Urban Heat Island Survey of the Tampere Inner City

Phased Tampere Inner City comprehensive plan – Council period 2021–2025

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Translations to pictures

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Abstract

Urban Heat Island Survey of the Tampere Inner City

This survey reports on the occurrence of the urban heat island effect in the inner city of Tampere. The first step was to create a map showing the temperatures of the land surface on a hot summer day. The map was studied together with the aerial photograph of the city. It was found that the hottest areas are industrial areas with large buildings and large plant-free surfaces, such as wide streets. The coolest areas are forested areas near water bodies. While carrying out the survey, a composite map of the land surface temperatures in eight separate heat waves in 2015–2021 was prepared. Although temperatures vary slightly, hot and cool zones are located in the same areas, in the same type of urban structure.

The land surface temperature map for the heat wave was also checked against the comprehensive plan map data for the central urban area. The thematic maps of the urban structure and the green network identified development areas in which the urban heat island should be taken into account in particular: Existing heat islands are to some extent located in central urban areas and in particular in areas designated as “mixed service and employment areas or sites”. The "Indicative Green Network Connectivity Areas" are in some places located over heat island areas. In the future, they could play a significant role in relieving the urban heat island, especially in areas where services and work places are mixed. It is also worth considering whether the comprehensive plan could include green space other than cycling and recreational connections to areas that are warmer than their surroundings.

Observations, a literature review and a statistical analysis were used to interpret the factors affecting the heat island in the central urban area of Tampere. The most significant of these are the amount of impermeable surface, a large fraction of which clearly contributes to higher land surface temperatures. A large number of trees were found to have a mild temperature-decreasing effect. Statistical analysis was used to predict, at the scale of the city, the effect of different increases in ground cover on land surface temperatures. An estimate of the impact of climate change on rising air temperatures was also presented. The number of very hot days in Tampere will increase by about 64% by 2035, and by the end of the century the number is projected to reach 50 per year. It is also worth noting that, although cold stress is a risk, the

urban heat island is more pronounced in cities than in other areas (Ruuhela et al. 2021).

The distribution of temperatures was studied in relation to population size, and the map was used to identify warm zones where particular attention should be paid to relieving the urban heat island effect. The limit value was set at +35°C. On the heat wave map, more than 60% of the population of Tampere lives in this zone that is warmer than its environment. The definition of a zone is based on a single point in time, as are population sizes. The temperature of the composite map is a couple of degrees lower across the board, with the warmest zones being slightly smaller. However, in terms of global warming, it is justified to survey the heat wave. In the future, the survey could be developed to take account of population projections.

The survey also defined so-called cool zones, with a minimum threshold of 0.75 hectares and a maximum surface temperature of +26°C. There are no cool zones in the city centre at all, but they are located on the outskirts of the central urban area in green areas and along water bodies. Seeking cooler areas is one way to protect yourself from the heat. Transitions along the street network and outdoor routes to the nearest cool place can be winding.

Urban structure

The wide open water surfaces in Tampere lakes and smaller lakes enable wind flow and have influenced the urban structure so that it breathes. Based on the aerial photograph and spatial data analysis, the urban heat island is more pronounced in the Tampere city centre, especially in the industrial and central urban areas. A key factor in intensifying the heat island is the impermeable surface and the large share of buildings in the area.

The survey was further deepened in four different types of urban structure, where modelling was also used to analyse the microclimate. This helped to better identify the importance of the factors influencing the urban heat effect island in different urban environments. The key findings are that in more densely built-up areas, buildings provide much-needed shade in the summer heat. In windier places, the cooling effect of wind has a significant role as well. Especially in the centre of Tampere, which is located on an isthmus between lakes, it is often windy and the streets in the city centre are therefore not necessarily unbearably hot. The courtyards of residential blocks, on the other hand, can be very hot if there is no wind flow and there are no trees or structures providing shade. The favourable effect of the wind was also clear in Kaleva, where the open courtyards of the ribbon-like apartment buildings are mainly oriented towards the prevailing south-west winds. On the other hand, it must be borne in mind that during heat waves it can be calm for a long time, so the cooling effect of the wind may not be available when it is needed most. In addition, in Tampere's climate, a balance must always be struck between summer comfort and winter comfort. The cooling effect of wind is just as important in winter.

Vulnerabilities

In order to locate the vulnerabilities, the heat island map studied the elderly population and, in particular, day-care centres and playgrounds related to small children, old buildings that are considered hot, and heat-sensitive elements of the urban landscape, such as small water bodies and spruce-dominated forests. For minor water bodies, the most vulnerable sub-areas to the urban heat island and valuable sites that are significant for preparedness were also identified. This allowed to highlight areas or sites with potentially higher than average social or ecological vulnerability for further analysis. More research is needed on these issues, as the risk of heat stress is influenced not only by living in a warm area, but also, for example, by the health status of the elderly person (a potential vulnerability factor) and the type of housing (adaptability). In terms of population, an assessment of the demographic trends in the different parts of the city is also important.

In the future, individual sites of high biodiversity value or valuable cultural habitats can be examined for prioritising adaptation measures. The assessment must examine the current state of the sites, i.e. the degree of vulnerability, and the urban development pressures linked to the effects of the urban heat island.

Recommendations for the comprehensive plan

As part of the survey, recommendations for relieving and preparing for urban heat island effect in the phased comprehensive plan of the inner city of Tampere were developed.

There are a number of ways in which urban planning and design can be used to relieve and prepare for the urban heat island effect. In particular, the comprehensive plan can be used to influence urban structure density and thus population density, as well as to the network of green spaces and water management at a general level, and to the location of infrastructure and services critical to the functioning of society. Much of the mitigation of the urban heat island is related to planning levels that go beyond the comprehensive plan, such as neighbourhood and block planning.

Many of the presented recommendations relate to the use of green infrastructure, which is a widely used tool for relieving and preparing for the urban heat island effect. Facilitating access to cooler areas also emerged. The most effective way to mitigate the urban heat island is to combine and implement a number of different actions.

1 Introduction

1.1 Background of the survey

Cities play a key role in both mitigating climate change and adapting to and preparing for its impacts. In urban planning in Tampere, climate change mitigation has been taken into account in a number of ways. One example of mitigation is the completion and densification of the urban structure in Tampere. Construction will continue to be concentrated in the vicinity of good public transport connections, such as tramways. Despite many mitigation efforts, the climate is warming and there is no longer any way to stop the change. This is why urban planning in Finland and Tampere will have to adapt to extreme weather events, such as heat waves, which are becoming more frequent as a result of climate change.

In addition to mitigating climate change, the importance of adaptation has been recognised in Tampere in a number of contexts. The adaptation perspective has been taken into account in many of the City of Tampere's plans, programmes, policies and strategy (compiled in Sitowise 2022). In the comprehensive plan of Tampere, adaptation to climate change has been discussed in the phased comprehensive plan for 2017–2021. An impact assessment on climate change adaptation and climate risk management was carried out as part of the survey for the proposal phase of the phase plan (Comprehensive Plan of Tampere 2020, Siivonen 2021).

In the 2021–2025 comprehensive plan, the processing of climate change adaptation is being deepened and expanded. In addition to the issues identified as key in the central urban area, the analysis will be linked to the broader context of comprehensive plan work and urban planning.

This report on the urban heat island is a background survey for the 2021–2025 comprehensive plan of the central urban area. In other words, the examination of the urban heat island is targeted at the region of the central urban area. The survey has been prepared as a follow-up to the Climate Change Adaptation Study (City of Tampere 2021) commissioned by the Climate and Environmental Policy Unit of the City of Tampere.

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1.2 Structure and methods of the survey

The report consists of two sub-project surveys, which have been combined into a single report. The content of the survey evolved and some of the material was updated as the work progressed. However, not all Phase 1 surveys were repeated in Phase 2 and have been submitted as such in the report.

The report starts with a background on the urban heat island effect in general and presents cities where the effect has been studied and adaptation to heat risk has been planned.

Using spatial data-based analyses, the survey addresses the urban heat island effect in the inner city of Tampere and the vulnerabilities associated with the effect. The single heat wave (3 July 2021) for land surface temperatures at the start of the project was later supplemented by a composite map of eight dates.

The vulnerability analyses have mainly used a map of a single heat wave to describe the conditions, as the number of hot days is predicted to increase as a result of climate change. In sub-project two, updated information on minor water bodies in the central urban area of Tampere was added to the survey.

The survey examines the causes and factors behind the urban heat island effect in the inner city of Tampere The urban structure has been analysed with the help of spatial data and statistical analysis throughout the central urban area. The analysis has been deepened by means of microclimate modelling implemented for different types of urban structure.

Finally, the report presents recommendations for the comprehensive plan and needs for further examination. The level of detail of the work focuses on the scale identified as essential for comprehensive plan work.

The survey was carried out in spring and autumn 2022 as two three-month projects. The work has been based on a literature review, weather statistics, spatial data sets and statistical and spatial data analyses. The methodology of the work is described in the relevant sections of the analysis carried out at the various stages.

1.3 Glossary

Albedo

Albedo, or reflectivity, is the ability of a surface to reflect radiation that hits it. The ratio of the amount of radiation reflected from the surface to the amount of radiation emitted.

Emissivity

Emissivity is the amount of radiation emitted by a body compared to the radiation emitted by a completely black body.

Evapotranspiration

Evapotranspiration, or total evaporation, describes the total amount of water that evaporates from an area in different ways, consisting of evaporation (evaporation from the ground) and transpiration (evaporation through plants).

Green infrastructure

Green infrastructure is a strategically designed network of natural and man-made green spaces, vegetated parts of yards, small water bodies and water areas, and other physical elements of nature, designed to provide a range of ecosystem services and managed for this purpose.

Heat island

Urban Heat Island (UHI) refers to the relative warmth of a city compared to surrounding rural or more natural areas.

LST (see land surface temperature)

Land Surface Temperature (LST).

Land surface temperature

Land surface temperatures can be calculated, in particular from the radiation measured by the satellite's heat channel, as has been done in this survey. Land surface temperature data, i.e. LST data, is available from satellite data (e.g. open data from Landsat 8).

Mean radiant temperature

Mean radiant temperature (MRT) is a measure of the total radiation exchange of the body with surrounding surfaces. The mean radiant temperature is the average of the radiation exchange in all directions. This is affected by the "visibility" (size and position) of the surrounding surfaces and their temperature. In outdoor areas, the most significant factor affecting the mean radiant temperature is direct solar radiation.

Mesoclimate

Mesoclimate refers to the climate in a wider geographical area than microclimate, such as a a city or a forest area, described by long-term averages and extremes of weather variables (e.g. temperature, humidity, wind). Mesoclimate may differ from the climate in the surrounding area.

Microclimate

Microclimate refers to the climate in a small geographical area described by long-term averages and extremes calculated from weather variables (e.g. temperature, humidity, wind). Microclimate describes the conditions at metric scale. Microclimate may differ from the climate in the surrounding area.

Mitigation

Mitigation refers to the means and opportunities to reduce the urban heat island and its impacts, especially in the existing urban structure. The main focus of relieving is on the impacts already observed in response (cf. preparedness).

Preparedness

Preparedness means anticipating, taking into account and mitigating the heat island effect and its impacts through various proactive actions. Preparedness focuses on proactive urban planning (cf. mitigation).

Sky view factor

Sky view factor (SVF) describes the amount of shading from overhead light (e.g. buildings, trees). It is used for example in the analysis of microclimates in cities.

UHI (see Heat island)

UHI (Urban Heat Island).

2 Urban heat island: Research and literature review

2.1 Summary of the literature review

The urban heat island is the effect where the temperature in the city centre is higher than in the surrounding areas. The heat island effect can be divided into two types: the surface urban heat island and the air urban heat island. A number of factors influence the formation of a heat island. Constructed areas, vegetation and water bodies are key factors explaining temperature differences. Buildings and impermeable surfaces increase surface temperatures, while vegetation and water bodies act as factors that lower the temperature.

The spatial and temporal fluctuations in the effect can be large in terms of diurnal, seasonal and annual variations. The differences between cities in the intensity of the effect are significant, and the intensity of the urban heat island also varies in different parts of the city. In several surveys, industrial areas and shopping centres have been found to be the hottest areas, whereas forests, larger urban parks and water bodies were found to be the coolest. As climate change progresses and heat waves become more common, the urban heat island can be expected to become more common in cities. Heat cycles have a wide range of impacts on people's health and quality of life, and the urban heat island effect increases the risk of mortality.

Surveys on the urban heat island can be roughly divided into two main categories: Firstly, surveys based on in situ air temperature measurements, and secondly, surveys based on satellite data describing the Land Surface Temperature (LST). The assessment of the effect using satellite data is a common method, although LST does not directly describe the heat stress caused by air temperature to humans. The use of air temperature in spatially based heat island surveys is not as common as satellite data, due to the geographically less frequent availability of air temperature data. The link between these two different methodologies is not entirely straightforward.

In Finland, the occurrence of the urban heat island has been investigated on the basis of measurements of air temperature at least in Turku, Lahti and Helsinki, and in Espoo the urban heat island of surfaces has been examined on the basis of satellite data. In Stockholm, the urban heat island has also been assessed on the basis of satellite data. The topic has also been studied and evaluated in many other cities. For example, various surveys, surveys and modelling have been carried out in Toronto, Vienna and Portland.

There are a number of ways in which urban planning and design can be used to prevent and relieve the urban heat island. Many of these methods are related to the utilisation of green infrastructure, and green infrastructure is a widely used method for relieving the urban heat island effect. Paying attention to the surface materials used in cities and their properties can also help to mitigate the urban heat island.

2.2 Presence, causes and factors of the urban heat island

Urban heat island (UHI) refers to a microclimate effect where the temperature in the city centre is higher than in the surrounding rural or more natural areas. Urban heat islands can be divided into two types: surface UHI and atmospheric UHI (Leal Filho 2021).

2.2.1 Factors that intensify the heat island

A number of factors influence the formation of a heat island. The key factors affecting the creation of the heat island are the release of solar radiation energy stored in the city's buildings and paved surfaces as heat, the waste heat caused by human activities and the low evaporation caused by the scarcity of plant cover. High buildings also have an impact on the effect, as they prevent the air from moving freely. In addition, seasons and times of the year, geographic location of the city, size and population density, urban structure and land use, topographical factors and surface materials, vegetation, climate and prevailing meteorological conditions, and human and industrial activities in the city influence the formation of an urban heat island. (Drebs et al. 2014; Tzavali et al. 2015)

Constructed areas, vegetation and water bodies are key factors explaining temperature differences. Buildings and impermeable surfaces increase surface temperatures, while vegetation and water bodies act as factors that lower the temperature. Indeed, urban heat islands are most likely to occur in areas with low vegetation and highly impermeable and non-reflecting surfaces. According to surveys, waste heat from human activities is also considered a significant factor in the urban heat islands (Zhou et al. 2019; Brozovsky et al. 2021; Tzavali et al. 2015)

The thermal properties of urban building materials affect how much energy is stored and, correspondingly, how much energy is released into the atmosphere by buildings. Materials such as stone, concrete and asphalt absorb and store heat. Due to drainage in cities, less of the rainwater evaporates as water vapour into the air. Because water vapour absorbs heat energy, less evaporation raises temperatures in cities. (Tzavali et al. 2015; Pilli-Sihvola et al. 2018)

2.2.2 Urban heat island effect variation

The spatial and temporal fluctuations in the effect can be large in terms of diurnal, seasonal and annual variations. According to satellite data, differences in surface temperatures between urban and rural areas are most pronounced during the day in summer, when the difference in surface temperatures between urban and rural areas can be more than 10 degrees Celsius. In surveys based on surface temperatures, the intensity of the effect is also greatest during the day, while in surveys based on air temperature measurements, the effect is strongest at night. (Zhou et al. 2019)

There are significant differences in the intensity of the effect between cities, especially in daytime. The intensity of the urban heat island also varies in different parts of the city. Temperature variations within a city can be even greater than the temperature differences between the city and surrounding more rural areas. In several surveys, industrial areas have been found to be the hottest areas. (Zhou et al. 2019) In surface temperature-based surveys of cities in cold climate zones, shopping centres and industrial areas have been found to be the hottest areas, whereas forests, larger urban parks and water bodies were found to be the coolest. (Brozovsky et al. 2021)

2.2.3 Observations from the north

In Finland, the occurrence of urban heat islands has been investigated in recent years on the basis of air temperature measurements at least in Turku, Lahti and Helsinki (Suomi 2014; Suomi 2018; Drebs 2011). In Espoo, the urban heat islands of surfaces has been examined on the basis of satellite data as part of the city's blue-green structure survey. Industrial areas were found to be the hottest. (Espoo 2019, see also section 2.5.2)

Studies show that the city centre of Turku is the warmest area on average. The average temperature difference compared to areas outside the city centre is two degrees Celsius, but at its highest the urban heat island can be as high as 10 degrees. The urban heat island does not occur continuously in Turku, but the city centre may occasionally be cooler than its surroundings. This is called a cold island. (Suomi 2014) In Lahti, the urban heat island is most pronounced in summer, with the highest temperatures being in the city centre (Suomi 2018). A regional estimate of the heat island of the city of Helsinki has been calculated based on air temperature measurements taken during one year (7/2009–6/2010). During the measurement period, the greatest differences in air temperatures were +4 degrees, compared to Kaisaniemi observation station. Individual large buildings and subcentres clearly created their own heat islands. (Drebs 2011)

In Stockholm, urban heat islands have been studied using a Land Surface Temperature (LST) method (Igergård 2021). The method is described in more detail in section 2.3.1. The survey found differences of approximately 8°C in the average maximum land surface temperature values. Key factors explaining the urban heat island were ground cover and types of urban structure. The Stockholm example is presented in section 2.5.1.

2.3 Consequences of urban heat islands

With climate change, average temperatures are rising all over Finland. Climate change will increase the intensity and frequency of extreme weather events such as heat waves. In Helsinki, for example, it is estimated that by the 2050s, the hours of moderate heat stress in summer will almost double due to climate change and urban densification. Based on the modelling carried out, the intensity of the heat stress varies from region to region. (HSY 2022)

As heat waves become more common, urban heat islands can be expected to become more common. The spread of the effect has many kinds of impacts in cities. For example, land surface and building facade temperatures have a direct impact on people's temperature comfort when outdoors. Heat radiating from surfaces increases discomfort in hot weather.

