in Finland includes buffer strips along rivers to retain nutrient leaching (Uusi-Kämppä and Yläranta 1992, Uusi-Kämppä and Jauhiainen 2010). The impact of a precipitation increase on nutrient leaching can be considered by optimizing buffer strip width and regulating fertilization (Qi and Altinakar 2011, Shortle et al. 2020).

Optimal adaptation to the climate change impacts in river water quality comprises both private adaptation and public adaptation measures. The model optimizes fertilization use on agricultural lands surrounding the river, buffer strip widths along riverbanks, and decisions concerning tree planting on the buffer zones until 2100.

Figure 6 shows how the ecological index develops at various locations of the river in different climate scenarios during the period 2022–2100. Planting trees along the riverbank increases the ecological index value by 0.2 units up- and midstream and by 0.15 units downstream. The water temperature rises consequently to air temperature increases, causing the ecological index to decrease. The hotter the climate scenario in question, the more steeply the ecological index drops.

We examined optimal adaptation using dynamic optimization. Results between the climate scenarios did not differ greatly from each other. Planting trees along riverbanks is an optimal adaptation measure for society in all climate scenarios and at all locations of the river (up-, mid-, and downstream) when the aim is to combat the ecological decline caused by water temperature increases. In the private optimum, a farmer optimizes their annual fertilization quantity by accounting for the climate change impact on crops, which is why the fertilization level is markedly greater than in the societal optimum, which also accounts for the externalities of production. The autonomic adaptation of private actors is therefore insufficient if the externalities of production are ignored. The NPV of the societal benefit is circa four per cent lower in the private optimum than in the societal optimum. The NPV in the societal optimum, i.e., the societal benefit, is greater than in the baseline scenario. The NPV of the societal benefit therefore rises by approximately two per cent when tree planting is used as an adaptation measure against river warming.

This analysis provides strong grounds for initiating geographically more comprehensive and accurate modelling of how the ecological states of both river and lake waters and coastal shore waters develop, and of their adaptation needs and the most efficient adaptation measures.

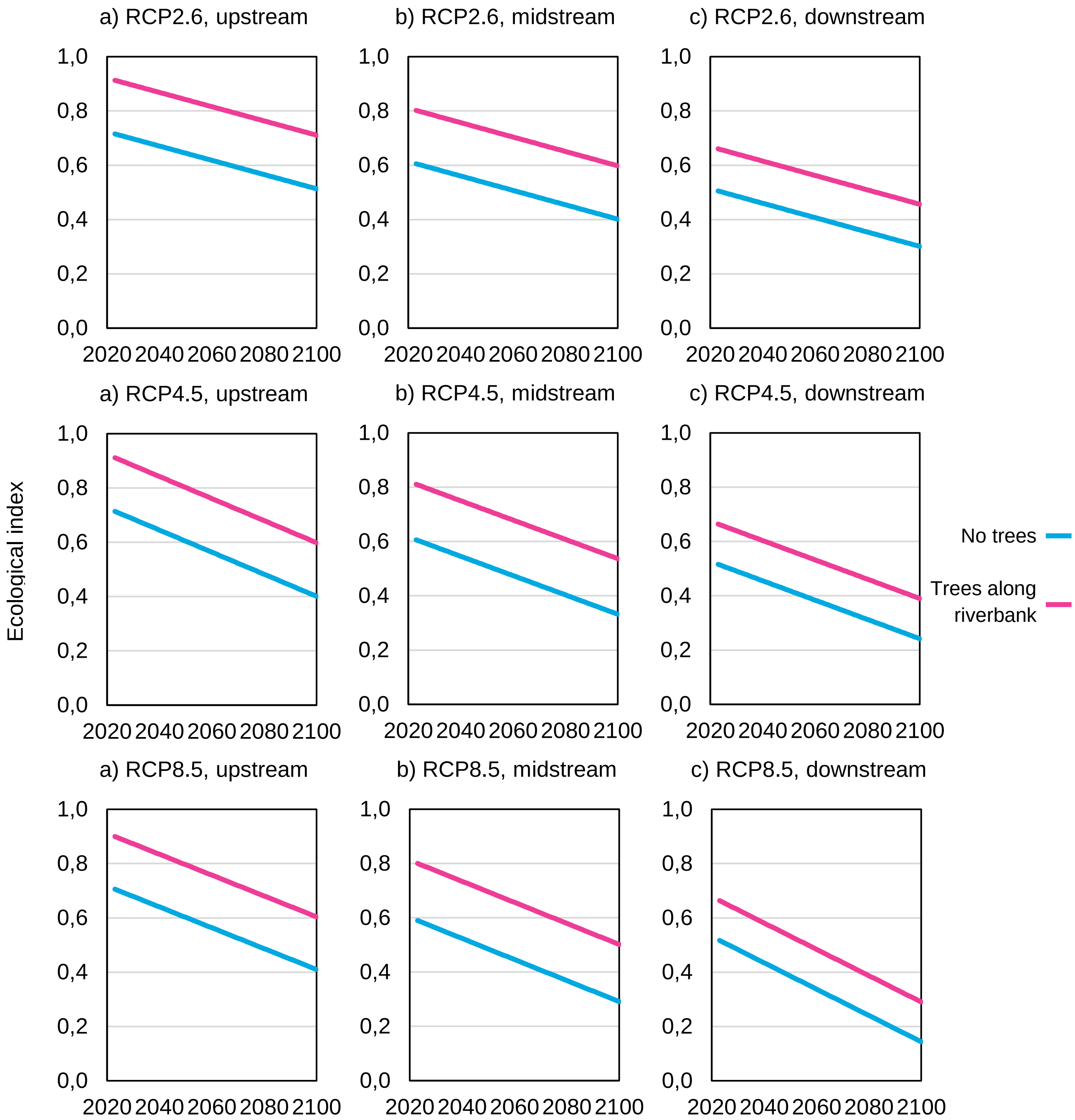

Figure 6. The decline in ecological index caused by a river water temperature increase in three locations along the river in conditions where trees line or do not line the river. Three scenarios are used in the modelling.

4. ADAPTATION MONITORING

Monitoring and assessment systems denote arrangements and procedures established by public administration, which are used to monitor the implementation of national adaptation policy and evaluate its efficiency or impacts, along with systematically reporting[5] the monitoring and assessment results (Leiter 2021). These processes can be separate or part of an integrated system, but their difference is often not clearly defined. Monitoring and assessment systems and their challenges are introduced in the Finnish Climate Change Panel publication 2/2022 (Juhola, Käyhkö and Hildén 2022).

System development varies by country, and best practices have not been identified to-date. For example, system development in Germany and Great Britain has been led by research and researcher communities and has engaged the corporate sector (e.g., insurance companies), whereas Canada (and Finland) has utilized steering groups already functioning within the central government to define the indicators (Leiter 2021). In countries where the integration of risk assessments, adaptation planning, monitoring, and assessment systems has been taken the furthest (in Europe: Germany and Great Britain), the systems are based on continuous iterative development, i.e., assessment and monitoring results are used to support planning and vice versa. For success, such a system requires an impact-based approach for adaptation planning and risk assessment and the combined monitoring of the adaptation process and its impacts (see Figure 7).