Heat waves have an impact on people's health and quality of life, and the urban heat island effect increases the risk of mortality. In addition, periods of heat and drought are detrimental to some urban habitats and to the thriving of animal and plant species. They also affect agricultural production, for example, and increase energy consumption for cooling.

2.3.1 Mortality and health hazards

According to a recent survey, the risk of heat-related mortality in Helsinki is higher than in the area around Helsinki. In terms of population, the survey found that the heat mortality rate in Helsinki was about 2.5 times higher than in the surrounding area. (Ruuhela et al. 2021) For example, the July 2010 heat wave caused an estimated 60 extra deaths in the HUS area, of which 30-40 occurred in Helsinki. (Pilli-Sihvola et al. 2018) The prolonged heat wave in summer 2018 caused about 380 premature deaths in Finland (THL 2019).

The overall public health impact of hot weather is significant, as the mortality rate increases sharply as the temperature rises. The mortality of the population increases markedly when the average daily temperature exceeds about 20 degrees Celsius. When a heatwave lasts four days or more, daily mortality increases by an average of 10%. (Ministry of Social Affairs and Health 2021)

In addition to increased mortality, heat also causes other health hazards that have been less well studied. However, surveys have shown that long periods of intense heat in Finland increase the need for hospital care, at least for respiratory diseases. The FINRISKI survey found that 80% of respondents experienced at least mild side effects in hot weather, with 7% reporting respiratory symptoms and 6% cardiac symptoms. (Ministry of Social Affairs and Health 2021)

Heat also reduces work efficiency and increases the need for breaks, thus increasing the costs of working. For example, in 2017, an estimated 153 billion working hours were lost globally due to heat exposure. (Chavaillaz et al 2019)

The most vulnerable population groups to the adverse effects of heat are the elderly, young children and those suffering from various long-term illnesses. The risk of serious adverse effects is particularly high for people over 65 years of age, and the ageing population is one of the factors that will increase the likelihood of adverse health effects from extreme temperatures in the future. Heat increases the mortality of older people living at home and in health and social care institutions. (Ministry of Social Affairs and Health 2021) Excessive heat is a problem especially in residential buildings, as mechanical cooling is not commonly used in them (Kosonen et al. 2021).

2.3.2 Cooling

Geographically, the cooler cities in Northern Europe appear to be more vulnerable to the effects of heat waves compared to the more adapted cities in Southern Europe (Ward 2016). In Northern Europe, heat waves are less common, and cooling systems in buildings are therefore less common than in warmer climate zones. This can be expected to increase the vulnerability of northern cities to the health impacts of urban heat islands. (Ruuhela et al 2021).

In addition to health hazards, this effect increases energy consumption in buildings equipped with mechanical cooling. In many cases, mechanical cooling also contributes to the effect by removing heat directly to the outside air. In case surveys, the cooling need caused by an urban heat island is estimated to be on average 13% higher in cities than in surrounding areas (Tzavali et al. 2015). During heat waves, the risk of a power outage is high due to the overload caused by cooling and air conditioning, which is also a risk for health care (Wang et al. 2016). As mechanical cooling becomes more common, this risk also increases in Finland.

2.3.3 Impacts on air quality

The effect can also increase ozone concentrations at ground level, as higher temperatures increase ozone formation. In addition, higher temperatures can increase the formation of smog in cities. (Tzavali et al. 2015) The urban heat island is typically the strongest in calm weather, which means that air mixing is low. Thus, then, poor air quality often reinforces the negative health effects of the urban heat island. (Suomi 2018)

2.3.4 Impacts on urban nature

Increasing heat waves and drought also have a wide range of impacts on nature. In Finland, the tree population is becoming more deciduous and spruce in particular is facing seasonal stresses ranging from storms to drought and pests. The growing season is getting longer, and in warm cities, plant species diversity and cultivation opportunities are increasing, but pests, invasive species and the need for irrigation are increasing. The warming urban climate is home to dragonflies, foxes, rabbits, raccoons, raccoons dogs, as well as numerous pest insects, parasites, rats and ticks. Some newcomers are harmful to native species or may cause diseases. Baby birds can die in the heat, fish species in minor waters change. Amphibians living in small wetlands, who cannot migrate to better habitats by land, are also at risk during droughts. (Zhou et al.

Summer heat waves are often followed by thunderstorms and heavy rainfall, increasing surface run-off from cities into water bodies. This means increased, sudden pollutant loads also during summers, and challenges for stormwater management and vegetation. (Zhou et al.

In addition to negative impacts, the effect may also have positive or neutral impacts. For example, the growing season may be longer in urban areas due to higher temperatures. Plants will begin flowering earlier in the spring, and horticulture will benefit from a longer growing season. Urban areas can also provide more suitable habitats for some plant and animal species that are good for biodiversity. For example, the spread of oak and oak belt species can be seen in Southern Finland along the Helsinki-Tampere urban chain. Cities may also act as a "refuge" in cold winters for species suffering from cold conditions, thus supporting the surrounding populations (Kullberg 2022).

2.3.5 Impacts during winter

Urban heat islands can occur during all seasons. Compared to a summer heat island, a winter heat island has more positive effects from a human perspective, such as reducing the need to heat buildings, thus reducing energy consumption during the heating season, and reducing the cost of maintaining transport routes. On the other hand, the adverse effects of the winter heat island effect include increased above and below zero temperatures, where melting and freezing processes can, for example, increase problems in water pipelines and make winter road maintenance more difficult (Drebs et al. 2014; Suomi 2014)

2.4 Methods for determining urban heat islands and their effects

2.4.1 Research methods for the occurrence of urban heat islands

Surveys on the urban heat island can be roughly divided into two main categories: Firstly, surveys based on in situ air temperature measurements, and secondly, surveys based on satellite data describing the Land Surface Temperature (LST) (Zhou et al. 2019).

Land surface temperature (LST) based on satellite data is currently considered the best research method for assessing urban heat islands (Igergård 2021). The method is commonly used even if LST does not directly describe the heat stress caused by air temperature to humans (Ward et al. 2016). LST data is suitable for studying the heat island effect, but LST data is not suitable as such for studying the heat stress experienced by humans, as it does not take into account environmental factors, such as air temperature and humidity. (Song & Wu 2018)

The majority of current surveys are based on satellite data, and the most widely used satellite data for studying the heat island effect is Landsat. The number of satellite-based heat island surveys has increased exponentially since 2005, driven by the development of satellite and geospatial monitoring in recent years. In terms of time, the effect has been studied most during the day in summer. Most of the surveys are based on LST data from a single point in time. Geographically, urban heat islands have been studied most in Asia, North America and Europe. (Zhou et al. 2019)

A key advantage of using satellite data over in situ air temperature measurements is that satellites can provide continuous and repeatable data at relatively high resolution (Zhou et al. 2019). The use of air temperature in spatially based heat island surveys is not as common as the use of satellite data due to the limited availability of the former. Cities often do not have a dense enough network of air temperature measurements to survey the heat island effect (Räsänen et al. 2019).

The link between these two different methodologies is not entirely straightforward. Differences in the results of the different methods depend, among other things, on the characteristics of the different surfaces (e.g. moisture, albedo, emissivity), the time of year, geography and prevailing weather conditions. (Zhou et al. 2019) On a hot, sweltering day (air temperature 33°C / 91°F), the temperature of the conventional roofing material can be up to 16°C (60°F) higher than the air temperature (EPA 2022). Surface temperature is very sensitive to changes in surface conditions, which is why the temporal and spatial variability of surface temperature measurements is much greater than that of air temperature measurements. While there is a link between air temperature measurements and surface temperature measurements, it is important to recognise that these are two different methods of investigating urban heat islands. (Tzavali et al. 2015)

The strength of the urban heat island can also be estimated using various calculated indices. For example, in North America, a heat island intensity index has been calculated for 159 cities and the index figures have been used to compare heat island intensity in cities. The index is based on parameters such as:

- albedo
- share of green areas
- population density
- height of buildings
- average street width

The index number calculated represents the potential temperature difference between the average temperatures in the city and the surrounding areas. (EPA 2022)

Various modelling techniques can also be used to assess the strength of the urban heat island and the factors affecting temperature differences. There are many different modelling methods. For example, Suomi (2018) has estimated the strength of the factors affecting temperature differences in Turku in their doctoral thesis using several different modelling methods, using different explanatory variables and spatial scales.

Also, mitigation actions related to the heat island effect can be assessed and compared using different numerical modelling methods, such as ENVI-met (Brozovsky et al. 2021; Balany et al. 2020). The above is one of the most common, and is particularly suitable for block-level microclimate modelling, such as the Toronto and Portland cases described in Section 2.5 of this report.

2.4.2 Vulnerability assessment

Social vulnerability to the effects of heat can be assessed using different vulnerability factors. Vulnerability is affected by people's physical characteristics, such as age and health, adaptability (capacity to prepare, ability to cope during the situation and ability to recover) and the living environment and its properties. The vulnerability can be assessed on the basis of factors such as age, access to information, social networks, income levels, ownership of the dwelling, housing stock and the characteristics of the physical environment. A breakdown of vulnerability factors helps cities identify ways to reduce vulnerability. (Kazmierczak & Kankaanpää 2016)

Vulnerabilities to the effects of the urban heat island have been examined, for example, in a spatial data-based survey carried out in Helsinki, which utilises LST data to assess the urban heat island. The following factors have been used as indicators of vulnerability in the survey: age (aged under 18 and proportion of people over 65), gender (proportion of females), low income, low level of education, migration background and weak social networks (unemployment rate). (Räsänen et al. 2019)

2.5 Preventing and preparing for an urban heat island

2.5.1 Reducing health hazards

Short-term and long-term actions can be taken to combat the health hazards caused by hot weather. Short-term actions refer to acute control actions during heat waves. Long-term actions include actions aimed at reducing exposure to excessive heat. For example, they aim to improve the management of indoor temperatures in buildings or to reduce the intensity of the heat island effect in urban areas. Developing social preparedness, improving monitoring and raising awareness among citizens, authorities and health and social care actors about the health impacts of heat and how to prevent them are also examples of long-term actions.

The implementation of short-term actions focuses especially on the social welfare and health care sector. Long-term actions can be implemented, for example, in construction and urban planning and in the renovation of old buildings. (Ministry of Social Affairs and Health 2021)

So far, some actions have been taken in Finland to combat health hazards caused by heat. One example of a concrete measure is the heat warnings issued by the Finnish Meteorological Institute since 2011.

The key development needs in the prevention of health hazards caused by heat are related to the preparedness of social welfare and health care units, as a large number of the most vulnerable population groups are located within the scope of these services and care and treatment institutions. (Ministry of Social Affairs and Health 2021)

To reduce the adverse health impacts of hot weather, both actions to protect the most vulnerable populations and broader societal mitigation and adaptation measures are needed. Raising awareness among citizens and health care personnel is essential, as is among decision-makers. It is important to take warming into account in the living conditions of homes and care facilities and in urban planning. (Kollanus et al. 2014)

One key measure for preparing for the urban heat island is the management of indoor temperatures in buildings. People spend a large part of their time indoors, which emphasises the importance of building temperatures (WHO 2008). The Decree on Housing Health in Finland (Ministry of Social Affairs and Health 545/2015) defines action limits for high ambient temperatures outside the heating season, and the Decree on the Energy Efficiency of New Buildings (YM 1010/2017) also aims to influence indoor temperatures. The urban heat island effect is strongest in industrial areas, shopping centres and other similar areas (Brozovsky et al. 2021). They do not live in these areas, but work. Therefore, particular attention must be paid to the working conditions of the areas concerned (working temperature, cooling possibilities) (Igergård 2021).

In general, an indoor temperature of 20–22ºC is considered appropriate, but the value is not officially defined. In accordance with the Housing Health Decree, the action limit for ambient temperature in apartments in summer is +32 oC. In nursing homes, sheltered housing, day-care centres and other similar facilities, the action limit is lower, +30 oC (STM545/2015). During the summer of 2018, the maximum temperatures of the researched buildings increased up to 35–38 °C. In the forecast climate of 2050, room temperatures are expected to rise from this by a further one degree in comparison to both normal summer and warm summer. Bedroom temperature and ventilation are particularly important for experiencing heat stress. It is therefore advisable to place the bedroom on the cooler side of the building (north, northeast) if possible. (Kosonen et al. 2021, Mikkonen 2021)

2.5.2 Green infrastructure

There are a number of ways in which urban planning and design can be used to prevent and relieve the urban heat island. For example, the orientation of streets and the ratio between the height of buildings and the width of the street space affect the exposure of buildings and outdoor spaces to solar radiation. Many of these methods are related to the utilisation of green infrastructure, and green infrastructure is a widely used method for relieving the urban heat island effect (Balany et al. 2020, Brandenburg et al. 2018, Norton et al. 2013). The term refers to a network of natural and man-made green areas and, for example, street trees and green roofs, which fosters natural organisms and processes and at the same time produces benefits for humans.

Green infrastructure can be used to regulate microclimates. Shading, which blocks solar radiation, reduces the rise in air and ground temperature, and evapotranspiration, or total dispersion, cools the air, improving the temperature comfort experienced by humans. The effects of green infrastructure depend on the type of vegetation (e.g. trees, green roofs, grassland) and its placement in the urban structure. Trees cool and improve temperature comfort, but can reduce wind. Green roofs are considered the best green infrastructure solution in densely built-up areas where green spaces are limited and roof surfaces are extensive, provided there is sufficient vegetation on the roofs (Balany et al. 2020). If the roofs are at high height, they have little effect on the temperature near the land surface (Makido et al. 2019, Wang et al. 2016). The implementation of green roofs may have conflicting impacts on construction emissions. Green roofs are recommended in this report, particularly from the perspective of relieving urban heat island effect. They also support other ecological and recreational benefits of green infrastructure.

The significance of vegetation for controlling urban heat islands is obvious. In winter, leafless plants do not mitigate the urban heat islands. For example, Canadian surveys have shown that planting vegetation and increasing urban albedo can reduce urban heat islands, especially during daytime (Brozovsky et al. 2021). Also in Manchester (Gill et al. 2009), a 10% increase in green spaces in city centres and dense residential areas was estimated to significantly mitigate temperature increase by 2080 (0.7°C) compared to no increase (1.7°C) or 10% removal (7–8°C). The articles do not say which green area was used as an additive in the spatial data analyses.

Some surveys have found that wooded and layered, mosaic-structured green areas cool the climate more effectively than open green areas, which may even increase the intensity of the heat island on hot days (Ward et al. 2016, Ingergård 2021). Mixing urban green with other urban structures reduces heat islands more effectively than large separate green areas. (Ward et al. 2016) Other surveys also emphasize the importance of the extent of green areas and the extent of their cooling effect to the built-up areas of the surrounding environment (Siivonen 2021). Ingergård (2021 p. 28–30) notes that the effects depend on whether the city as a whole or individual neighbourhoods are considered.

For green infrastructure to work, it is important to ensure the preservation of critical natural capital and total green area, as well as to improve the quality and ecological functionality of existing green areas and to improve green infrastructure at renovation sites and new developments. Street space also plays a key role. The need to irrigate green areas in a sustainable way is essential for green infrastructure to work. (Brandenburg et al. 2018, Gill et al. 2009, Norton et al. 2013).

Increasing green areas has also other benefits than mitigating urban heat islands. Green areas also help to manage flood risks, and they can support biodiversity and increase the attractiveness of cities.

2.5.3 Buildings and surface material

Paying attention to the surface materials used in cities and their properties can also help to mitigate the urban heat island. In urban areas, a significant proportion of the ground cover is roof surfaces and roads. Various reflective roof coatings can be used to mitigate urban heat islands. However, surveys show that reflective roofing has little effect on street-level temperatures, especially if the roof is installed on a tall building (Mikkonen 2021, Wang et al. 2016, Makido et al. 2019).

Reflective street surfaces, on the other hand, remain cool in terms of surface temperatures, but the radiation reflected from them can heat up adjacent objects, such as buildings and structures, or people walking on the streets. The benefits of reflective street surfaces are therefore not clear-cut. In contrast, surveys have shown that the use of permeable pavements has positive effects on both urban heat islands and stormwater management. (Mikkonen 2021)

Pizarro (2019) highlights the paradox of urban planning: A dense, energy-efficient urban structure that mitigates climate emissions in line with sustainable development may conflict with a resilient urban structure that adapts to climate change. The optimal density and height of the urban structure depends on the climate and topographical factors.

In different types of urban structure, different means will produce the most meaningful results. Research shows that the most effective way to mitigate urban heat islands is through a combination of several of the above means. (Wang et al. 2016, Makido et al. 2019, Pizarro 2019).

2.6 Examples from other cities

2.6.1 Stockholm

In addition to the Land Surface Temperature (LST) grid, the thesis (Ingergård 2021) assessing the urban heat island effect in Stockholm used the municipality's ground cover data in a somewhat simplified form and urban structure types (data from the city compared to an aerial photograph). The highest observed land surface temperatures – not the most common ones – were plotted on the land surface temperature grid map as a combination of several dates. The areas identified as problematic in the data represent 5% of the hottest and 10% of the coolest.

Next, the survey looked at the statistical ratio of land cover to land surface temperature, such as the proportion of forest versus vegetation-free area. An average LST was calculated for the different types of urban structure. Temperatures in built-up areas were studied especially. In addition, the types of urban structure were compared with the ground cover.

In Stockholm, the hottest areas are the most densely built-up and have the least vegetation. They also have a high level of traffic and activity (industrial areas, airport). The coldest areas are on beaches and in nature reserves. The proportion of open vegetation areas was not found to play a strong role in relieving the urban heat island effect, but vegetated areas do have lower temperatures than built-up areas.

In a further review of the survey (Wiborn 2022), a land surface temperature of +35°C has been chosen as an indicator of hotspots (heat contours) in the city. The reason for the choice is not given in the available material. Heat islands have been vectorised so that they can be viewed on, for example, a population map and new spatial data analyses can be carried out for them, such as the number of the most vulnerable populations, such as people 0–4 year olds and people over 70 years of age, in the area of the heat islands.

The survey also takes into account the proportion of forests and lakes in each of the city's statistical units as a mitigating factor for heat, i.e. access to cool locations for residents. The detailed analyses concern, for example, the distance between pre-schools and cool zones.

The built environment was analysed in 250 x 250 m squares, from which soil surface temperature, the amount of hard surfaces, tree crown cover, building heights and water surface were calculated. The analysis found that the amount of hard surfaces increases the land surface temperature, while tree crown cover lowers temperatures. Based on the analysis, the urban structure was classified into seven different types of clusters, in effect block types, based on the relationship between the above characteristics and temperature.

2.6.2 Espoo

The City of Espoo's Viherkudelma (green fabric) (2019) has studied urban heat islands using Landsat 8 satellite data, producing a map of the land surface temperature (LST). A very hot day was chosen as the time when the temperature of the air at the nearby Helsinki-Vantaa Airport was at its highest at +29.6°C. At that time, the temperature of the land surface varied from +21°C to +33°C.

In Espoo, the proximity of the sea generally has the effect of balancing the cold and hot weather temperatures. However, a map of the land surface temperature shows that the hottest areas of the city are also near the sea, where construction is denser than in the northern parts of the city. The hottest areas in Espoo were "large industrial areas with a lot of uniform paved dark surfaces." The survey also found that sports parks with artificial turf are exceptionally warm.

2.6.3 Toronto

Wang et al. (2016) conducted a survey in Toronto, one of the fastest urbanising northern cities. In cold climates, the consequences of an urban heat island can be more devastating, as residents and urban nature are not used to the heat. In Toronto, the average annual temperature in 26 days is above +30°C, and by 2100 count of hot days are predicted to rise to 65. In Canada, as the average daily temperature rises above +20°C, mortality has been studied to increase by 2.3% for each degree increase. Heat-related deaths are forecasted to double in Toronto by 2050.

In Toronto, the urban heat island occurs especially at night and during winter months. The proximity of the lake and the winds mitigate the effect. Around 30% of the city's land surfaces are asphalt and concrete, and the share is higher in city centre areas. The Land Surface Temperature (LST) map shows that the hottest areas are on the outskirts of the city centre, away from the lake, where surfaces store heat. In a densely and highly built central urban area on the lakeshore, air flows between buildings are likely to mitigate the effect of the urban heat island, with buildings providing shade during the day. In parks, temperatures are 3-4 degrees lower.

In Toronto, the Toronto Green Standard mitigates the urban heat island, for example through requirements for new buildings, surface materials and stormwater management. In addition, the city's policies recommend planting trees, which has been found to have greater impacts than roofing materials. Microclimate modelling has been used to find a theoretically optimal ratio of building height to street width for the city. Researchers have also considered the development of urban structures to optimise air circulation, sunlight and wind.

Previous simulations from Toronto (Akbari & Taha 1992 and Krayenhoff 2003, cited in Wang et al. 2016) show that increasing the area of land surface vegetation by 30% could reduce the cooling energy demand of buildings by 10–20%. Adding more pale building materials (albedo 0.2) reduced the cooling energy demand even more (30–40%). Changing 50% of the roof surface area to green roofs and high albedo (0.6) materials had little effect on air temperature, at least at skyscraper height and presumably at ground level.

Toronto prepares for the growth of 2.4 million inhabitants, for example, by planning high construction. Due to strong urbanisation, research will be carried out on how urban planning affects temperature comfort and how the consequences of the urban heat island could be avoided. The survey (Wang et al 2016) selected three different types of urban structure: a high-rise building central area, a medium-high-rise area (a typical suburb) and an area of detached houses. The properties of these areas (built areas, green areas, height of buildings) were used in an analysis in which the ENVI-met software simulated the climate of a typical summer and winter day. Construction materials and human activities, such as heating, were not taken into account in Toronto's modelling. In addition to the modelling of the current state, four modified versions of all areas were made, in which the soil surface materials, the amount of vegetation, cooler roofs and their combined version were changed. The survey visualised both air temperature (Ta) and mean radiant temperature (MRT) and used the value calculated using RayMan software, which best describes human physiological equivalent temperature (PET).

In the survey, the "sky view factor", or openness of the space, affects the amount of sunlight that reaches the area during the day, and open urban areas are hotter than dense, high-rise cities. High blocks shade the land surface, but store more heat in the night. Replacing the asphalt surfaces with concrete (albedo change 0.2) reduced the maximum ground temperature by more than seven (7) degrees in all typologies, and mostly in the suburbs, as there are fewer trees and building stock that shade the street space. Replacing roof materials with more reflective materials reduced roof temperatures by 9.6 to 11.3 degrees. Roof material has the greatest effect on the temperature sensed by people in low-rise buildings, where roof surfaces are close to the ground. A 10% increase in vegetation will reduce the temperature, especially on hot summer afternoons, and both day and night air temperatures in all areas by at least 0.8°C and radiant temperatures by up to 6.1 to 8.3°C depending on the type of site.

According to the survey, it is advisable to increase the number of trees especially in areas that are busy during the day. In winter, vegetation plays a small role in the urban heat island when trees are deciduous. Roof and ground materials alone will not make much difference to the current situation, but the most effective approach was to combine different methods. The effectiveness of the methods varied depending on the type of built environment.

2.6.4 Vienna

In research cooperation, the City of Vienna has drawn up a strategy for preparing for the heat island effect, which guides the designers and stakeholders of the built environment (Brandenburg et al. 2018). The strategy guides procedures and concrete actions to combat urban heat islands in both strategic urban planning and the implementation of individual sites. In addition to climate work, political policies and economic methods, the strategy emphasises the role of comprehensive plans and local detailed plans as legally binding urban development supervisors. They define urban and green structures. For comprehensive planning, it is recommended that the urban heat island is taken into account throughout the whole process, from surveys and target setting to planning and implementation of the planning material and planning for monitoring.

In Vienna, comprehensive planning and local detailed planning make use of climate experts, including, for example, planning competitions, consultation with relevant sectors and landowners. Microclimate analyses are a standard part of the impact assessment of construction projects, especially at the local comprehensive plan level. Particular attention must be paid to the adequacy of green areas, and requirements for relieving heat islands must be added to the calls for tenders in more detail. In addition, the City of Vienna aims to lead the way in climate-smart design in its construction projects and act as a role model for private developers. The city influences adaptation measures, for example by setting conditions for building plot tenders and providing funding for green roof projects.

Vienna’s strategy sets out a number of actions to prevent and mitigate the urban heat island. The benefits of each action in terms of micro- and mesoclimate, biodiversity and quality of life, as well as the costs of implementation and maintenance, have been estimated using a spiderweb diagram. The challenges of individual actions have also been identified. The actions are divided into strategic and practical applications.

Strategic actions, which are considered at the city-wide scale (including 13 actions):

- Safeguarding airflows and open green areas in the city
- Urban structure adaptation (streets, buildings)
- More pale construction and surface materials and adding permeable surfaces
- Securing and expanding green areas
- Protecting and increasing (street) trees

Practical actions, technical and structural solutions for outdoor spaces and buildings (including 24 actions)

- Increasing street greening and developing non-productive land
- Greening and cooling of buildings
- Increasing water in the city
- Shading outdoor spaces and routes
- Cooling public transport

In addition to these activities, the Vienna strategy includes raising awareness among citizens, planners, politicians and other urban development stakeholders.

2.6.5 Portland

Portland has a Mediterranean climate, but summers are cooler than in Mediterranean cities due to ocean currents. The survey (Makido et al 2019) modelled green infrastructure for six different land use areas. The modelling used ENVI-met® software, which analyses the microclimate by simulating temperatures for different built environment scenarios. The software is one of the most widely used and accurate modelling tools, according to the wider literature. The survey used six land cover variables found to be relevant in previous research: 1) tree crown cover volume 2) vegetation volume 3) biomass density 4) average building height 5) total construction mass 6) change in building height. Based on the granularity of the blocks typical for Portland, the research area was divided into 100-metre squares, which were analysed by simplifying (cluster analysis) the landscape factors affecting the occurrence of the heat island. The MCLUST package of the R software was used for the analysis. The survey excluded water, protected forests and dense business parks, which are unlikely to change and are land use exceptions. Six different clusters were selected for further survey on the basis of land use, including industrial areas and urban environments with different types of vegetation. Their current state variables such as buildings, vegetation, and different land covers were then input into ENVI-met. Changes were then modelled for each block type by adding vegetation, green roofs and increasing the albedo of roofs and land surfaces. A combination of these was modelled, as well as an alternative where vegetation was removed and the land surfaces replaced with asphalt. The last one raised air temperatures at a height of 1.4 metres in all block types in the afternoon.

All adaptation measures reduced air temperatures, with the greatest impact via increasing vegetation as well as via a combination of actions. The impacts of different adaptation measures varied between different block types. Increasing green roofs had the least impact on all block types, but they worked best in areas with large roof surfaces. Similarly, increasing the albedo of roofs and of street surfaces had the best effect (0.9 to 1.4°C reduction in temperature) in industrial and urban non-vegetation areas. Of the individual actions, the most temperature-reducing effect was achieved by increasing the number of street trees and vegetated surfaces (1.0 to 2.6°C) – except in the block type with high existing crown cover. Individual adaptation measures were found to be less effective than a combination of actions, which reduced air temperatures by 1.7 to 3.4°C in all other types and by 0.7°C in the high crown cover area. The results cannot be directly compared to other cities, but they give an idea of the impact of different nature-based solutions and material choices in different urban environments. The survey provides general guidelines, and it is recommended that modelling is used as a basis for examining the impacts of different options in urban planning. The survey points out that in addition to relieving the urban heat island effect, green infrastructure has other benefits in terms of increasing the resilience and comfort of the urban environment.

3 Heat islands in the central urban area of Tampere

3.1 Urban heat island map

3.1.1 Map from the heat wave period

At the beginning of the survey, a map was drawn showing the land surface temperature in the central urban area of Tampere on 3 July 2021 (Map 1). Calculated from the radiation measured by the Landsat-8 satellite's thermal channel, the land surface temperatures in the survey area ranged from +23 degrees Celsius to over +47 degrees Celsius at selected times. The material does not contain water bodies.

The map has been drawn on a hotter than usual summer day, as the aim of the survey is to get an initial idea of the thermal conditions in the central urban area of Tampere on hot summer days. In Finland, weather is considered to be hot when the maximum temperature of a day exceeds +25°C. The average daily temperature at Tampella station on 3 July 2021 was +24°C and the maximum air temperature at 2 metres was +28°C (Finnish Meteorological Institute, www a). At the Härmälä weather station, the day's maximum air temperature on 3 July 2021 was +27.9°C. The date was preceded by a 15-day period when the daily maximum temperature was above or close to +25°C, with only one day below +25°C (meteorological data from Härmälä station).

In 2021, there were 13 days with average air temperatures of +24°C or above measured at the Tampella weather station (Figure 1). The average temperature in July between 1991 and 2021 in Tampere was 17.4°C, and the deviations are shown in Figure 2 (Finnish Meteorological Institute, www b). The graph of average temperatures also shows an increasing trend in the number of hotter days.

The photographing time on the first phase of the study was carried out as recently as possible in order to reflect the current urban structure as closely as possible. In the second phase of the survey, two (2) hotter days suitable for satellite imaging were found in summer 2018 (Appendix 1). They have been used in the composite map together with the land surface temperature data for 3 July 2021 and with the land surface temperature data of five other dates (map 2).

Map 1 and Map 2 therefore show the land surface temperature, which is commonly used to map the urban heat island (Zhou 2019). It is not directly comparable to the air temperature or the temperature comfort experienced by humans. In many places, land surface temperatures were several degrees warmer than air temperatures at 2 metres above the surface (Figures 3 and 4).

Outside the city, the average temperature at the Siilinkari measuring station on the day shown on the map was +23 degrees Celsius. In a survey of several summer days of weather data from 2019 to 2021, the air temperature at the Siilinkari station on the water body outside the city was 2–3°C lower at midday than at the Tampella and Härmälä stations (Finnish Meteorological Institute, www a).

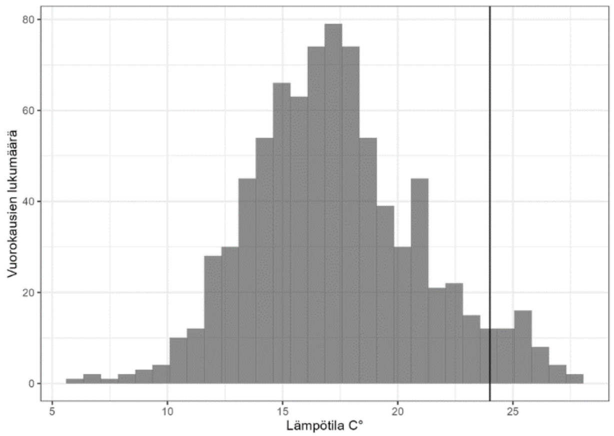


Figure 1. A histogram of temperatures in Tampere in 2021. The average temperature rose to +24°C or above for 13 days.

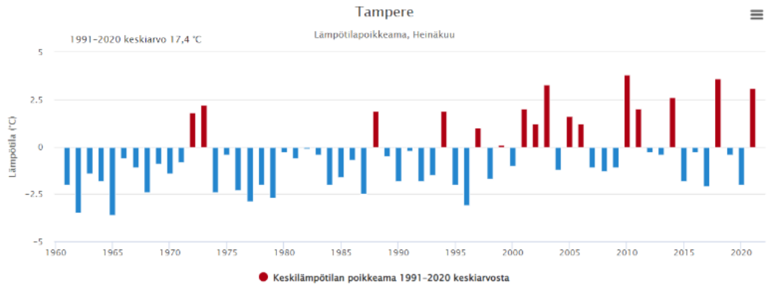


Figure 2. Deviation from the 1991–2020 average July temperature (17.4°C) in Tampere. From 2000 onwards, the average is exceeded more frequently. Finnish Meteorological Institute.

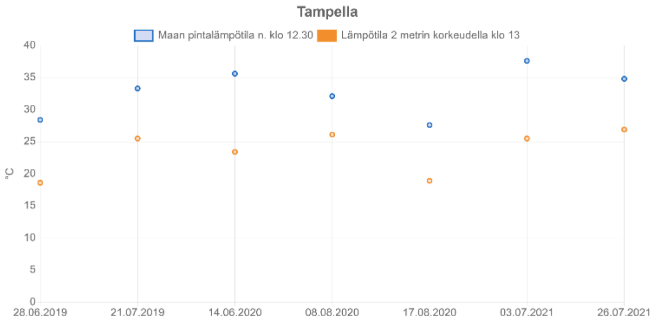


Figure 3. Differences in land surface and air temperatures at the Tampella station. The ground temperature has been 6–12.2 °C higher than the air temperature at the time of measurement. (Finnish Meteorological Institute, www a) The station is located in the block area of the central urban area.

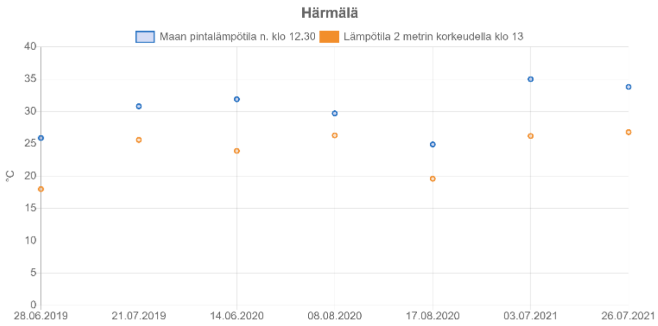
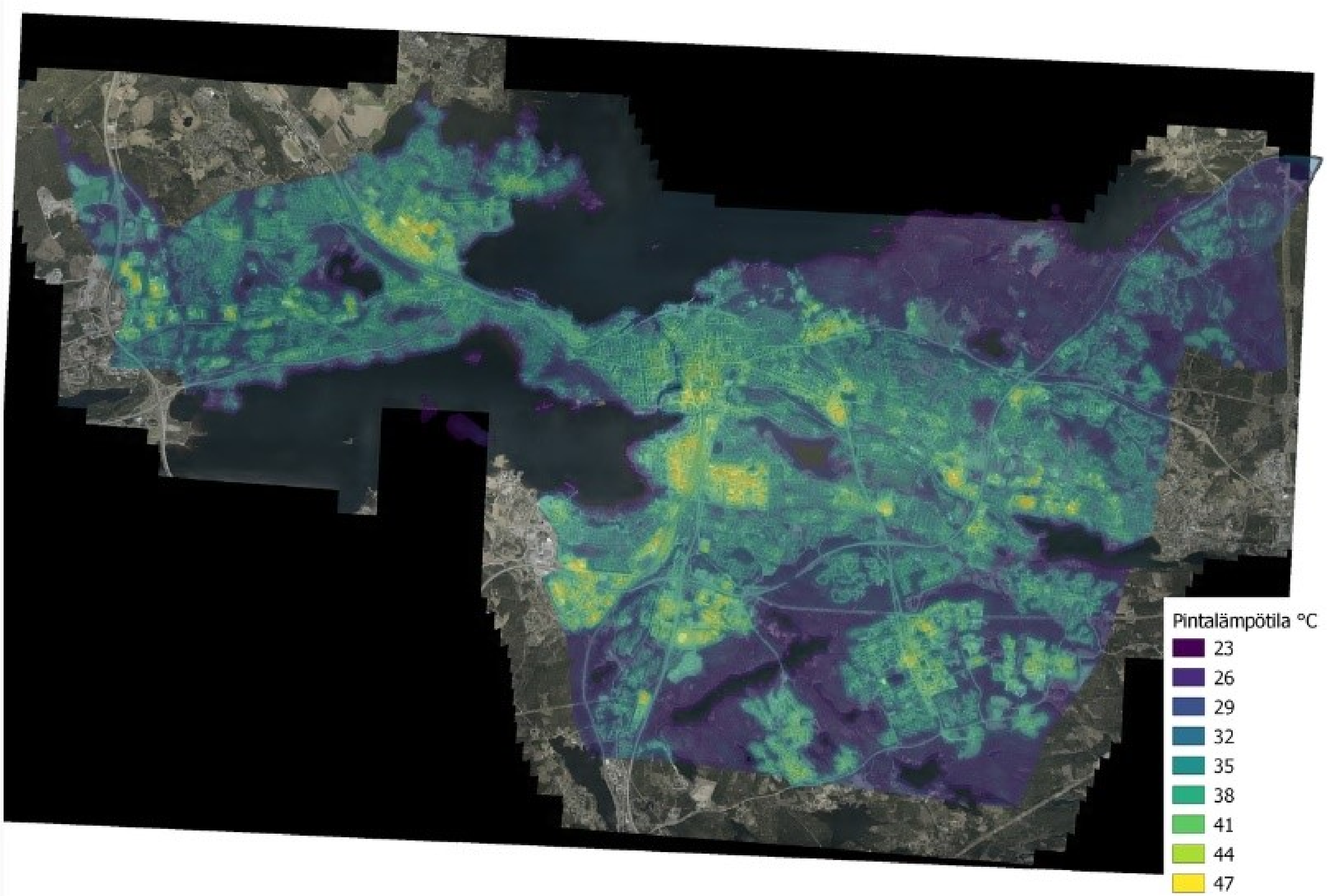


Figure 4. Differences between land surface and air temperatures at Härmälä station. The ground temperature has been 3.4–8.8 °C higher than the air temperature at the time of measurement. (Finnish Meteorological Institute, www a) The station is located between the industrial area and the single-family house area.