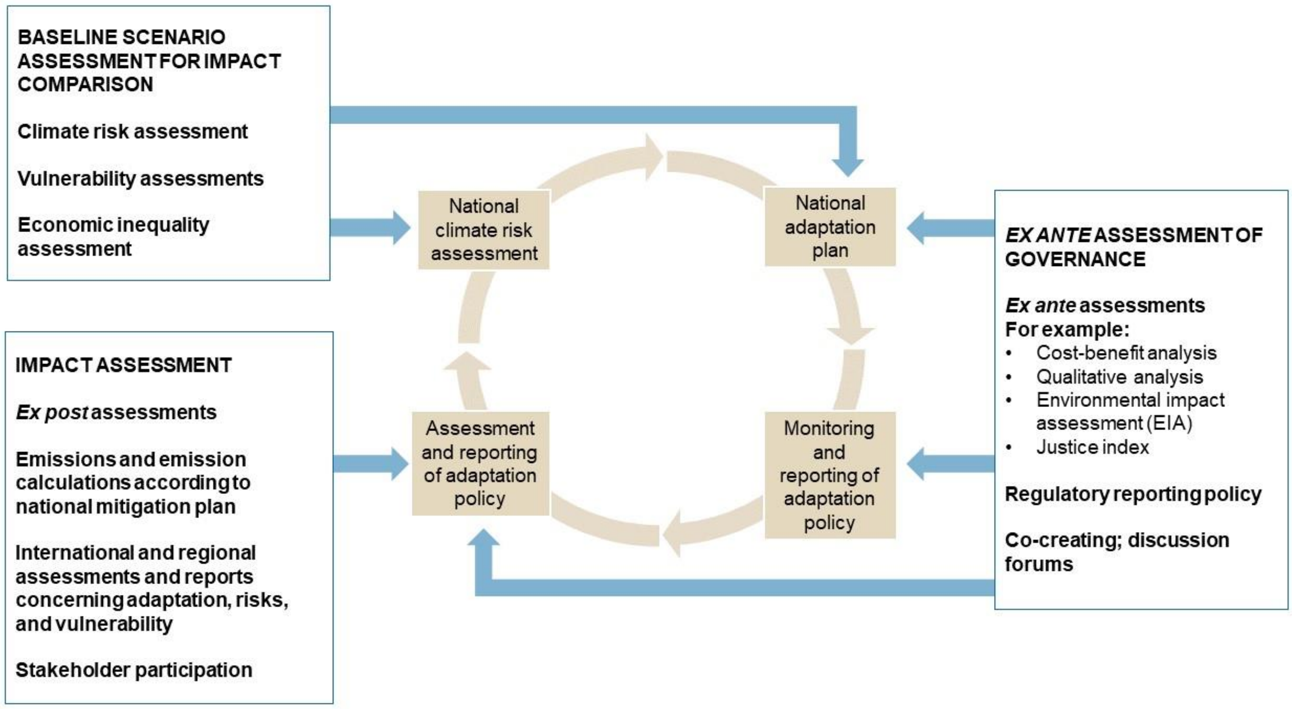

Figure 7. The cycle of planning, monitoring, assessing, and reporting of the national adaptation policy aggregated with opportunities for assessing adaptation impacts at various stages (adapted from Juhola and Käyhkö 2023). *Ex ante* = prior to event, *Ex post* = after event.

[5] Mitigation and assessment (M&E) systems are often also referred to as 'MRE systems', where 'reporting' is added to the abbreviation.

A commonly used instrument for measuring adaptation *success* is whether an adaptation policy has led to adaptation implementation and how broadly it has been integrated into other policies. During recent years, the quality and effectiveness of adaptation plans have also been used as assessment criteria, i.e., the decreases in risks and vulnerability (see Table 1). It is often useful to lean on adaptation indicators, for both goals and monitoring. An indicator denotes a parameter, or a value inferred from a parameter, which presents, offers information, describes the state of a phenomenon, environment, or region, and which has a broader meaning than just a parametric value. An index means a summed or weighted set of indicators or parameters; a parameter is measurable and observable (OECD 2002).

The underlying assumption when using indicators is that the National Adaptation Plan 2030 uses risk assessments to indicate the required adaptation measures and aims to further these measures. Adaptation measure monitoring and assessment requires defining which risks (what, where, and how) and, if necessary, which risk subcomponents are attempted to be influenced (and which are not). This systemic definition is the basis for developing systematic indicator-based adaptation monitoring and assessment (Klostermann et al. 2018).

The monitoring and assessment of adaptation effectiveness therefore requires defining novel indicators. The definitions of indicators[6] and the reported monitoring means differ between countries, and many indicators have not been applied in practice. Indicator development is continuous, and it is not known how their number or quality are monitored (a change in relation to the baseline or trend). The central challenges related to adaptation measurement (e.g., Leiter and Pringle 2018, Berrang-Ford et al. 2019, Dilling et al. 2019, Leiter 2021) are:

- Unlike for climate change mitigation, no clear-cut metrics exist for measuring adaptation progress.
- Due to contextuality and dynamism, no clear-cut methods exist for identifying adaptation *needs*, i.e., for assessing vulnerability.
- The availability and handling of long-term data significant to monitoring may be difficult and burdening for administration.
- Unlike linear project-level monitoring and assessment practices, the development of adaptation monitoring and assessment at the national level requires continuous work.
- The dual role of adaptation must be acknowledged when developing a national monitoring and assessment system: 1) advancing national-level adaptation and 2) participating in assessing the international state of adaptation.

[6] ”[I]t is not necessarily the value of an individual indicator that needs to be considered, but instead whether or not the set of indicators developed for a specific sector or theme provides a coherent and robust picture of adaptation progress as a whole.” (EEA 2015).

Table 1. Frameworks for monitoring and assessing the quality and effectiveness of adaptation plans.

Executor	What is measured?	With what indicator?
UNEP*, Adaptation Gap Report	Adaptation plan success is determined by its • adequacy • effectiveness	A total of 11 indicators in five themes: adaptation plan comprehensibility, inclusiveness, feasibility, integration degree, and development level of monitoring and assessment
Theoretical framework (Berrang-Ford et al. 2019)	Evaluative assessment of national adaptation policy: • sufficiency of objectives & targets • sufficiency of adaptation measures; attribution and contribution (a decrease in vulnerability following adaptation; objective reaching)	No single indicators, but rather central subcomponents of assessment (descriptive assessment: (i) vulnerability profile and context (leadership, organization, policy), (ii) adaptation goals (leadership, organizations, policy), (iii) adaptation measures, (iv) adaptation results
EEA** (Mäkinen et al. 2018)	Indicator use in national adaptation plans: • descriptive and analytical examination of adaptation plan or adaptation strategy	Indicator typology as a basis of analytical examination (see Table 2): classifying indicators according to various stages of the risk/response and according to risk subcomponents. Additionally: impact categorization of climate change, attributes of indicator monitoring and assessment (qualitative/quantitative, monitoring interval, geographical scale, presentation of results), and reporting cycle

*UNEP: United Nation’s Environment Programme; **EEA: European Environment Agency

Procedural indicators, i.e., indicators describing process stages, outline the progress of an adaptation policy and its adaptation measures (see Table 2). Monitoring adaptation policy progress is focused on the use of simple indicators. For example, assessing the progress of mainstreaming adaptation is evaluated by how many public sector branches of activity have their own adaptation strategies in place. Adaptation progress monitoring can also be conducted using input and output indicators. *Input indicators* measure the change in use of various resources needed for certain adaptation measures, for example budgeting for coastal protection or for the disease control of tick-borne diseases. *Output indicators* describe the output of specific adaptation measures without intervening with actual adaptation effectiveness. Examples include the number of levees built in coastal regions or the vaccination coverage for tick-borne encephalitis. An *impact indicator* can be derived from this if it is possible to define which risk subcomponent the adaptation measure attempts to influence and whether measuring its effectiveness is possible. Impact indicators have mainly been used at the national level without connecting them to adaptation measures.