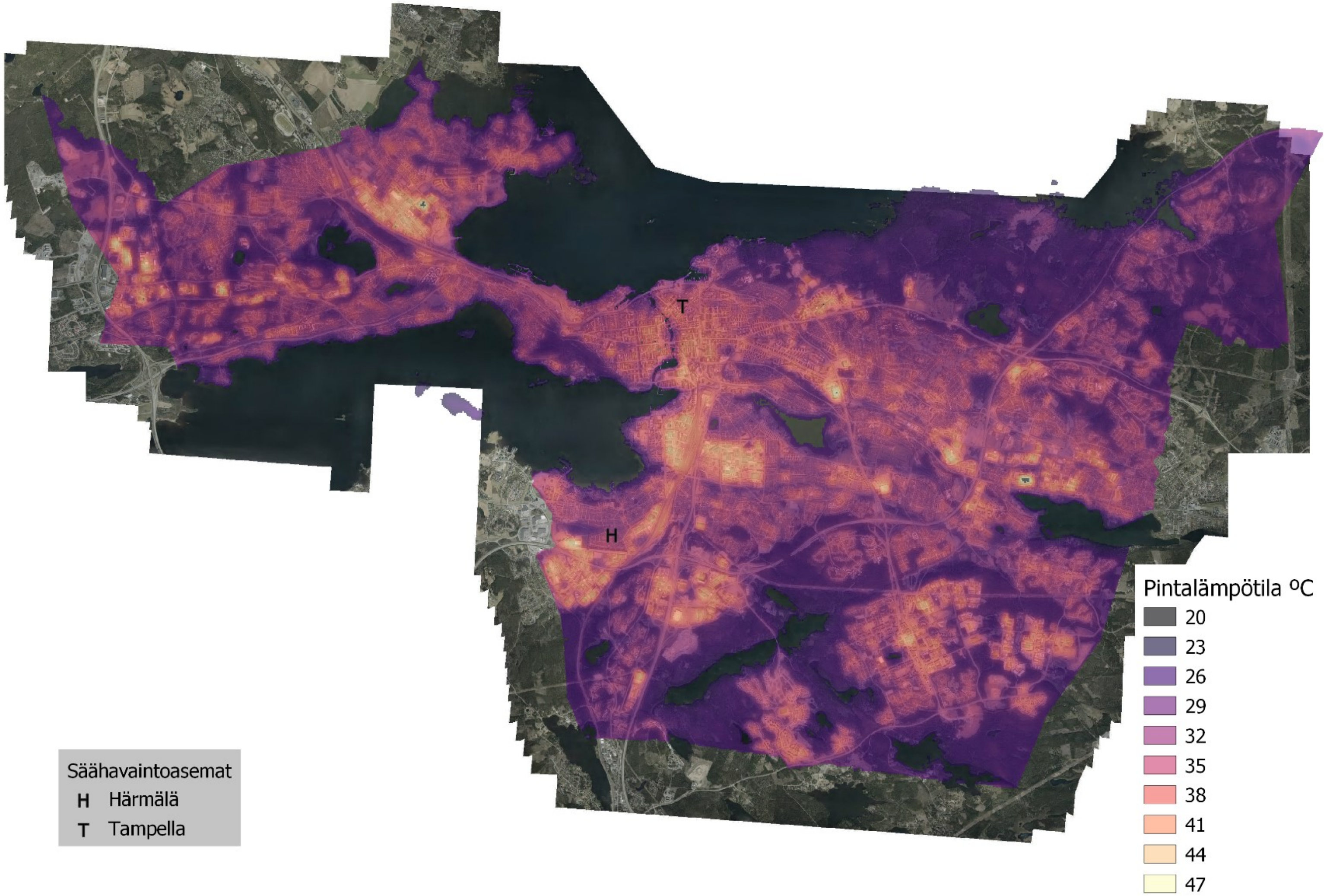
Map 1. Land surface temperature in the central urban area of Tampere on 3 July 2021. Aerial photograph from 2020 in the background.

3.1.2 Composite map

In addition to the single heat wave map produced in the first phase of the survey, a composite map of land surface temperatures was later produced for eight heat waves (map 2). On the composite map, the land surface temperatures follow a very similar spatial distribution to that of a single heat wave (map 1). Temperatures are about 2 degrees Celsius lower on the composite map because some of the periods were less hot.

The composite map of land surface temperatures shows the situation for hot summer days from 2015 to 2021, when the average daily temperature was above +20°C.Among the eight land surface temperature maps (Figure 5), 18 July 2018, 27 July 2018 and 3 July 2021 fall within a period of several days when the daily maximum temperature has reached or exceeded the limit of +25°C (weather data from Härmälä station of the Finnish Meteorological Institute). One date was 14 June 2020, when the average daily temperature was clearly lower than the others, +20°C, and the air temperature in the afternoon was below +24°C. However, the lowest land surface temperatures are not on this map, but on 8 August 2020. Air temperature is not the only factor explaining the heating of the land surface. This could be, for example, variations in cloudiness or temperatures over the previous days.

The heat wave map of 3 July 2021 (map 1) presented at the beginning of the report is among the hottest of the selected dates. The date was preceded by a two-week heat wave. It can be thought to foreshadow more frequent future events as temperatures rise and heat waves become more frequent as a result of climate change (see Section 4.2). Therefore, in this report, the map for 3 July 2021 is used to examine with the phased comprehensive plan maps (section 3.2.2) and to show vulnerabilities (sections 5.1 and 5.2).



Map 2. A composite map of land surface temperatures for eight heat waves in 2015–2018.

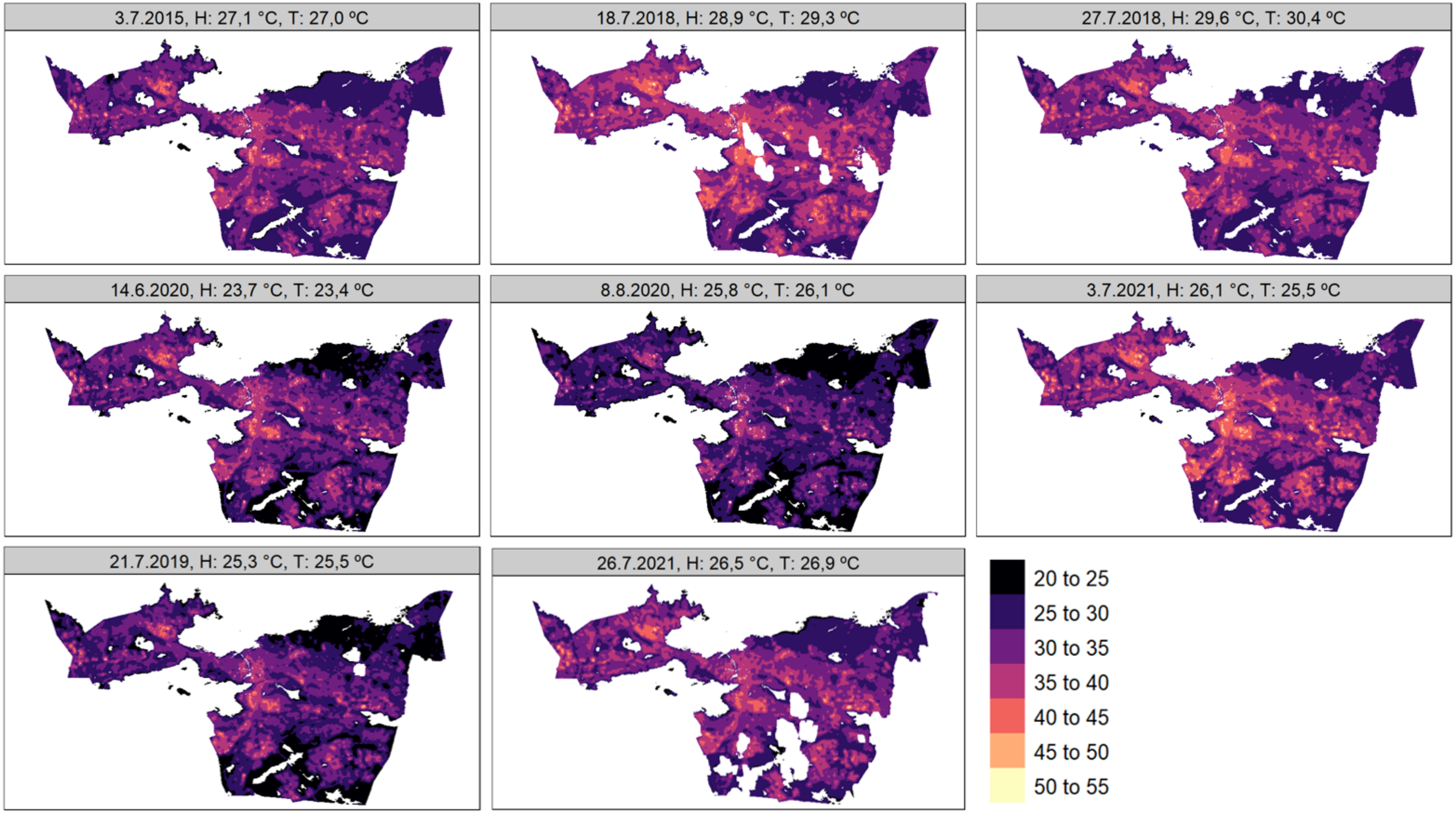


Figure 5. Land surface temperature grid from eight times selected for the combined map. The temperatures in the map header represent the air temperature at the time of the image in the afternoon from the meteorological stations H=Härmälä and T=Tampella of the Finnish Meteorological Institute.

3.1.3 Methods and data used in the survey

The land surface temperature data source used in the survey was the Landsat 8 satellite thermal channel data, which was downloaded from the Remote Sensing Lab download service (http://rslab.gr/downloads_LandsatLST.html). The service calculates the land surface temperature for the selected area at a pixel size of 30 metres and produces a grid that can be downloaded and used almost as it is. The service instructs that NDVI and MODIS are the most appropriate emissivities for the urban structure, of which the higher resolution NDVI was chosen for this survey.

Clouds prevent the measurement, so the data must be selected on a day when the sky is clear as the satellite passes over the target area. In summer 2021, there were three to four measurement results per day in a month.

For a map of one point in time, the survey examined the cloudiness of the different measurement dates and compared the measurement dates with the temperature data from the Finnish Meteorological Institute's Tampella weather station, on the basis of which the date chosen for the heat island map was 3 July 2021. The summer of 2021 was quite warm, with an average and maximum daytime temperature of +24 and +28°C on 3 July. Between 2013 and 2020, the average number of such warm days was less than five, in some years none and in 2018 15. The Tampella weather station has data from 2013 until early 2022. (Finnish Meteorological Institute, www a).

The surface temperature data was selected on a cloud-free day, but there were still small gaps of 1 to 3 pixels in size or width (Figure 6). The gaps were corrected using the QGIS fill nodata tool by calculating the values from a distance of up to 2 pixels, i.e. 60 metres, in place of the missing pixels. Most of the gaps appear to be located in warm spots where the temperature gradient is one directional, so replacing the missing value with an adjacent one does not introduce bias.

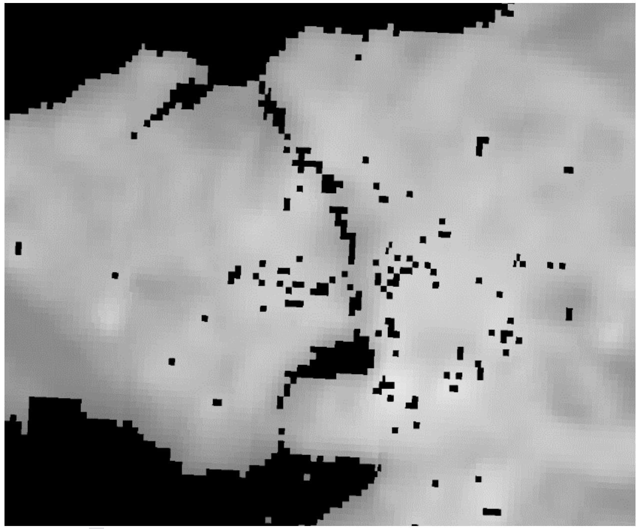


Figure 6: Satellite data gaps.

In the later composite map, eight dates have been selected from the summers 2015–2021 when the daily mean air temperature at the meteorological station Härmälä in Tampere exceeded +20°C and when cloud cover was 15% or less. These days are hotter than the average July temperature of +17.4°C in Tampere between 1991 and 2020 (Appendix 1).

The choice of dates was limited by the availability of Landsat 8 thermal imagery, which is not available for every day. In addition, days with as little clouds as possible were chosen as there are gaps in the surface temperature map for clouds, as explained above. Landsat 8 satellite data was not available at the time of writing for the summer of 2022 from the Remote Sensing Lab download service.

3.2 Heat islands in relation to urban structure and the local comprehensive plan situation of the central urban area

3.2.1 Current situation

The land surface temperatures were compared with the 2020 orthophoto, and from this, observations were made on the relationship of urban structure to warming (map 1). The map used for the analysis was the 3 July 2021 map, which was previously chosen to represe/nt a heat wave.

The analysis shows that the hottest areas in the central urban area of Tampere are the following industrial, manufacturing and retail areas, where buildings are large and street spaces are wide: Nekala, Lielahti, Sarankulma and Lahdesjärvi. Built-up areas are extensive and vegetation is sparse. Individual large buildings (large units) also stand out on the map as hotter than the surroundings in the eastern parts of the central urban area and in Myllypuro. In the city centre, the Ratina shopping centre and the Nokia Arena construction site stand out.

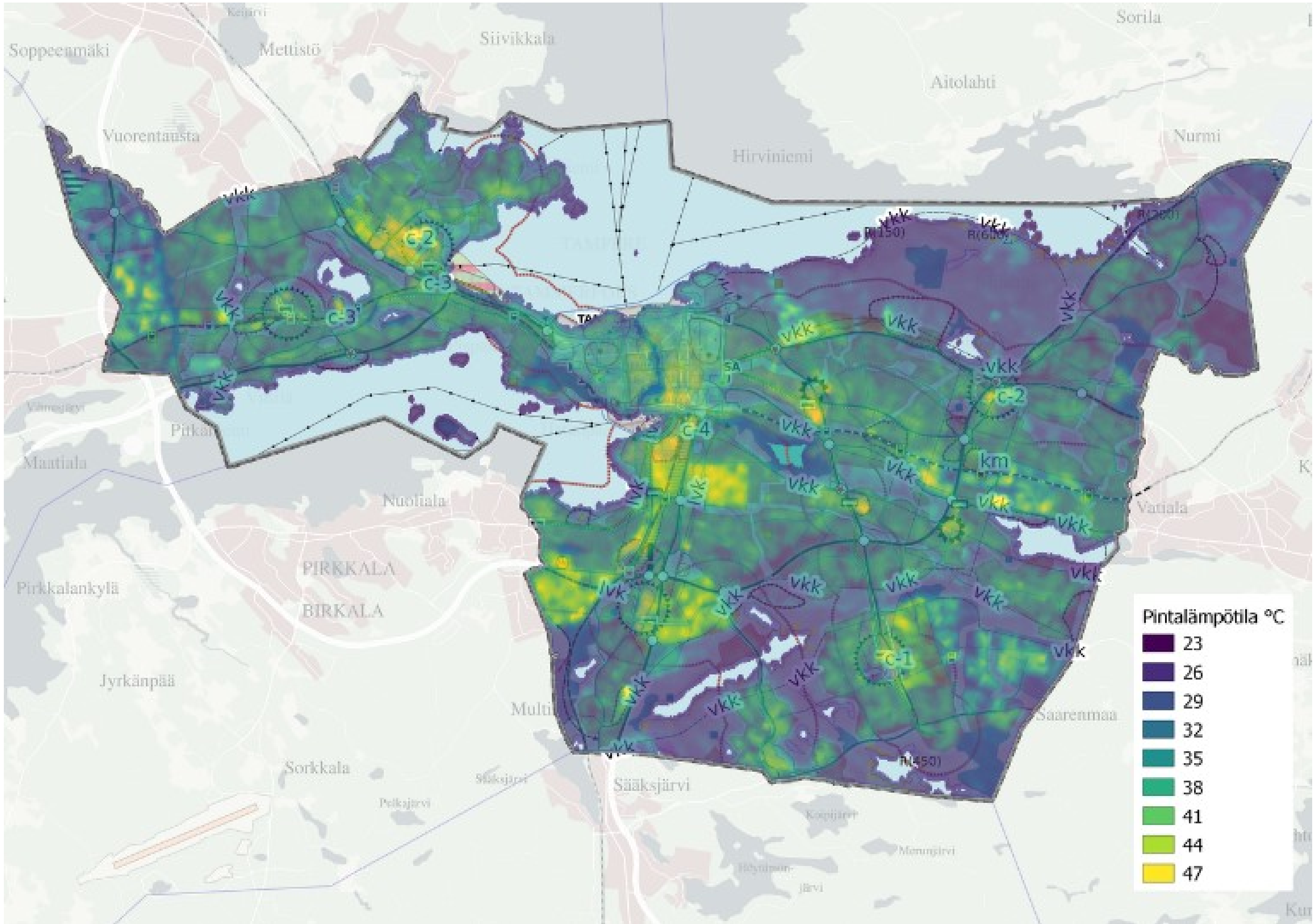
The coolest areas are forested areas and single-family house areas. The densely built city centre is not highlighted on the map. Temperatures in the city centre are likely to be influenced by the location of large water surfaces to the north and south of the city centre. The findings are in line with the literature review on the occurrence of urban heat islands in urban structures presented in chapter 2. The hottest and coolest areas also follow the same type of distribution in the subsequent analysis of the different time points (Figure 5) and in the composite map (Map 2).

The characteristics of urban structure in relation to land surface temperatures are examined in more detail in section 4.1 of this report by combining statistical and spatial data analysis.

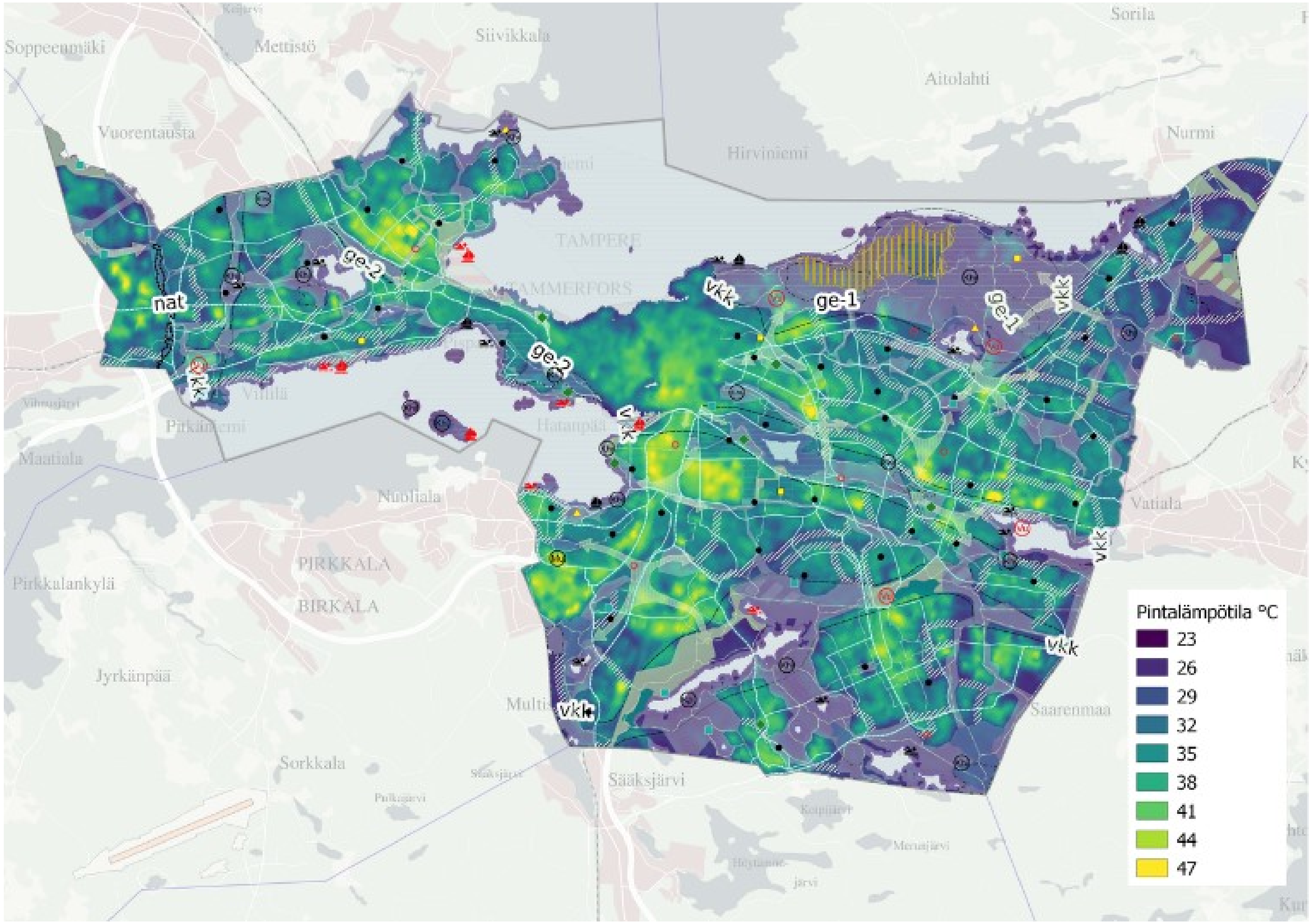
3.2.2 Comprehensive plan situation of the central urban area

On 3 July 2021, the land surface temperature map was also examined on top of the thematic maps 1 (urban structure) and 2 (green environment and leisure services) of the downtown's phased comprehensive plan in council period 2017–2021. It should be noted that the land surface temperature grid shown is the actual situation on the satellite imagery date. For this, therefore, no change in temperatures is seen for planned land use changes or changes in land use after the satellite imagery date. The purpose of the assessment is to identify which areas of the comprehensive plan may need attention to mitigate effects of the urban heat island and prevent heat-related risks.

On the thematic map of urban structure (Map 3 on the next page), existing heat islands are particularly concentrated in the "mixed service and employment area or location" and to some extent in centre areas. The size of large units is taken into account in the comprehensive plan regulations, but the importance of adding green areas to the microclimate could also be taken into account, as a one-sided low and wide street space increases the intensity of heat (e.g. Ward et al. 2016, Wang et al. 2016). In the area covered by the strategic sub-area comprehensive plan of the city centre, relatively high land surface temperatures are observed, especially around the railway station and in the Ratina area. In the plan, they are a central business area.



Map 3. Land surface temperature grid and thematic map of the urban structure in the comprehensive plan of the central urban area.



Map 4. Surface temperature grid and the thematic map of green environment and leisure facilities for the comprehesive plan of the inner city

An examination of the green environment thematic map (Map 4 on the previous page) reveals the overlap of heat islands with "indicative green network connectivity areas" and the scarcity of neighbourhood parks in hot areas. The latter is probably explained by the fact that parks primarily serve residential areas. In the future, indicative green network connection zones could play a significant role in relieving the urban heat island effect in areas with mixed services and work places. The challenge, however, is that they are located, for example, at large intersections. The map describing the green environment does not contain any plan markings for the hottest areas. Depending on the type of area (industrial/residential), they are served by network of recreational and cycling routes as line shape map features. The risk areas and vulnerabilities of urban nature are described in section 5.2.

4 Factors intensifying the urban heat island effect in Tampere

4.1 Urban structure analysis

Based on the observations described above, the urban heat island is most pronounced in the central urban area of Tampere in areas with large buildings, a lot of road or street surface and sparse vegetation. This corresponds to the perception in the literature review of factors that intensify the urban heat island.

To refine the visual analysis, a statistical analysis of the following urban structure factors in relation to land surface heat was carried out:

- Number of trees (Tampere's land cover data)
- Other open vegetation & agricultural fields (Tampere's land cover data)
- Roads & other impermeable surface (Tampere's land cover data)
- Area efficiency of construction (floor area divided by area of the square, "buildings as points" data)

The factors have been selected based on the literature review. It is possible, however, that other factors that strengthen or weaken the urban heat island are not considered. For example, air conditioning in buildings and traffic heat the air. Tall buildings shade and thus protect the street space from the sun's rays. The number of water bodies in Tampere is likely to cool the climate. The reason for excluding the water body from the statistical analysis is explained below.

The central urban area was divided into 250 x 250-metre squares and the average land surface temperature of each square was used, calculated from the grid values of the land surface temperature map of 3 July 2021.

Land cover data was attached to the 250 x 250-metre squares to the 200 m buffer calculated from the centre of the square in order to create sliding boundaries instead of precise boundaries that are arbitrary to the effect. At the same time, the area of land cover to be counted on the grid will at least double to around 125 thousand square metres. The connection was implemented with a simple intersects connection.

Grids covering water bodies larger than 50,000 m² have been excluded from the analysis, as the land surface temperature value in water bodies is 0 and the land cover used in the analysis is not present, distorting the model explaining the average temperature and the temperature in the grid. Grids with no analysable land surface data having a floor area of 2,500 m² or more were also excluded from the analysis, as grids with low data coverage may introduce bias in the modelling (such as cool grids with no land surface data).

From the land cover data, roads and other impermeable areas, other low vegetation and fields were combined because the ratio between land cover and temperature was assumed to be very similar. It is also worth noting that not all of Tampere's land cover data was available from the whole north-eastern part of the downtown.

Figure 7 shows the ratio between different land cover areas and land surface temperature. The area has been converted using the square root for the figure to make the shape of the link easier to interpret and to avoid the y-axis being stretched by huge values. The figure shows that different land cover types have fairly clear links with temperature, but the link with low vegetation remains tentatively unclear. When drawing conclusions, it is good to note that land covers are a measure of each other, as often the built area implies impermeable areas and the built area combined with the impermeable areas excludes the area of trees and vegetation.

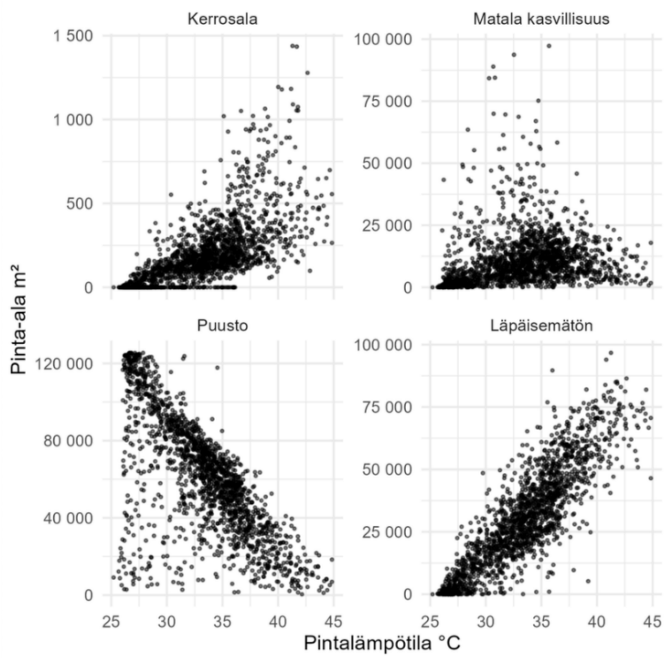


Figure 7. The ratio of land cover to land surface temperature. The floor area is square-rooted.

Regression analyses were carried out to perform the analysis. In the modelling, the average land surface temperature of the grid was used and land cover areas were used as explanatory factors. The first step in the analysis was to try a linear regression model, but the model diagnostics showed that the relationships between land cover and temperature are not fully linear. The dispersion is large in places. Because of the non-linear statistical relationships, the analysis was carried out with a generalised additive model, where land cover areas were fitted to the model with regression splines to deal flexibly with variation in the explanatory variables. The distribution of the response variable variation was defined as the normal distribution.

In a linear regression, the explanatory variables should not be too correlated with each other, which is partly unavoidable in land cover data (buildings occur with impermeable surfaces reducing the wood area), but in an additive model the explanatory variables should not be dependent on each other in such a way that a smooth curve (concurvity) can be fitted between them. Interdependence between the explanators was found to the extent that floor area/area efficiency was excluded from the model.

The final model takes the form

$$\gamma = \beta_0 + f\left(x_{impermeable} x_{tree\ area}\right) + f\left(x_{other\ vegetation}\right) + \varepsilon$$

where impermeable surface (roads and other impermeables) interacts with the tree area, and model also includes other low vegetation, including fields, as an explanatory variable. The interaction controls the interdependence between the impermeable and the tree surface area.

The generalised additive model cannot report the regression coefficients typical of linear regression, such as the temperature increase per unit area of land cover, because the slope coefficient varies drastically. The easiest way to interpret the model results is through forecasts.

Figure 8 shows the surface temperature forecast by impermeability and tree area. The figure shows that the temperature increases dramatically according to the impermeable area, but the temperature decreases differently depending on the area of the trees, depending on the amount of area that is impermeable. Combinations of areas not found in the observations have been removed from the figure.

Figure 9 shows the relationship between surface temperature and low vegetation in the case of 10,000 m² of both impermeable surface and tree cover. For this reason, the curve on the y-axis is slightly below 35 degrees. The figure shows that the average temperature decreases slightly as the amount of low vegetation increases. Very large amounts of low vegetation are very rare, so the confidence interval of the mean increases. However, there is a moderate amount of dispersion, as can be seen from the points shown in the figure.

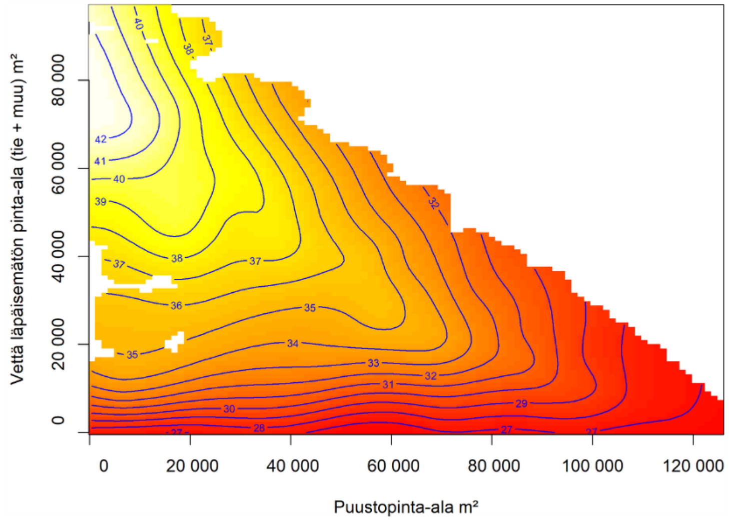


Figure 8. Surface temperature forecast based on the area of the trees and impermeable area.

Overall, based on the model metrics, these explanators are able to predict the surface temperature with almost 90% accuracy (when compared to the observed). The impermeable surface, together with the surface area of trees, is a very strong predictor of the land surface temperature. In particular, an impermeable surface, a road or other surface such as asphalt, explains the increased temperatures. Even in a small area of trees, the temperature remains low if there is little impermeable area. If the impermeable surface area is large, the tree area can have a multi-degree effect on the average land surface temperature of the area.

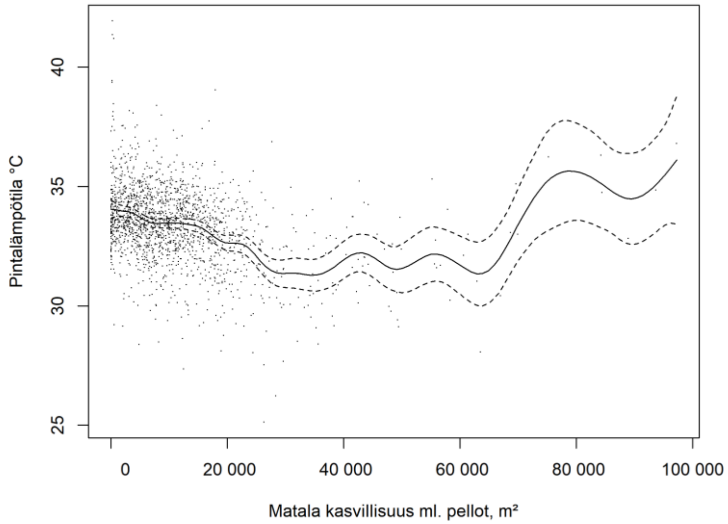


Figure 9 shows the relationship between surface temperature and low vegetation in the case of 10,000 m² of both impermeable surface and tree cover.

4.2 Impact of climate change on temperatures

The data used in this survey for one day of surface temperatures is from a day (3 July 2021) when the average daily temperature at the Tampella station was +24°C.

The prevalence of such very hot days as the climate warms was estimated using data from WeatherShift (www.weathershift.com). WeatherShift is a service developed by Arup North America Ltd and Argos Analytics LLC that uses global climate models to estimate climate change based on a range of Intergovernmental Panel on Climate Change (IPCC) scenarios.

The figure below (Figure 10) shows the development of the meteorological type year in the coming decades. The values shown in the figure represent the highest temperature of each day. The present situation is based on the Tampere climate description file saved on the climate.onebuilding.org page (FIN_TR_Tampere.Satakunnankatu.027440_TMYx.2007-2021.epw). When this data is compared with the weather data for Tampere in 2021, it can be seen that +24 degrees Celsius is exceeded roughly as often in the average daily temperatures for 2021 as it is exceeded in the maximum temperatures of the type year used. The difference is explained by global warming over the past 14 years.

On the basis of Figure 10, it can be concluded that the number of very hot days (+22.2°C in this graph) will increase by approx. 64% by 2035 and approx. 80% by 2090. At the end of the century, it is estimated that there will be 50 such days in Tampere every year.

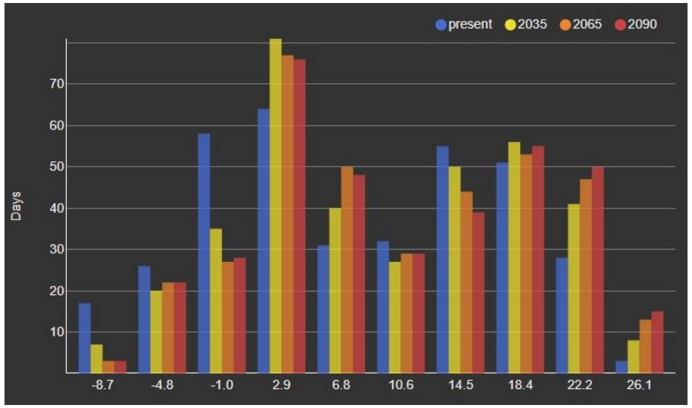


Figure 10. Global warming in Tampere in the coming decades. "Present" means the current situation.

The future scenarios used in the figure are based on the IPCC Fifth Assessment Report and the Representative Concentration Pathways (RCP) scenario 4.5. This scenario describes a situation in which climate change is moderately mitigated. The data used represents the average warming in scenario 4.5. The scenarios contain uncertainty, which is accounted for by each scenario's internal estimate of the probability of warming.

Climate change may also affect the urban heat island effect indirectly, as people change their behaviour in response to climate change. Possible impacts include at least the proliferation of air-source heat pumps and their use for cooling.

5 Vulnerabilities in heat waves in Tampere

The 3 July 2021 ground temperature map (Map 1) was used as the base map for the vulnerability analyses, as it describes a hotter situation than the combined temperature map. This gives a better understanding of the potential heat risk.