National climate risk assessment is used to derive the impact indicators describing climate risk subcomponents – hazards, exposure, and vulnerability (adaptive capacity and sensitivity). Which risk subcomponent data are available also influences the assessment. Climate risk assessments identify and examine central risks. These are proxies that can be used to point the direction of change once a baseline has been set. Additionally, the IPCC Working Group II for the Sixth Assessment Report (IPCC 2022) proposes that a *response factor* be used as part of the risk framework, i.e., a response (adaptation measure) or a lack of response shapes the risk. To-date, this has not been used a great deal in modelling or in empirical research.

The impacts of climate change vary between the sectors of society. So far, a comprehensive index has not been developed for any sector in Finland. However, comprehensive development of climate change impact indicators has begun in the forestry sector (Arnkill et al. 2017). For example, a broad Swedish review shows that climate change impact indicators directed at the forestry and agriculture sector are essential for developing climate services, but the indicators do not currently identify the risks and vulnerabilities connected to the sector (Wiréhn 2021). Nordic case studies of monitoring and assessment development include a review of the geographic information-based assessment methods in connection to transport network vulnerability; public service vulnerability and risk analysis using end user participatory methods (Johnsson and Balstrøm 2021, Opach et al. 2020); and of the assessment frameworks for the indirect impacts of the energy sector (Groundstroem and Juhola 2019). Ongoing schemes are also developing more small-scale risk-specific indicators, for example the Finnish Environment Institute's INDISEURA project is developing adaptation indicators for drought risk and the risk of biodiversity decline.

Table 2. Adaptation indicator typology and examples (adapted from Mäkinen et al. 2018). The table includes examples where an indicator describes both the risk response stage and the risk subcomponents. These combinations could not be identified for certain factors. G = Germany, UK = Great Britain, SC = Scotland, na = not reported.

Indicator type	**1) Process**	1.1) Input	1.2) Output	**2) Impact**
Hazard (e.g., number of heatwaves)	na	na	Number of landslide events affecting transport network functioning (SC)	Agricultural damages caused by hail events, € trend (G)
Exposure (e.g., number of households in flood risk area)	Number of nationally significant infrastructure projects that have passed environmental assessment[7] (UK)	na	na	Change in number of residential properties that have moved from a high-risk[8] to a low-risk level (UK)
Vulnerability (aggregated sensitivity and adaptive capacity)	Areas prioritized or restricted for groundwater conservation (G)	Potential price change in flood insurance payments (UK)	Water usage intensity in the production sector (G)	Selection of and biodiversity index of agricultural crop species (SC)
Sensitivity (direct, e.g., a crop change due to a temperature increase; indirect, e.g., an increase in coastal flood damages due to rises in seawater levels)	na	na	Change in agricultural total productivity (UK)	Prevalence of mental health problems (proportional to population size) and trend after flooding or extreme weather events (UK)
Adaptive capacity (e.g., how many regional authorities have an adaptation plan in place)	Number and content of published local-level flood strategies (UK)	Investments in coastal region protection, € trend (G)	Number and proportion of non-permeable surfaces in region (UK)	Number of volunteer work in significant flood risk cases (SC)

[7] Exposure to climate change must be considered in project EIA
[8] Exposure to climate change impacts is a risk status criterion for real estate properties

Finland’s National Adaptation Plan 2030 defines thematic objectives and their measures that are used to strengthen commitment to adaptation, develop adaptation measures, and improve national adaptive capacity. Responsible parties have been defined for the measures and monitoring methods have been identified, but impact indicators have, as yet, not been determined. Great differences in the consistent implementation of adaptation policy exist between administrative and industry-specific strategies. Advanced strategies, such as the Climate change adaptation plan of the Ministry of Social Affairs and Health (Meriläinen 2021) and the Action Plan for the Adaptation to Climate Change of the Environmental Administration 2022 (Reports of the Ministry of the Environment 25en | 2016) identify essential adaptation measures and their responsible actors. However, these advanced strategies do not carry out comprehensive risk assessments or define objectives for adaptation measure effectiveness. This can be seen as a considerable shortcoming regarding the success of national adaptation policy. For example, the strategy of the Ministry of Social Affairs and Health (Meriläinen 2021) does not implement a systematic vulnerability assessment or any related monitoring indicators. Measuring the impacts of healthcare sector adaptation is challenging, as the impacts may reach far into the future, responses to impacts are individual, and access to health records is often strictly restricted. However, national research literature shows that the Finnish healthcare sector can, in several ways, promote the implementation of heat adaptation, along with monitoring implementation progress and the impacts of adaptation measures (see Appendices 2a and 2b). The identified key adaptation needs in the healthcare sector can be divided, based on risk subcomponents, into measures monitoring the change in a hazard, measures assessing vulnerability, measures decreasing exposure, and measures increasing adaptive capacity. These measures must have suitable, identified indicators (see Table 3).

Table 3. Examples of heat adaptation needs in the healthcare sector of Finland, and suitable indicators.

Adaptation needs	Indicator
MONITORING CHANGE IN HAZARD	
1. More efficient use of existing and measurable temperature data	• Number of hot days/heatwaves per year • Temperature/temperature distribution in region/municipality
VULNERABILITY ASSESSMENT	
2. Identification of vulnerable population groups	• Number (proportion) of elderly individuals in region/municipality • Number (proportion) of homeless individuals in region/municipality
DECREASING EXPOSURE	
3. Predicting exposure to extreme conditions and the health risks related to such exposure	• Number of annual healthcare/hospital visits due to hot weather • Number of annual deaths due to hot weather • Number and accessibility (coverage) or heat-related warning systems
4. Controlling indoor temperature conditions and ensuring recommendations are followed	• Number (proportion) of apartments/indoor spaces that have cooling devices and/or cooling methods in place • Proportion of (municipal) indoor spaces with monitorable and controllable temperature conditions
5. Implementation and development of physical structures/solutions that increase cooling	• Number (proportion of covered area) of cool (reflective) surfaces in region/municipality • Proportion of vegetation coverage of municipality surface area
INCREASING ADAPTIVE CAPACITY	
6. Developing citizens' knowledge and competence regarding extreme weather conditions and increasing appropriate preparedness behaviour: empowerment, information dissemination, and education	• Amount, availability, and accessibility of heat and heat adaptation-related guidance materials • Number (proportion) of municipal/regional persons that are aware of/trained for implementing heat-related adaptation measures
7. Improving preparedness and adaptive capacity of the healthcare system and healthcare professionals	• Proportion of healthcare professionals that are trained in identifying and treating heat-related health impacts • Proportion of healthcare units with heat-related preparedness and action plans in place

5. SUMMARY AND RECOMMENDATIONS

Climate change adaptation requires both private and public sector adaptation measures. Public authority, i.e., the state and municipalities, is particularly responsible for securing public goods and critical infrastructure. Public health, environmental quality, and managing environmental changes are the most important public goods. Public authority must additionally support private sector adaptation by disseminating information concerning climate change impacts and by advancing preparedness related to economic risks, for example. The IPCC risk framework offers a systematic base for modelling adaptation policy when private sector adaptation and public authority adaptation measures are examined in an integrated way (Ara Begum et al. 2022).

We applied this approach to three model cases concerning public goods. We analysed how to curb heatwave-caused deaths when promoting residential cooling and increasing municipal zoning-based and targeted greening, i.e., green spaces, are the adaptation measures available. The environmental impacts of climate change were examined through the decline in ecological state of a model river caused by water temperature increases, which can be mitigated by establishing wooded buffer strips along riverbanks. In addition to modelling, we perused the literature related to adaptation. Based on the literature review, we examined the information needs and the indicators that are suitable for monitoring climate change development and for analysing policy impacts.

The goal of this report is to show how science-based adaptation policy can be comprehended through modelling and through the creative utilization of research data. The considerable uncertainty related to climate change cannot be an obstacle for adaptation, as it can be processed through monitoring, modelling, and by examining private adaptation. Modelling also allows for examining and quantifying the impacts of uncertainty, which clarifies policy target-setting. A well-planned monitoring system and its indicators also help in decreasing the impacts of uncertainty on the adaptation policy choices.

Healthcare is a classic public authority responsibility. Climate change challenges public and occupational health in many ways, e.g., through heatwaves, the spread of zoonotic diseases, and changes to outdoor working conditions. The model examination for preventing heat-related deaths produced clear recommendations for developing healthcare adaptation policy:

- The increased health risks related to heatwaves should be prepared for by gradually offering cooling to the entire vulnerable population. This requires public authority to compile a plan together with district heating plants and real estate properties to ensure municipal cooling coverage. Concurrently, a separate plan should be formulated for providing cooling solutions to senior citizen housing and to other units offering elderly services, and to hospitals and daycare centres across the country.
- In cities, temperature increases can also be limited by greening, i.e., by increasing green spaces. Greening as an adaptation measure has a positive NPV for society, especially in southern Finland. Reaching a positive NPV In northern Finland requires targeted greening instead of zoning-based greening.

Healthcare-related adaptation plans are already urgent. A study by the Finnish Institute for Health and Welfare shows that the national social and healthcare system is insufficiently prepared for challenges caused by hot weather (Ung-Lanki et al. 2017). Adaptation plans should cover all aspects of public health, including identifying the knowledge needs of healthcare professionals in terms of extreme heat exposure, along with increasing their awareness and competence on the issue.

Climate change causes pressure, stress, and changes to ecosystems, thereby threatening their abilities to produce useful ecosystem services. Our examination of preventing a decline in river ecosystem state using wooded buffer strips indicates that national adaptation policy must be expanded to include natural habitats and their species. This expansion requires geographically more comprehensive and ecologically more accurate modelling of the ecosystem state development, ecosystem adaptation needs, and of the most efficient adaptation measures.

Adaptation policy goals should be as clear as possible. When goals are stated clearly, cost-efficient solutions for reaching these goals can be defined. Adaptation requirements that encompass existing knowledge must be developed with precision, plans must be identified by sector, and their goals must be defined clearly. It is also important that the cost-efficiency analyses and environmental impact assessments (EIA) of societally significant schemes, such as large investments and construction projects, include examinations of adaptation advantages and disadvantages.

Adaptation goal monitoring should be enhanced using well-chosen indicators. Using indicators for monitoring and assessing adaptation requires that the Adaptation Plan 2030 identifies necessary adaptation measures according to risk assessments, along with methods for promoting these measures. Adaptation process indicators are recommended for monitoring the implementation progress of the Adaptation Plan 2030. Effectiveness indicators should additionally be utilized to gain knowledge for resource allocation and for updating the Adaptation Plan 2030. Monitoring and assessing adaptation measure impacts requires defining which risks (what, where, and how), and, if possible, which risk subcomponents, the measure is attempting to influence (and which it is not).

Knowledge gaps concerning adaptation measure impacts currently limit the development of an indicator-based system. However, the process can nonetheless be started by defining goals for various levels and by using the principles of continuous development to refine these goals with accumulating knowledge. Implementing *ex ante* adaptation policy analyses is important for supporting adaptation planning, as this allows making assumptions based on best available knowledge of measure impacts, monitoring the effectiveness and implementation of the plan, and, if necessary, editing it.

Long-term monitoring is required for following environmental state changes. This allows for better planning and adjusting of adaptation policy as climate change progresses. Plans must be made according to the principles of continuous development while accepting knowledge incompleteness. We must invest in developing our knowledge of climate risks and in the open availability of this knowledge, to allow for developing adaptation plans.

APPENDICES

APPENDIX 1: Methods and data

Greening

Various greening alternatives and their sensibleness in Finnish cities were discussed with city representatives from Helsinki, Oulu, and Turku. The cost of increasing canopy coverage was discussed with Aki Männistö, arboreal specialist for the city of Turku. Based on the discussion, the expenses were calculated using standard costs for the rooting times of park trees and street trees, presented in a guidebook for urban tree value determination (Tajakka 2019), published by the Finnish Association of Landscape Industries. Removal expenses for planted trees were calculated using costs presented in the same publication for damaged tree removal. When estimating the impact of tree planting on canopy coverage, an assumption was made that the canopy diameter of a single plantable tree is nine metres. Half of the plantable trees were assumed to be park trees and the other half were street trees. The calculations assume that the trees are planted at the beginning of the analysis period (2026–2100). For tree removal and replanting, calculations were performed for two scenarios, where 50 per cent and 100 per cent of the planted trees are removed and replanted with new individuals during the abovementioned period.

Regional greening implementation plans for the cities of Helsinki, Oulu, and Turku were prepared in two ways and at two spatial scales. A wider planning horizon was based on the cities' master plan materials, and it focused on the entire zoned area of each city. The narrower, targeted plan was based on population density, and its focal area was each city's most densely habited nine-square-kilometre area. Using zoning plans to support the more comprehensive zoning-based planning process was discussed with each case city. The cost calculations for zoning-based greening were performed for three greening options of varying intensities, so that each greening option in each city included two types of regions: areas with larger greening potential and areas with lower greening potential. Increasing canopy coverage as percentage points in relation to the area's total surface area was used as a variable to describe greening intensity for both zoning-based and population density-based planning. In the least intensive greening alternative, canopy cover is increased by 20 percentage points in areas with larger greening potential and by 10 percentage points in areas with lower greening potential. The corresponding values in the mid-intensity greening alternative are 30 and 15 percentage points, and 40 and 20 percentage points in the most intensive alternative, respectively. In the population density-based, targeted greening scenario, costs calculations were performed for four greening alternatives of varying intensities, so that the greening potential was assumed to be of the same magnitude within the entire target area. In these greening alternatives, canopy coverage is increased by 10, 20, 30, and 40 percentage points.