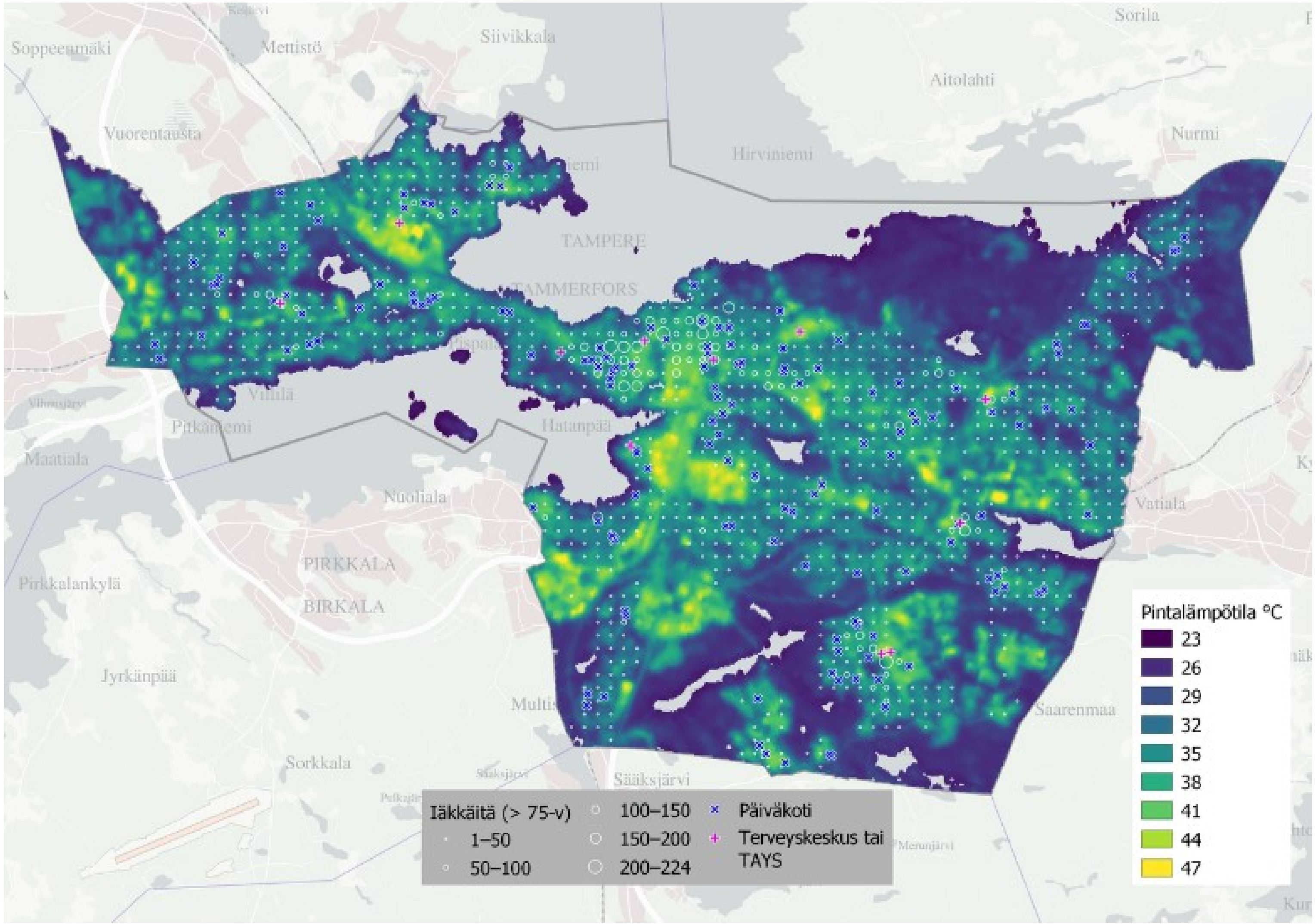
5.1 Social vulnerability

5.1.1 Population and building stock

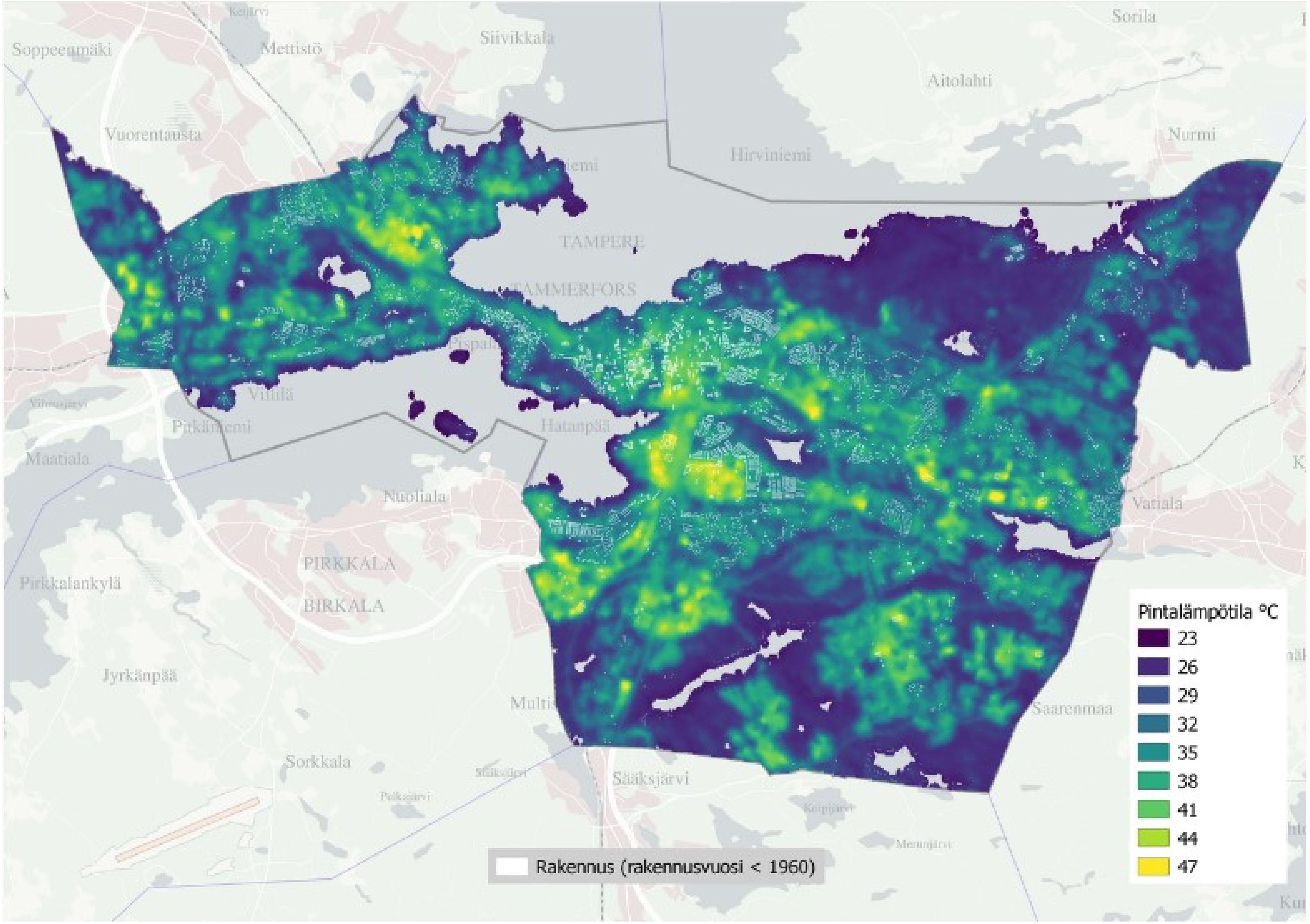
Age increases vulnerability to heat and increases the risk of illness and death, for example. The map on the following page (Map 5) shows the location of the elderly population, i.e. exposure to heat islands in a situation in accordance with 3 July 2021. The size of the white circle describes the number of people over 75 years of age living in each 250 x 250 square according to the 2021 statistics. Most of the elderly population is located in areas with hot surface temperatures in Hervanta, around Linnainmaa health care centre and in the centre of Tampere.

Map 5 also shows day-care centres from the Tampere service map material and the Suomi.fi service information resource interface as well as municipal health stations and Tampere University Hospital (TAYS). Not all day-care centres and health stations are included. Almost all of the health care centres shown are located in areas where the surface temperature of the ground is at or above the high end of 40 degrees Celsius at the time of the LST photography. The day-care centres are located fairly evenly throughout the city. If not considering the hottest regional centres, they are mainly located between heat islands and cooler areas.

The material does not contain information on, for example, the person's state of health or the building stock and form of housing, or the possibilities of adapting to heat by improving housing comfort. The above factors affect vulnerability and adaptability within the older population. A composite indicator has been developed for assessing social vulnerability (Kazmierczak & Kankaanpää, 2016).



Map 5. The surface temperature grid on 3 July 2021 and the population aged over 75, day-care centres and health stations.



Map 6. Land surface temperature grid on 3 July 2021 and buildings built before the 1960s.

The building stock was also studied in this survey. It can be assumed that buildings built before the 1960s are particularly hot. Before the 1960s, insulating the frame of an apartment building was relatively rare (Neuvonen 2006). In uninsulated, massive structures, solar heat moves from the façade to the interior more easily than in the insulated structure.

The building stock built before the 1960s presented on map 6 on the previous page is mainly single-family house areas. There are older apartment blocks in the city centre in areas that are clearly warmer than the surrounding area. In addition, some industrial buildings are in particularly hot spots. The map does not take into account the fact that some buildings have been insulated later. The temperature of the apartment is also affected by whether the apartment is on the shadow side or whether the resident can afford air conditioning. In addition, it should be remembered that the temperature map describes the land surface temperature, not the temperature of the air outdoors or in buildings.

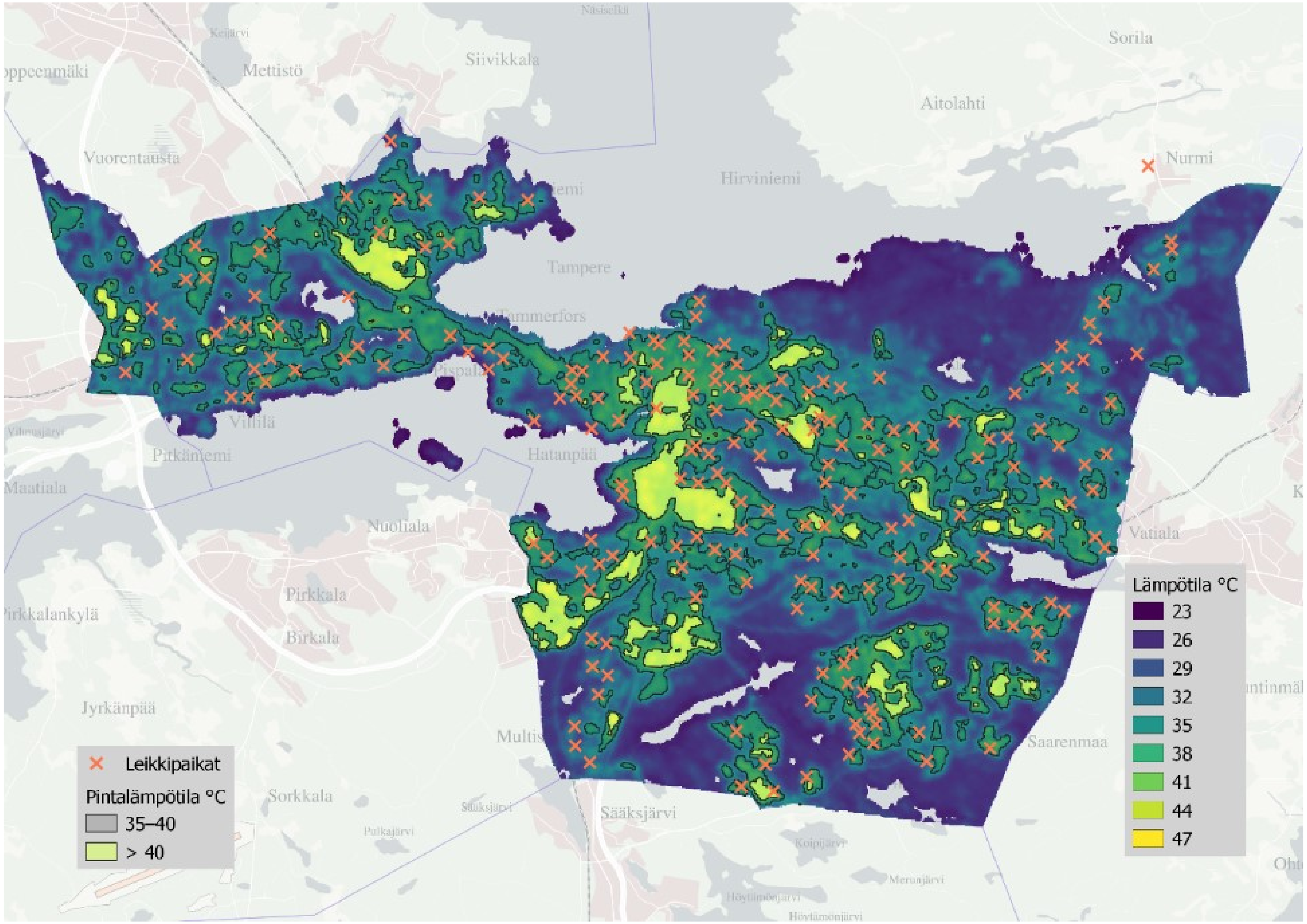
5.1.2 Playgrounds

The analysis of vulnerabilities also examined the location of playgrounds in the central urban area in relation to the land surface temperature. The data used were playgrounds located in parks or other public areas with no parks, managed by the Urban Environment Service Area, as retrieved from the open interface of the City of Tampere on 12 October 2022. Playgrounds are often in outdoors use during the day and young children are vulnerable to heat stress (see section 2.3.1).

The heat risk of playgrounds located in the central urban area of Tampere was surveyed on the heat wave land surface temperature map (3 July 2021) (Map 7). Many playgrounds are located in the hot zone of +35–40°C, but not in areas where the ground temperature rose above +40°C. Further away from the city centre, playgrounds are also located in cooler surface temperature zones. Playgrounds are often located on the edge of residential areas, connected to green areas. Special attention should be paid to playgrounds in the city centre area and, for example, courtyards where temperatures can become hotter. The number of users can be higher in the area of a more dense urban structure.

The land surface temperature is not indicative of the air temperature or the shade of trees and wind conditions in the playground, but playgrounds are often sparsely wooded in areas with play equipment and playgrounds. The more comprehensive land surface temperature composite map of the current situation places playgrounds on the edge and outside of the hot zone.

The challenge with Finland's climate is that the adaptation needs for microclimates in winter and summer are very different. From the point of view of preparing for summer heat waves, it would be a good idea to place playgrounds at the edge of larger green areas and in places where some air flows in the summer. In the middle of a dense block structure in connection with playgrounds, it would be a good idea to plan shadowing trees or, for example, water elements that can alleviate heat stress. At the comprehensive and local comprehensive plan level, easy routes to cooler places should be taken into account. In the most densely built areas, playgrounds as well as green areas can also function as cooler areas when compared to the rest of the environment.



Map 7. Land surface temperature grid on 3 July 2021 and playgrounds in parks and public areas on 12 October 2022. Warm zones highlighted.

5.2 Blue-green structure and vulnerability of urban nature

Urban nature is a driver of climate change adaptation, but also vulnerable in a changing climate (Kotakorpi 2020). Previous surveys in Tampere have identified the importance of blue-green infrastructure in preparing for climate risks (Comprehensive plan of Tampere 2020, Sitowise 2021). Minor waters and spruce-dominated forests are part of blue-green structure and were found to be vulnerable to heat and drought.

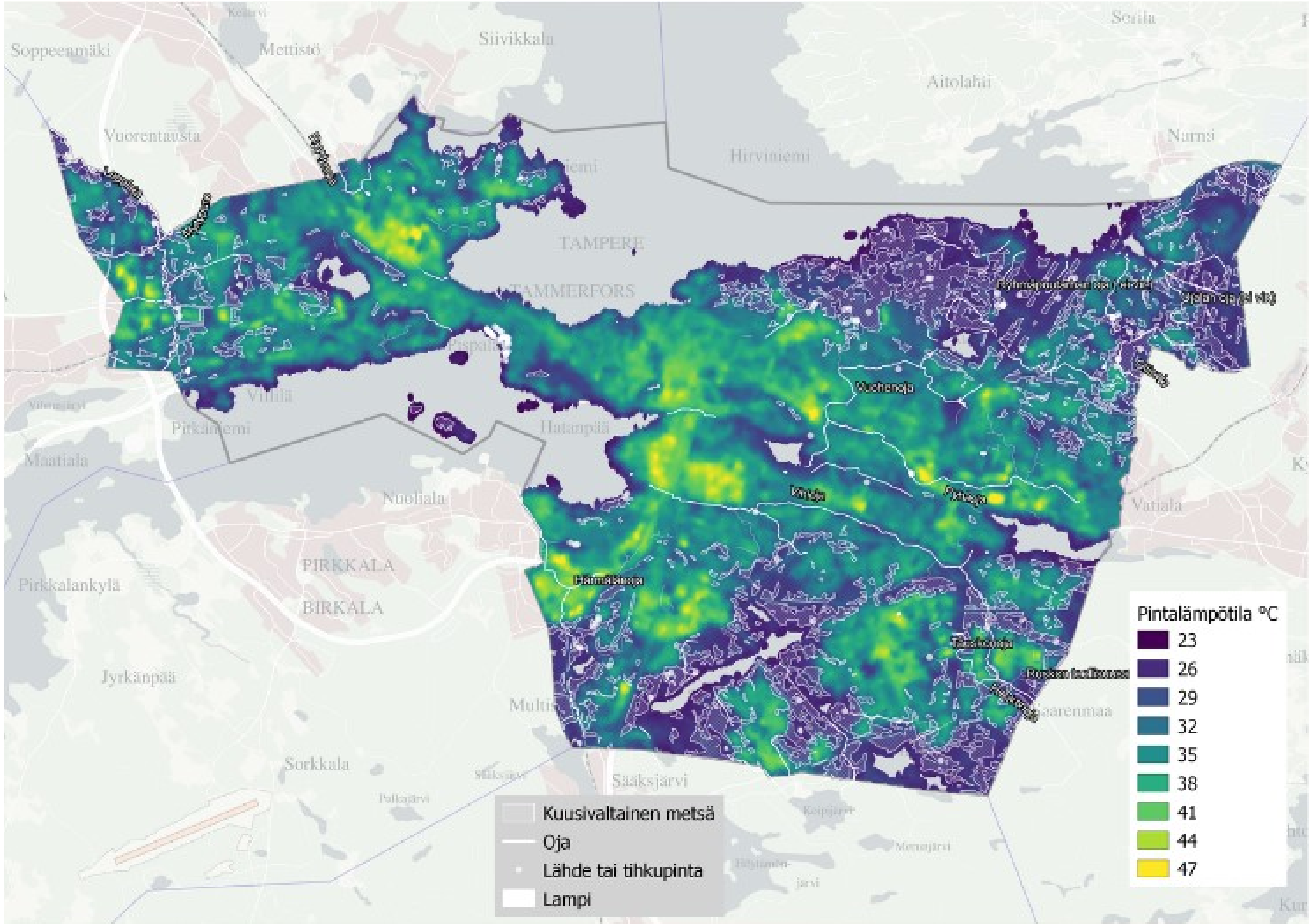
In addition to heat and drought, spruces are also vulnerable to floods, storm damage and pests. There are also plenty of spruces in the forest areas of Tampere. Spruce, for example, is an important habitat shelter and nesting tree, but also a sheltering passage tree for the endangered flying squirrel, which is why it is important to nurture spruce trees. Spruce is an important species for Finnish biodiversity. In spruce-dominated areas, ecological connections may be at risk of deterioration or breakage in the event of strong storms, and as the frost cycle becomes shorter or disappears altogether. For this reason, it may also be justified to designate alternative connection locations in local detailed planning and pay particular attention to the quality of connections, such as multi-species trees.