The impact that increasing canopy coverage has on limiting the urban heat island effect was examined using temperature data collected by the TURCLIM weather observation network upheld by the Turku University Department of Geography and Geology. The TURCLIM network was built for monitoring the local climate of the Turku region, and it consists of 83 observation points where air temperature and humidity are measured from a three-metre height above sea level every 30 minutes. The temperature data from 71 observation points were used to examine canopy coverage impacts by modelling the temperatures with a linear regression model to produce a continuous temperature surface. The modelling utilized CORINE Land Cover (CLC) 2018 data, SLICES 2010 land use data, and a digital elevation model (DEM). Temperature was the dependent variable in the regression model, and the explanatory variables were formed based on CLC 2018, SLICES 2010, and DEM data. Canopy coverage data from Natural Resources Finland (LUKE) was used for estimating the temperature impacts of greening. The estimation compared the temperatures of regions with differing canopy coverages and land covers, and the observed difference was proportioned to the change projected by the land cover variable in the regression model. The regression model was formed based on average temperatures of a week-long heatwavel during 23–27 July 2014. The urban heat island effect is usually strongest at night. However, we chose to examine mean temperature because it reflects the temperature conditions throughout a 24-hour period, thereby providing as comprehensive a picture of heat exposure as possible. Previous Finnish studies (Kollanus and Lanki 2021, Ruuhela et al. 2021) have also found mean temperature to describe the link between heat exposure and mortality. According to the regression model, increasing canopy coverage by 10 percentage points would attenuate the urban heat island effect by circa 0.5 °C per 24-hour period, while increasing canopy coverage by 20 percentage points would attenuate the urban heat island effect by approximately 1 °C per 24-hour period. The modelling used an impact range of slightly over three hectares, which is why reaching the abovementioned cooling effect would require increasing canopy coverage over an equivalent-sized area, at the very least.

Cooling

The mean installation costs for air conditioners are 3275 €[9]. The average service age for a device is 20 years at most. We therefore divide installation costs by 20 and add them to the yearly operating costs. The average energy consumption of cooling is 200 kWh/year (GlobalPetrolPrices.com[10]). We use an energy price of 0.222 €/kWh, which is the 2023 price for Finland, when this report was written[11]. This equates to annual costs of 44.40 €/year. Cooling is an important way of preventing heatwave-induced mortality in midsummer, i.e., from June to August, when Finland experiences heatwaves. Energy prices are typically low in Finland during these months, which is why the annual costs of air conditioners are also fairly low.

In Helsinki, the household expenses of district cooling (DC) per building include a connection fee (1500–1800 €) (energy producer Helen Ltd., website). At the time of writing (2023), Helsinki and Turku have circa 100 and 50 residential buildings, respectively, that are directly connected to district cooling. The investment costs of a direct current connection, i.e., the cost of connecting a building to a direct current network, is approximately 150 000 € (Helen, personal communication). Helsinki had 11 401 multistorey buildings in 2022 (pxdata.stat.fi)[12]. These buildings had circa 333 481 apartments (stat.hel.fi)[13]. When the number of apartments is divided by the number of buildings, one building averages 29.25 apartments. Consequently, the mean investment cost per apartment in Helsinki is 150 000 €/29.25 = 5128 €. Turku has 2946 multistorey buildings (pxdata.stat.fi)[14], with a total of 93 919 apartments (pxdata.stat.fi)[15]. The corresponding figures for Oulu are 2572 (stat.hel.fi)[16] and 65 141 (pxdata.stat.fi)[17]. Therefore, the investments costs in Turku and Oulu are 150 000 €/31.88 = 4705 € and 150 000 €/25.33 = 5922 €, respectively.

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[9] https://kodinplaza.fi/iv/iv-asennus/hinta [Air conditioning installation costs, in Finnish]

[10] GlobalPetrolPrices.com: https://www.globalpetrolprices.com/Finland/electricity_prices/ Accessed 9.8.2023.

[11] https://www.globalpetrolprices.com/Finland/electricity_prices/

[12] Statistics Finland: Number of buildings by intended use and year of construction https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__rakke/statfin_rakke_pxt_116g.px/

[13] Helsingin asunnot talotyypin ja valmistumisvuoden mukaan 31.12. PxWeb [Dwellings in Helsinki by building type and year of construction, in Finnish]

[14] Rakennukset muuttujina Alue, Rakennuksen käyttötarkoitus, Tiedot, Vuosi ja Valmistumisvuosi. PxWeb (hel.fi) [Buildings in Uusimaa by usage type, year of construction, and floor area, in Finnish]

[15] Statistics Finland: Dwellings by type of building, occupancy, and year of construction https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__asas/statfin_asas_pxt_116f.px/

[16] Rakennukset muuttujina Alue, Rakennuksen käyttötarkoitus, Tiedot, Vuosi ja Valmistumisvuosi. PxWeb (hel.fi) [Buildings in Uusimaa by usage type, year of construction, and floor area, in Finnish]

[17] Statistics Finland: Dwellings by type of building, occupancy, and year of construction https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__asas/statfin_asas_pxt_116f.px/

Controlling for model-related uncertainties

We used Monte Carlo simulation to examine the net gains of adaptation measures, as several uncertainties are linked to heatwaves and related mortality and to the adaptation measures themselves. The heatwave and river warming data were based on local climate scenarios compiled by the Finnish Meteorological Institute, which calculated daily mean and maximum temperatures until the end of the century. The Finnish Meteorological Institute also provided data on daily precipitation levels. These daily scenario trajectories are simulations containing uncertainty. This is why straight lines were fitted to the data. First, we reshaped the data into annual heatwave numbers and July mean temperatures. The fitted lines represent the annual development of these two variables (heatwave number and July mean temperature) until the end of the century. We used the annual number of heatwaves, provided by the lines, as the lambda parameter for a non-homogeneous Poisson distribution. Therefore, the number of heatwaves in our simulation was determined according to the Poisson distribution. Mortality risk estimation also includes uncertainty. This was accounted for using the standard deviation of the estimate. The calculations were repeated 10 000 times in the Monte Carlo simulation, which decreased the uncertainty related to these factors, and we were able to describe the uncertainty by providing net gain distributions rather than single values.

The climate scenarios themselves also naturally contain uncertainty. We therefore examined three separate scenarios: the mildest scenario (RCP2.6), the base scenario (RCP4.5), and the strongest warming scenario (RCP8.5). Including the extreme scenarios is important because the scenario that is eventually realized most likely lies between the extreme parameters. Our objective was to examine several scenarios and to present how the results differ between the scenarios, without taking a stance on their probabilities. Which scenario is finally realized does not greatly influence the results in cases where the results differ only slightly between the scenarios.

Some of the parameters also contain uncertainty. For example, discount rate, which is used to convert future gains and costs into present value, is a well-known uncertainty factor that is usually considered a sensitivity parameter. The relevance of discounting is highlighted when the time span of the examination lengthens. Adaptation measure expenses and the statistical value of human life are other important uncertainty factors in this context. We examined the impact of these uncertainty factors using a sensitivity analysis, which is the standard procedure in cost-benefit analyses. The sensitivity analysis produces parameters, and their uncertainties have the greatest quantitative effect on the results. This allows quantitatively illustrating the effect that the parameter uncertainties have on the results.

Appendix table 1. Modelling uncertainties and how they are accounted for in this examination, along with how they can be observed in future research.

Modelling and data	Uncertainty factors	Alternatives for improving model accuracy
Climate data	Climate data are based on modelling and therefore contain uncertainty. The uncertainty increases as a function of the examination time horizon.	Monte Carlo analysis. As the number of simulations increases, the calculable variable estimates become more accurate.
Climate modelling	The chosen three RCP scenarios provide a limited picture.	Expanding the examination to include all scenarios. On the other hand, the extreme scenarios provide a picture of how scenario uncertainty impacts the variation range of the calculable variables.
Adaptation cost, impact, and benefit estimates	Partially based on specialist estimates, as no applicable literature is available. Cost estimates use mean values; not all possible variables have been accounted for, e.g., the impact of crises. Utility values are simplifications. Impact values are based on existing estimates obtained from the international literature, as no Finnish literature exists on the topic. Extreme event impacts on forest stands are left out of the model due to their laborious nature.	A sufficiently comprehensive sensitivity analysis, which shows the direction of change of the results and the magnitude of change if the costs and benefits are altered.
Policy trajectory: mechanical cooling	Possible cooling-related technological developments during the examination period and their impacts on expenses were not accounted for.	A sensitivity analysis can also examine expenses that decrease with time. The impact of such decreases on the results, i.e., on net present value, is most likely slight, as costs that are realized in the future are discounted, in which case their impact approaches zero when the examination approaches the end of the century.
Policy trajectory: greening	Apart for health benefits, other possible benefits were not included, e.g., benefits from carbon sinks, erosion prevention, income, health, wellbeing, and comfort	Examining other benefits can broaden the overall picture of adaptation measure profitability
	The canopy coverage data included shadow zones, so the impact of canopy coverage on temperature was assessed indirectly based on a variable from the CLC2018 data	If canopy coverage data were available for the entire research area, including them into the regression model as one explanatory variable for temperature would be possible.

Policy trajectory: adding wooded buffer zones	The optimal tree species chosen for the examination (a rapidly growing deciduous species) is not necessarily the only practical option. Possible other benefits (as in greening) are not included in the model	Widening examination to other tree species. Examining other benefits can broaden the overall picture of adaptation measure profitability.
Ecological index	Several uncertainties relate to defining an ecological index, including which factors are accounted for when calculating the index and over what period.	A sensitivity analysis is conducted on the monetary value of the ecological index, as it impacts the results. Concurrently, it can be seen to reflect other uncertainties linked to the index.
Cost-benefit analysis	Many assumptions and delimitations must usually be made in cost-benefit analyses. The effectiveness of greening is calculated in relation to heatwave prevalence, in which case the impact is not directed at the strongest heatwaves.	Assumptions and delimitations must be documented and reported openly and clearly in a publication, so that readers are aware of them. They must also be acknowledged in the conclusions and possible recommendations. Supplementing the impact calculations of the most intensive heatwaves into degrees-based calculations. However, the availability of suitable comparative studies may be challenging.

APPENDIX 2: Recommendations and literature review of applicable health-related adaptation measures and indicators linked to heat exposure and literature review of Finnish studies dealing with extreme heat health effects

WHO (2021) recommends that national prevention adaptation plans for heat disadvantages should include deciding on responsible parties, up-to-date extreme temperature warning systems, a communication plan, decreasing exposure levels, attending to special population groups, preparedness of healthcare and welfare services, urban planning, and regular assessments of action plan and warning system effectiveness and cost-efficiency (Matthies et al. 2008, Ikäheimo and Jaakkola 2019). The objective of the previous National Adaptation Plan 2022 was to formulate a national operating model for preventing hazards caused by extreme temperature exposure. This operating model should include both long-term preparedness and short-term measures at various levels and when operating in various sectors. The current Adaptation Plan 2030 established health protection with Objective 14: By 2030, health hazards have been identified and adaptation to these hazards and their monitoring have been developed at various administrative levels. According to this plan, a national action plan should be formulated for preventing heat-related hazards, and, based on this national action plan, heat preparedness and adaptation measures should be implemented, a monitoring mechanism for tracking heat-related mortality should be established, and the action limits in Decree 545/2015 (Decree of the Ministry of Social Affairs and Health on Health-related Conditions of Housing and Other Residential Buildings and Qualification Requirements for Third-party Experts) should be revised. The roles and responsibilities of, and cooperation between, focal stakeholders should also be defined in advance (Kollanus and Lanki 2021). Regional and local heat preparedness should be invested in, national steering should be focused, the timeliness of adaptive measures and implementation should be ensured, and the preparedness competence and ability of social welfare and healthcare professionals should be developed (Kollanus and Lanki 2021).

Increasing social and healthcare professionals' heat competency is an example of a reasonably quickly implementable adaptation measure that is simultaneously both effective and manageable in cost structure. The preparedness, action, and adaptation plans of the social and healthcare system should incorporate, at all levels, the basic, advanced, and in-service training of social and healthcare professionals along with the regulation of working, treatment, and care conditions. To more effectively impact the disadvantages caused by extreme temperatures to wellbeing and health, healthcare professionals should be more comprehensively aware of the extent of extreme temperature exposure, of vulnerable population groups (e.g., the elderly, children, and the chronically ill), and of potential exposure-induced health impacts. Research-based guidelines for extreme temperatures and protective and adaptation measures should be incorporated as integral components of social and healthcare operations and culture. Purposeful indicators incorporating both quantitative and qualitative knowledge should be implemented when monitoring and assessing the effectiveness of adaptation measures.

When estimating the impacts of high temperatures and the urban heat island phenomenon on mortality, it is recommendable to base the estimate on the following: knowledge of high temperature effects on mortality, knowledge of high heat occurrence probability, knowledge of the intensity and regional characteristics of a city's urban heat island, and knowledge of vulnerable groups (who are vulnerable, their numbers, and where they are).

It is recommendable to assess the impact of greening efforts as an adaptation measure by comparing the impacts and regional characteristics of a city's urban heat island before and after greening implementation. Weakening of the heat island effect shows that greening efforts have led to the desired end result. Paying attention to the greening intensity and choice of areas to be greened must be considered when planning and implementing greening, to optimize its effectiveness and cost-efficiency. Cost-effectiveness and cost-efficiency are applicable indicators for assessing the adaptation effectiveness of heatwave-induced health risks despite the uncertainties related to such examinations.

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Appendix table 2a. A list of potential health-based measures linking to climate change adaptation and heat exposure. List is based on national literature.