Minor waters, on the other hand, may dry late in spring or summer during long heat waves and drought periods. The vegetation and biota of streams and small ponds may therefore be at risk of disappearing if they are unable to move to better habitats. Even if small water bodies are not threatened by drought, rising water temperatures are harmful to many aquatic organisms, fish, amphibians and reptiles. It can also cause an increase in aquatic vegetation, which in turn can reduce flow capacity and increase flood risk.

Map 8 shows the spruce-dominated forests, minor waters and ditches overlapping the land surface temperature grid of 3 July 2021. Of the urban water bodies, the Härmälänoja, the central parts of the Pyhäoja and the lower reaches of the Vihioja along Lahdenperänkatu pass through particularly hot areas. In addition, sites vulnerable to heat may include Tauskonoja on the side of the Rusko industrial area and a drainage ditch from Lake Iidesjärvi to Lake Pyhäjärvi.

The groundwater bodies in the central urban area of Tampere and their formation area do not appear to have the hottest land surfaces, but the effect of rising land surface temperatures can also extend to groundwater (Brozovsky et al. 2021).

The spruce-dominated forests are mainly located in green areas that are cooler than the built urban environment. The spruces located in the middle of the urban structure are likely to be individual or small groups, and the survey on this scale does not comment on them. The protection of spruce-dominated forests and their edge zones and water balance should be taken into account in the planning of land use change areas.



Map 8. Land surface temperature grid of 3 July 2021 and small water bodies and spruce-dominated forests.

5.2.1 Risk sites of minor waters

The data on minor waters used in sub-project 1 has been supplemented with more recent data prepared by the City of Tampere, which distinguishes streambed sections in their natural state and the concentrations of nature values of minor waters. Minor waters are shown on the heat wave land surface temperature map (3 July 2021) (Map 9).

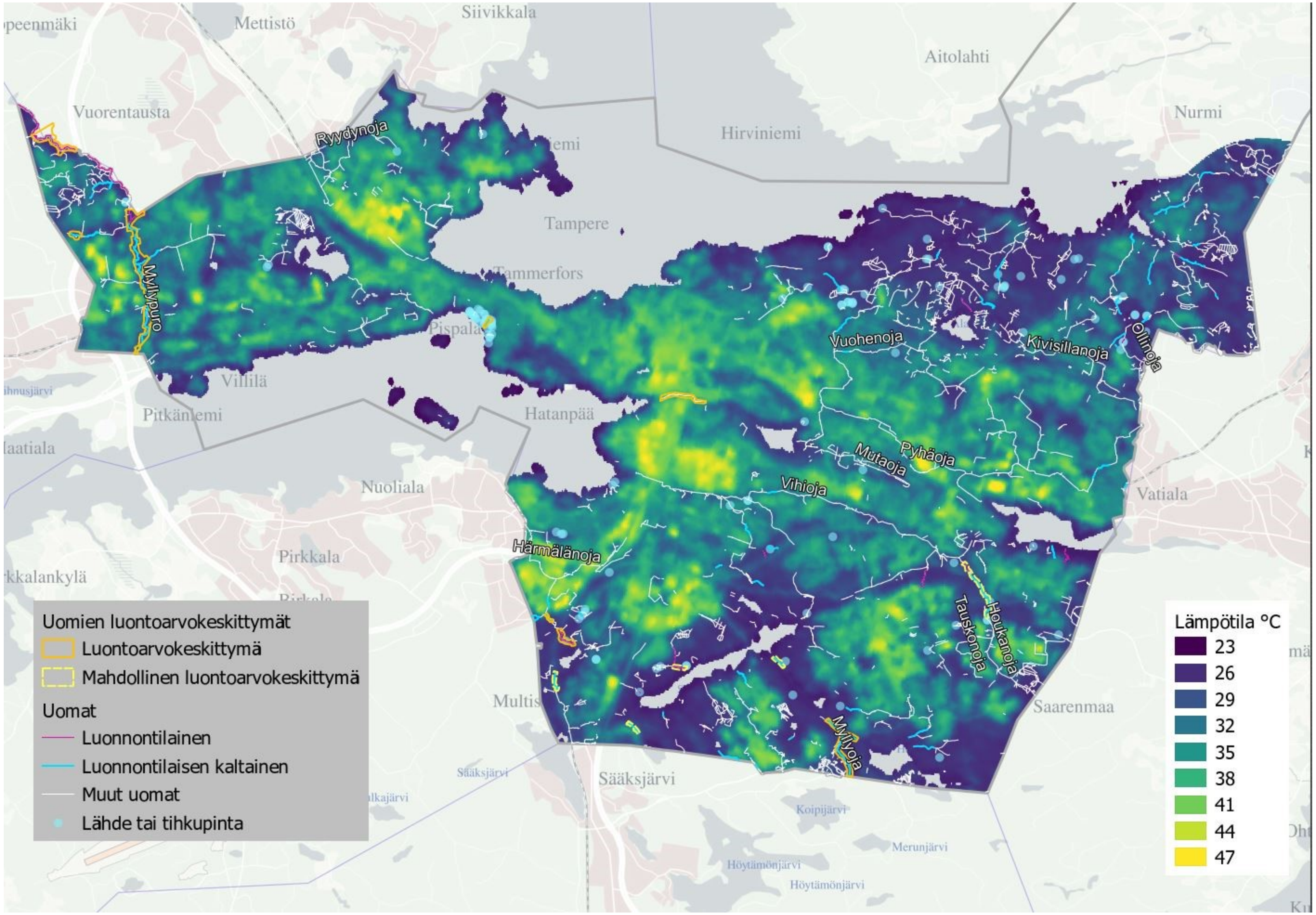
The main network of watercourses, especially springs, is located in the cooler green areas and forests on the outskirts of the central urban area. The survey identified Härmälänoja, the middle parts of Pyhäoja and the lower reaches of Vihioja along Lahdenperänkatu as potential risk areas that pass through particularly hot areas. In addition, Tauskonoja on the outskirts of the Rusko industrial area and the drainage ditch from Iidesjärvi to Pyhäjärvi, which also contains a concentration of natural values in the network of watercourses, were identified as heat-sensitive sites.

The nature value clusters of streambeds and the areas in the most natural state are also mainly located on the edges of the central urban area in green areas. The common drainage part to Vihioja of Houkanoja and Tauskonoja emerges from watercourses in natural state, from watercourses in natural like state and from concentration of natural values. Their waters come through the industrial area of Rusko, where the ditch runs in a fairly open, heat-prone environment. The warming of the waters upstream may affect the status of the waters in the natural value cluster.

The Myllypuro environment is already heavily built up, and in order to preserve its ecological values, attention must be paid to maintaining the coolness and shade of the stream environment. In Myllypuro, this means preserving trees in practice. Härmälänoja also flows in a narrow space in the middle of hot areas, and the trees that shade it are a narrow strip that could be developed. If trees are felled or trees die along streambeds as a result of heat or other hazards, it also affects the ecological status of waters in the streambed and, for example, the water temperature, weakening the living conditions of water species.

With regard to the natural values of minor waters, it can be considered whether they can be "moved" or developed elsewhere in Tampere area – whether something irreplaceable will be lost if the natural values of streambeds and the status of the waters would be compromised due to, for example, warming.

Land-use change areas could be identified in the comprehensive and local comprehensive planning process where construction in the vicinity could have potential impacts on water status (evaporation, ecological and chemical changes) due to warming. Changes can be partly avoided by reserving green areas as well as shading trees along waterways and upstream.



Map 9. Minor waters on the surface temperature map of 3 July 2021.

6 Especially warm zones and access to cool locations

One of the aims of the work was to define the areas in which the urban heat island is emphasised in the central urban area of Tampere and may become a particular risk. This way, for example, it is possible to prioritise the planning of relieving the urban heat island effect and preparing for heat risks.

6.1 Method and delimitation

Finding a boundary is not straightforward, as science defines a heat island as an area warmer than its surroundings (Section 2.1). It depends on geography, seasons, etc., whether the difference with the rest of the environment is, for example, 2 or 10 degrees Celsius. There are a number of criteria for defining particularly hot areas, and it would be useful to consider a number of factors. The planning of risk preparedness, on the other hand, should also take into account vulnerabilities, the specification of which is a separate work phase.

In this report, the topic has been approached through the limit value for land surface temperature. The distribution of surface temperatures, the graininess of the city and the locations of the population in different temperatures was selected as a limit value of +35°C. This value has also been used in Stockholm (Wiborn 2022) as an indicator of the specific 'hotspot' (see section 2.5.1) and has been vectorised into 'thermal curves'.

On the temperature map of 3 July 2021 (Map 1), the land surface temperature varies from +23°C to +47°C. +35°C is halfway up the scale, so above it was hotter than average on the selected day. However, there are also residential areas in the central urban area where the surface temperature of the land was below +35°C. Thus, the selected restriction will not result in all residential areas of the central urban area being included in the above +35°C zone.

The distribution of population size in relation to land surface temperatures was also examined as a preliminary. Figure 11 indicates that approximately one third of the population lives in areas where the land surface temperature is below +35°C. The majority of the population lives in areas where the temperature is over it. In areas with land surface temperatures above +40 degrees Celsius, the number of inhabitants is considerably low. This is probably due to the fact that the hottest places are, for example, industrial areas and large commercial units. For people over 75 years of age, the distribution follows the population as a whole.

From the perspective of the urban heat island, Map 10 highlights the areas where the land surface temperature was +35-40°C and areas where the surface temperature of the soil exceeded +40°C, on 3 July 2021. Their extent can be considered to reflect the situation of hot days becoming more common in the future. However, it should be noted that as the urban structure changes, hot areas may then be located elsewhere. The warm zones map also shows residential buildings (Map 11) and employment buildings (Map 12).

The warm zones extracted from the composite map of land surface temperatures, i.e. +35-40°C and above +40°C zones, at several points in time (Map 13), are smaller than those shown on the 3 July 2021 map. This is because the temperatures of the composite map are approximately 2°C lower than on the map of 3 July 2021. This can be considered to depict typical warm summer days in the current situation. Thus, compared to a single heat wave event map, the smaller zones in the composite map indicate the areas that are first and most likely to be exposed to heat.

This is a presentation of areas of particular concern as heat islands, based on the land surface temperature. The map is not a forecast of the future, but it is worth remembering that the number of hot days is expected to increase. The criteria for the selected limit value of + 35°C are described above, but its criteria should be deepened in the future, as numerous factors affect microclimates. The land surface temperature does not indicate air temperature, experienced thermal comfort or indoor temperature in buildings.

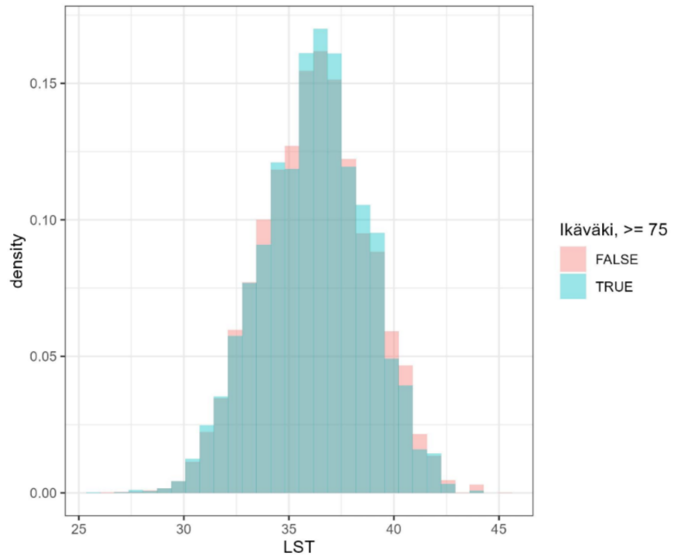
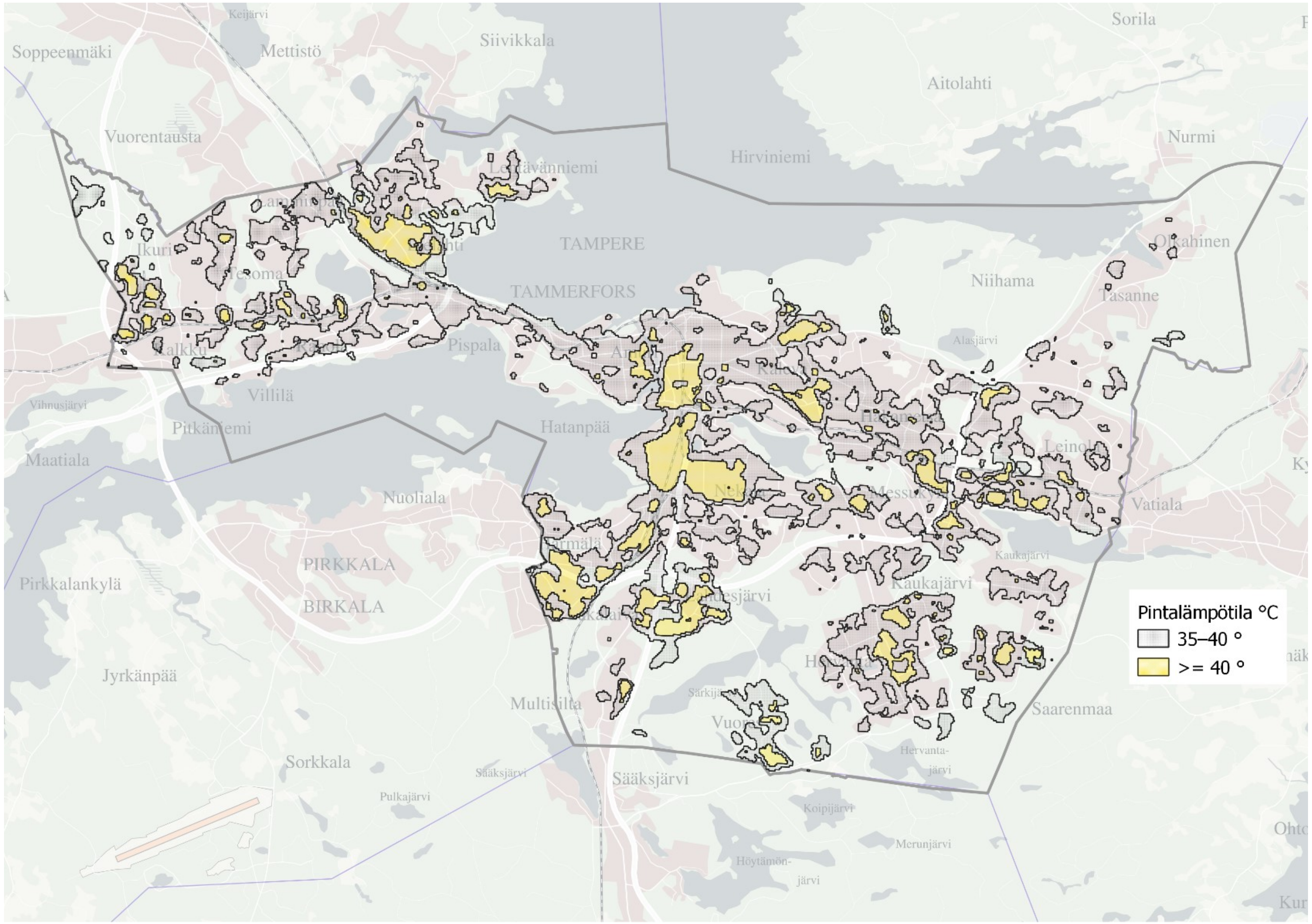
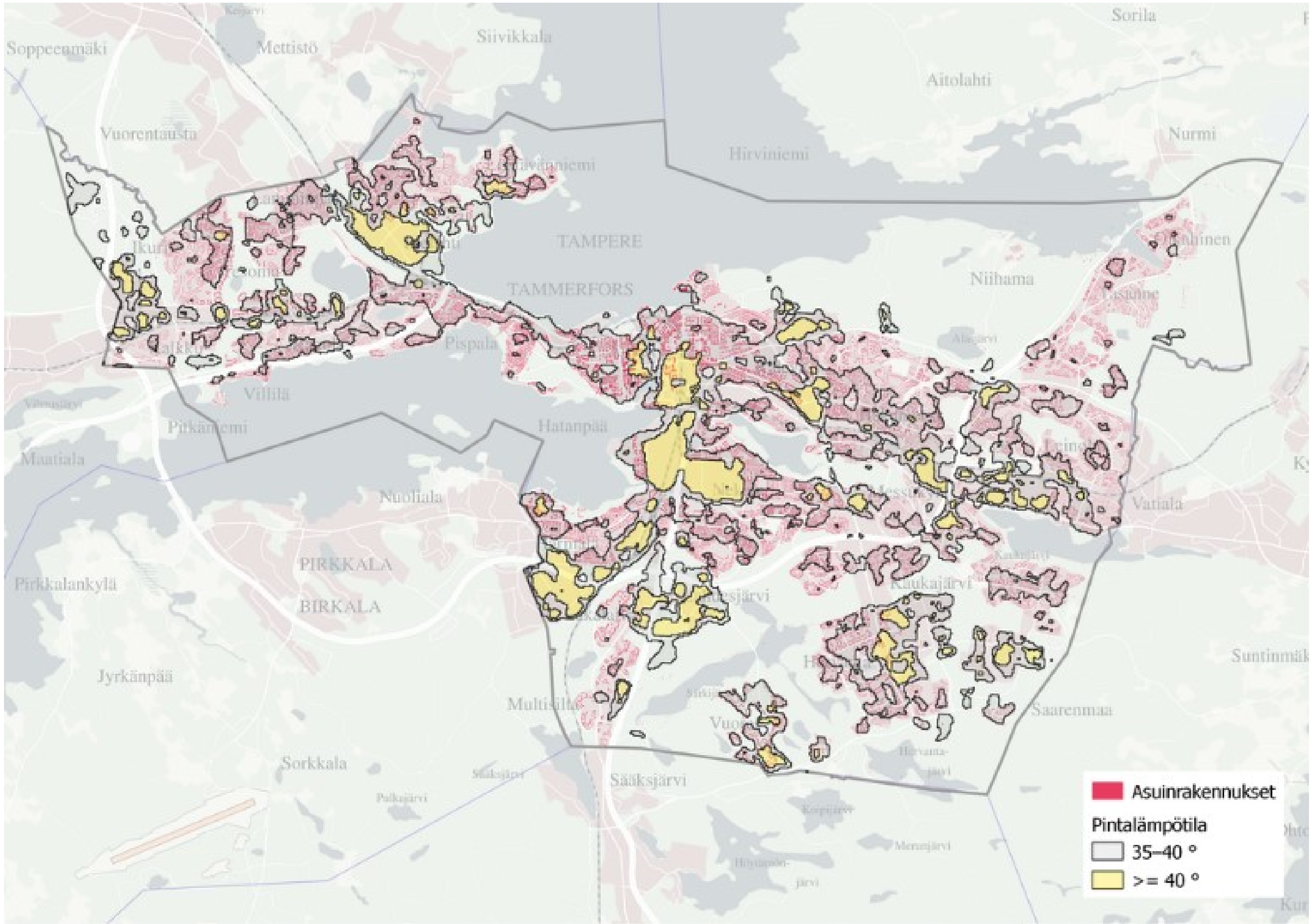