Adaptation measure (Heat exposure (> +25 °C))
Increasing the recognition ability, adaptive measures, and selfcare of heat-related symptoms and/or illnesses in the general public*
Heat preparedness and securing healthcare capacity*
Identifying the changing service, knowledge, and education needs of the social welfare and healthcare system, and responding to these changes*
Identifying heat-related symptomology and/or illness (impacts) and improving treatment efficiency in healthcare*
Identification, preparedness, and control of heat-related risks to occupational safety, occupational health, and work capacity*
Monitoring, management, and cooling solutions for residential, occupational, and recreational spaces*
Securing electricity/energy distribution and sufficiency
Regular inspection, maintenance, and upkeep measures for ensuring the appropriate functionality of buildings and for accounting for heatwave impacts
Development and implementation of heat-related forecast, observation, warning, and control systems*#
Accounting for heat incidence and impacts at various levels and sectors of decision-making, land use planning and management, and construction*
Generation and implementation of heat-related risk management, adaptation, and action plans at various levels and sectors*#
Development, assessment, and implementation of risk management tools
Assessment of vulnerabilities and adaptive capacity related to heat and its impacts, and preparedness planning and training#
Cost-effectiveness calculations and assessment of heat-related adaptation measures*
Advancing development and maintenance of supply security and service systems related to extreme weather events and securing general societal functionality*#
Development and implementation of heat-related risk assessments and adaptation measures at various levels and sectors*#
Development and implementation of heat-related adaptation measure monitoring and impact assessment*
Development of national indicators for assessing adaptation measures#
Preparing for national and international indirect impacts related to extreme weather events*#
Increased international and national political, official, and research collaboration and information exchange related to extreme weather events*#
Integrating the climate viewpoint and adaptative measures more strongly into national and EU development policy, development aid, investments, and financial instruments *#
Political commitment for realizing climate change-related adaptation measures
Identifying the current state of adaptation and adaptation-supporting structures and identifying future adaptation needs*
Funds and other resources allocated to heat-related research and development of adaptation solutions*
Advancement and funding of experimental, feasibility, and development projects related to adaptation measures*#
Interdisciplinary heat-related research, product development, and collaboration and knowledge dissemination between knowledge producers and end users*
Development and production of education and communication related to heat and its adaptation measures (including guidance materials)*
Increasing risk awareness at various levels*
Incorporating climate change impacts and adaptation measures into education plans and basic studies at various levels of education#
Development and implementation of heat-related responsibilities and guidelines at various levels and sectors (including hot work guidelines)*

Development of legislation and steering systems for controlling heat exposure*#
Official guidance and recommendations for controlling heat exposure, including various administrative strategies and programmes#
Development and implementation of insurance systems and operations related to climate change and its impacts
Development and implementation of cooling (reflective) surfaces in construction and buildings*
Identifying vulnerable population groups and protecting them from heat and its hazardous impacts*
Construction, maintenance, and upkeeping of green and water structures and their surroundings*
Development and implementation of the Green Factor tool
Development and implementation of green roofs and/or green walls in construction and buildings
Regional monitoring and communication of air pollutants, temperature, and humidity

*At least partially acknowledged in the Climate Change Adaptation Plan of the Ministry of Social Affairs and Health (2021–2031)

#At least partially acknowledged in the Finnish National Adaptation Plan 2022

Appendix table 2b. A list based on national literature of potential health-based indicators linking to climate change adaptation and heat exposure.

Factor	Indicator
Heat exposure (> +25 °C)	Number of hot days per year (number/year)
	Heatwave duration (days)
	Number of heatwaves (number/year)
	Number of heat-related medical visits annually (number/year)
	Number of heat-related diagnoses annually (per year)
	Impact of heat exposure to work ability and performance
	Number of heat-related deaths annually (number/year)
Adaptation measures, preparedness	Number and accessibility of heat-related warning systems
	Number of heat warnings per year (number/year)
	Accounting for heat-related needs in municipal decision-making, municipal land use planning and steering, and construction
	Share of cities/regions that have heat-related risk management, adaptation, and action plans
	Share of cities/regions that have implemented heat-related risk assessments and adaptation measures
	Share of cities/regions that have implemented heat-related adaptation measure monitoring and impact assessment
	Amount (share) of resources allocated to national heat-related research and to the identification of adaptation measures
	Amount (share) of resources allocated to heat-related adaptation measures in region/municipality
	Amount, availability, and accessibility of heat- and heat adaptation-related guidance materials
	Number (share) of municipal/regional personnel that is aware of/trained to implement heat-related adaptation measures
	Heat-related responsibilities and instructions for various municipal sectors/actors (including hot work guidelines)
	Number (share of coverage) of cooling (reflective) surfaces in region/municipality

	Number (share) of apartments/spaces with no cooling device and/or cooling methods
	Number (share) of apartments/spaces that are at risk of exceeding permitted, legally defined maximum temperatures
	Share of (municipal) indoor spaces that have monitorable and controllable temperature conditions
	Location and accessibility of cool areas and cooled indoor spaces, and communication concerning these spaces in municipality/region
Characteristics of population and environment	Number of elderly/sensitive population groups in region/municipality
	Number of unemployed/individuals on social benefits in region/municipality
	Share of vegetation and waterway coverage of municipal surface area
	Share of water-impervious surfaces in municipality surface area
	Number of trees (share of coverage) in region/municipality
	Number of green roofs and/or green walls (share of coverage) in municipality
	Air pollution level in region/municipality
	Temperature/temperature distribution in region/municipality
	Air humidity and humidity distribution in region/municipality

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Appendix table 2c. A systematic literature search of studies utilizing or analysing Finnish data that examine the health effects of heatwaves/extreme heat.

Author	Target area of study	Study type	Study period and participant number	Predisposing factor	Response	Main results
Baccini et al. 2008	Helsinki [a]	Time series	April–September 1990–2000	Daily (apparent) maximum temperature	Mortality due to all causes	Above a threshold temperature of +23.6 °C, a one-degree increase in daily (apparent) maximum temperature (95% CI 21.7–25.5) was connected to a 3.72% (1.68–5.81) increase in mortality.
Baccini et al. 2011	Helsinki [a]	Time series	April–September 1990–2000	Daily (apparent) maximum temperature	Mortality due to all causes	The per cent changes in mortality for every one-degree increase in daily (apparent) maximum temperature, when a temperature threshold (23.4 °C) is exceeded, were 3.85% (95 % CI: 0.38–7.78) in the age group of 15–64-year-olds, 4.12% (0.72–8.01) in the age group of 65–74-year-olds, and 1.96% (-0.33–4.27) in the age group of over 75-year-olds.
Baccini et al. 2013	Helsinki [a]	Time series	April–September 1990–2000	Maximum temperature	Life years lost due to heat	Annually, 18 life years were lost (80% CI: 6–31; harvesting effect standardized)
Näyhä et al. 2013	Finland [b]	Cross-sectional	January–March 2007			
N=4007	Heat	Heat-related symptoms	81% of respondents reported experiencing at least one heat stress symptom, such as thirst, dry mouth, decreased stamina, sleep disturbances, and symptoms related to the cardiovascular and respiratory systems. Cardiovascular and respiratory system symptoms increased with age. Most symptoms			

			were more prevalent in women than in men.			
Kollanus and Lanki 2014	Finland (excluding northern Finland)	Time series	2003 and 2010	Heatwaves [c]	Mortality due to all causes	Daily mortality during heatwaves increased significantly in over-75-year-olds (average increase 21%). Mortality was higher in women than in men.
De' Donato et al. 2015	Helsinki [d]	Time series	April–September 1996–2000 (period 1) and 2004–2010 (period 2)	Daily mean temperature	Mortality due to all causes	Relative daily total mortality risk (RR, 95% CI) during the first and second study period: 1.02 (0.93–1-12) and 1.24 (1.14–1.35). Respiratory-related mortality risk during the first period 1.42 (1.05–1.92). Corresponding cardiovascular-related mortality risk during the 2nd period 1.18 (1.02–1.35).
Baker-Austin et al. 2016	Finland and Sweden	Cohort study (retrospective)	May–December 2014, n=89 (total number of cases in Finland and Sweden together)	Sea water surface temperature	Vibrio infections	Exceptional summertime heat conditions were responsible for temporal and regional distributions of infections.
Näyhä et al. 2017	Finland [b]	Cross-sectional	2007, n=4007	Warm and hot weather	Symptoms and complaints related to warm/hot weather	Incidence of heat-related cardiopulmonary symptoms was 12%. Symptoms increased with age. Symptom risk was linked to e.g., unemployment, low education level, heavy alcohol consumption, female gender, heavy physical labour, and inactivity during leisure time.
Ruuhela et al. 2017	Helsinki–Uusimaa	Time series	1972–2014, n=465 553	Extreme temperatures	Mortality due to all causes	Relative mortality was larger in extreme heat than in extreme cold. The increase in risk was strongest in ≥75-year-olds. Sensitivity to heat stress decreased over the past decades.
Gasparrini et al. 2017	Helsinki [e]	Time series	January 1994–December 2011, n=130 325	Daily mean temperature	Mortality due to all causes	By 2050–2059, the estimated percentage increase in excess mortality was 1.8% (1.0–3.1) and 3.5% (2.0–5.5) in climate scenarios RCP2.6 f and RCP8.5 g, respectively.
Guo et al. 2018	Helsinki [e]	Time series	1994–2011, n=130 325	Heatwaves	Mortality	Relative mortality risk (RR) linked to heatwaves: 1.13 (95% CI 1.05–1.22).

Ruuhela et al. 2018	21 hospital districts	Time series	2000–2014	Daily mean temperature	Diurnal mortality due to all causes	Compared to minimum mortality temperature (+14), relative mortality risk (RR) grew by 16% at a temperature of +24 °C (95% CI 1.12–1.20).
Kuhn et al. 2020	Nordic countries (Denmark, Finland, Norway, and Sweden)	Time series	2000–2015, n=64 034; reported Campylobacter cases	Weekly mean temperature, number of heatwaves	Campylobacter cases	A weekly summertime forecast of the increase in reported Campylobacter cases in the aggregated data was 13% with a one-degree temperature increase. The annual mean number of cases and the number of excess cases are projected to grow in Finland by the end of the century.
Lee et al. 2020	Helsinki [e]	Time series	1994–2011, n=130 395	Daily temperature change	Diurnal mortality due to all causes	Connection between excess mortality and diurnal temperature range (DTR): (95% CI): 2.4 (-2.8–7.2). The mortality risk linked to diurnal temperature range per interquartile range (IQR) during the four warmest months was 2.3 (-0.8–5.6)
Sohail et al. 2020	Helsinki Metropolitan Region	Time series	July–August 2001–2017	Daily mean temperature and heatwaves	Healthcare service utilization due to cardiopulmonary symptoms	Both short and long heatwaves linked to increased pneumonia incidence. In ≥75-year-olds, long heatwaves linked to medical treatment due to respiratory symptoms. Short heatwaves linked to respiratory illnesses and COPD-related treatment periods in the 18–64-year-olds age group and to myocardial infarction in the 65–74-year-olds age group. The risk of cardiac arrythmia decreased during heatwaves.
Kollanus et al. 2021	Finland, excluding Lapland and Åland Islands	Time series	May–August 2000–2014, n=208 315	Heatwaves [h]	All deaths in ICD-10 disease categorization (excluding accidental deaths)	Both short (4–5 days) and long (≥ 10 days) heatwaves increased mortality by 9.9% (95% CI 7.7–12.1). Impacts proved greater for long heatwaves. Women and the elderly were at greater risk. Greatest increase in total mortality was observed in renal diseases (mean for all age groups 38.4%), mental health and behavioural disorders (29.7%), and respiratory illnesses (25.3%). In 65–74-year-olds, the link between exposure to exceptionally high temperatures and increased

						mortality risk was statistically significant in cerebrovascular diseases, chronic lower respiratory tract diseases, and mental health and behavioural disorders.
Ruuhela et al. 2021	City of Helsinki and Hospital District of Helsinki and Uusimaa (HUS)	Time series	2000–2018 [i]	Daily mean temperature	Diurnal mortality due to all causes	Heatwaves increased the mortality risk due to all causes for all ages and for the over-75-year-olds age group in Helsinki. Mortality risk in Helsinki at +24 ℃ (aggregated RR for all age groups 1.30, 95% CI 1.01–1.69) and elsewhere in the Hospital District of Helsinki and Uusimaa (1.16, 0.90–1.45). Corresponding risks for over-75-year-olds: 1.56 (1.11–2.19) and 1.36 (0.97–1.90).
Vicedo-Cabrera et al. 2021	Helsinki [e]	Time series	1994–2014, n = 48810	Daily mean temperature	Mortality due to all causes	Mean number of annual heat-related deaths attributable to anthropogenic climate change (16; 95% CI, 0–29). Share of heat-related deaths attributable to climate change 42.0%.
Wu et al. 2022	Helsinki [e]	Time series	1994–2014, n = 153 308	Short-term temperature fluctuations	Mortality due to all causes	Per cent change in mortality linked to the interquartile increase in temperature fluctuations: 0.35 (95% CI 0.33–0.37).
Alahmad et al. 2023	Helsinki [e]	Time series	1987–2018, n = 90 992	Daily mean temperature s	Cardiovascular system-related mortality	Minimum mortality temperature (MMT) was +18.4 ℃. The relative risk due to aggregated cardiovascular deaths caused by excessive heat (99th percentile vs. MMT) was 1.12 (1.07–1.17). Excess aggregated cardiovascular deaths (per 1000 deaths) related to extreme heat (97.5th percentile) and all hot temperatures (>MMT): 3.05 (0.82–4.94) and 3.7 (0.69–6.21), respectively.
Masselot et al. 2023	Helsinki [e]	Time series	1994–2011, n = 130 395	Daily mean temperature s	Mortality due to non-external causes	The number of annual heat-related excess deaths, the standardized level of excess deaths per 100 000 person-years, and the disease share (5) among ≥ 20-year-olds were 69 (26–108), 5 (2–8), and 0.29 (0.11–0.45), respectively.

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