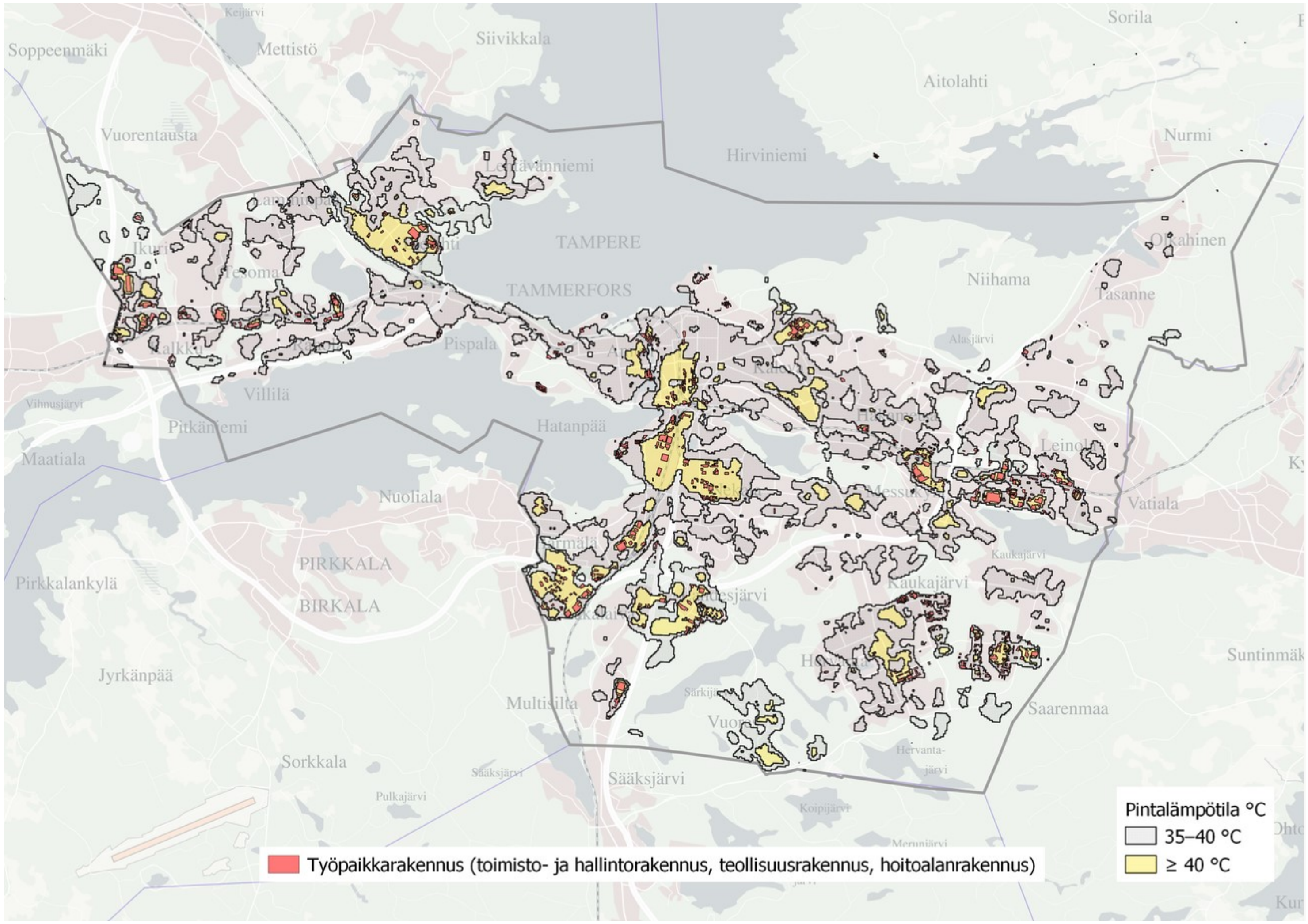
Figure 11. Distribution of the entire population of the central urban area of Tampere in relation to the land surface temperatures. In the histogram, the proportion of the population aged over 75 is shown in blue (true) and the proportion of the rest of the population in red (false) per different land surface temperatures. There are no major differences between the population segments in this respect



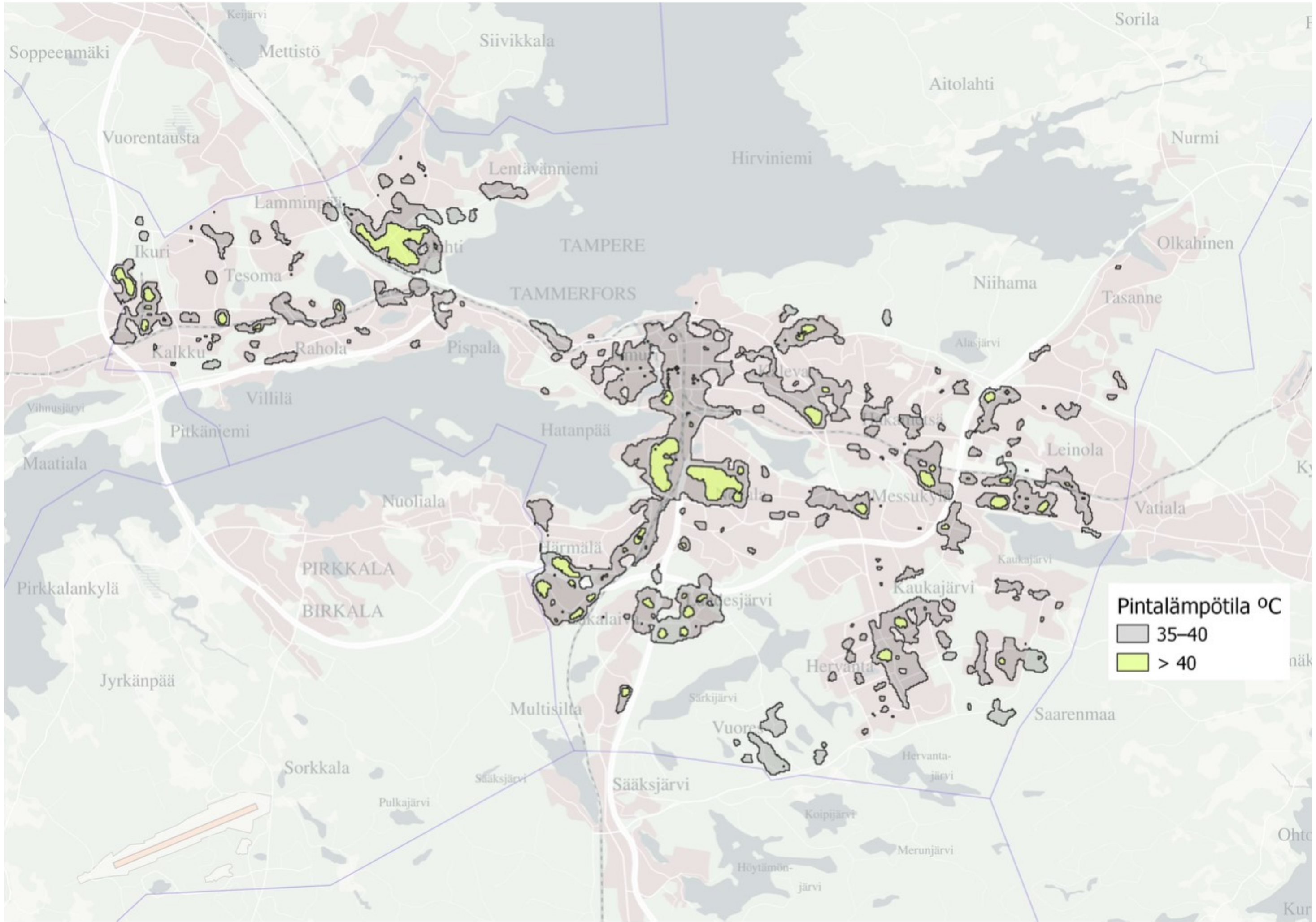
Map 10. Areas where the land surface temperature on 3 July 2021 was above 35–40°C and areas where the land surface temperature rose above +40°C. This can be considered to describe the situation of hot days that will become more common in the future. The map also shows residential buildings.



Map 11. Areas where the land surface temperature on 3 July 2021 was above 35–40°C and areas where the land surface temperature rose above +40°C. This can be considered to describe the situation of hot days that will become more common in the future. The map also shows residential buildings.



Map 12. Areas where the land surface temperature on 3 July 2021 was above 35–40°C and areas where the land surface temperature rose above +40°C. This can be considered to describe the situation of hot days that will become more common in the future. In addition, the map also shows workplace buildings.



Map 13. Areas where the land surface temperature was above 35–40°C and areas where the land surface temperature rose above +40°C from a composite map of eight time points from 2015–2021. This can be considered to describe the warm summer days and areas of the current situation, which are most likely to be exposed to heat.

6.2 Locations of the population

With the proposed delimitation for further actions, the +35-40°C range in particular can be considered as a residential environment on the 3 July 2021 map (Map 10). Land surface areas above +40°C can also be distinguished. The latter areas have a significantly low number of residential buildings. However, special attention should be paid to them from the perspective of possible exposure to heat, for example from the perspective of working life.

The total area on the map of temperatures between +35-40 on the 3 July 2021 is 35.5 km^2 and accounts for 25.5% of the entire central urban area of Tampere. In April 2022, 61.3% of the city's population lived in the zone. A total of 12,823 people over 75 years of age lived in areas between 35 and 40°C, which is 64% of the elderly population. The number of people aged between 0 and 3.5 years living in the area was 5,041, which is 60.4% of the age group of young children in question. A total of approximately 12% of the inhabitants are elderly and young children in the zone with surface temperatures of +35–40 degrees Celsius.

Surface temperatures of more than +40 degrees Celsius total 8.7 km^2, which is 6% of the central urban area. According to April 2022 census data, 7% of the city's population lived in this zone. There were 1,114 people aged 75 and over living in the zone, representing 5.5% of the total age group. There were 409 persons aged 0–3.5 years living in the +40°C area, i.e. 4.9% of the age group. The population data are for April 2022 and are calculated separately for those born before 1947 and those born in 2018 or later. The combined count of elderly and young children is approximately 9% of the total population count in areas with surface temperatures above +40°C.

6.3 Urban structure

Zones with a surface temperature of +35-40°C on the map of 3 July 2021 consist of built areas. In these areas, the urban structure varies from apartment building areas to detached house areas. The +35–40°C zone includes the entire city centre, high-rise building areas such as Hervanta, Kaleva, Janka and parts of Linnainmaa, and small apartment and terraced house areas such as Annala, Lukonmäki, Hakametsä, Haukiluoma, Uusikylä and parts of Linnainmaa. However, the land temperature does not rise above +35 degrees Celsius on the Peltolammi hill and around the apartment buildings in the Ruotula forest.

Also, in various types of residential areas where detached houses prevail, land surface temperatures have exceeded 35°C on a hot summer day at the chosen time. These include Risso and parts of Viinikka, Koivistonkylä, Lamminpää and the Lukonmäki area (although there is a forest) and large parts of Härmälä next to a bay of Lake Pyhäjärvi. In residential areas of small houses, the urban heat island is provisionally thought to be influenced by the terrain, by the age of the areas (older trees, width of streets) and by the quality and quantity of vegetation.

In over +40°C zones, the urban structure is almost without exception comprises of industrial areas and other large units with extensive street and car parking areas. The land surface temperature also rose above +40 degrees Celsius in Kyttälä in the city centre and in the Nalkala and Tammerkoski areas. The hottest sites also include the new apartment building areas in Haukiluoma, Lentävänniemi and in a small part of Vuores, as well as in the Kauppi campus area and in the middle parts of Hervanta. In the future, special attention should be paid to these individual sites in order to mitigate the urban heat island.

The aerial photograph does not show a clear type of urban structure, apart from industrial and high-rise building areas, in which the urban heat island is particularly pronounced. The data and the characteristics of the areas and the factors of the urban heat island have been assessed in more detail in chapters 7 and 8 using land cover data and microclimate modelling.

6.4 Cool zones

One way to protect from the heat is to seek cool locations. Major cities have recently published so-called cool zone maps. A map of London (London City Hall, www) shows air-conditioned and accessible indoor public spaces, as well as wooded outdoor spaces and fountains. In addition, the map utilises a land surface temperature map. The map of Berlin (Odis-Berlin: www) also takes into account wind conditions, bathing areas and benches for resting. It allows viewing the cooling possibilities at different times of the day. Such maps are not actually a means of adapting to climate change, but they can be a tool for digitally skilled citizens to survive for a short period of time and to make them feel comfortable more easily. In the Stockholm heat island survey, cool zones are defined based on forests and water bodies (Wiborg 2022).

The cooling effect of water bodies on microclimates is not unequivocal. Water evaporates moisture into the air, which cools the air. Water warms more slowly than soil and air, but in the case of a small, shallow water body and a long heat cycle, the water temperature may rise close to the temperature in its surroundings. Waters also cool more slowly than land, which means that when the air cools at night or in autumn, the water can still be warmer than the surrounding air and land. According to Achim Drebs, an expert at the Finnish Meteorological Institute, the impact of water bodies on the heat island effect is not straightforward, as many other factors also affect the microclimate of cities (oral communication of 9 September 2022, see also Drebs 2011 pp. 10-12).

In Dutch surveys it was found that small water bodies do not have a significant effect on air temperature during the day, especially not at night (Steeneveld et al. 2014, Jacobs et al. 2020). The cooling effect of modelled channels and pools on air temperature was less than 1°C and was largely dependent on the trees and buildings shading them and the free airflow (Jacobs et al. 2020). According to surveys conducted in China, the cooling effect of water bodies and wetlands on the land surface temperature during the day may reach hundreds of metres (Sun et al. 2012; Wu & Zhang 2019). However, the results depend on the extent of water bodies, season and time of day, and whether the land surface or air temperature and human temperature comfort are measured.

The wide open water surfaces in Tampere lakes and smaller lakes enable wind flow and have influenced the urban structure so that it breathes. Even in Tampere, the cooling effect of waters is affected by their size and depth.

On hot days in Tampere, the wind direction may be from south, warm. On calm summer days, the cooling experience on the beach can be a small one. This is why access to water and swimming plays a major role in cooling. Swimming and misting from fountains on the skin can also help in cooling down.

Waves and the sound of fountains and rushing streams also have a psychological effect in relieving the sensation of heat.

In addition to the factors mentioned above, shading of buildings and windy conditions contribute to a cooler experience. In the analysis of the cool zones, they have not been assessed, and air-conditioned indoor areas have not been mapped. However, Chapter 7 presents modelling of microclimates in the outdoor areas of different blocks of residential areas.

In this survey, the composite map of land surface temperatures (see Map 2) was used to examine the cool zones of the central urban area of Tampere, as it shows the areas that are most likely to be exposed to heat in the first place. Sites in public outdoor spaces where the following are realised are defined as cool zones:

- Area of at least 0.75 hectares

- Up to +26°C land surface temperature.

The areas are shown on Map 13.

6.5 Access to cool locations

The groups most vulnerable to heat are young children and the elderly population. On Map 13, access to cool has been examined by analysing the distance from day-care centres and health stations and from the TAYS unit to the nearest cool zone. The distance was calculated from the spatial data set along streets and outdoor routes. The analysis does not take into account the accessibility of the route. The map template used is a composite map of land surface temperature grids (see map 2).

Map 13 shows that:

- cool zones (in this work: public areas of more than 0.75 hectares where the land temperature is below +26°C) are located on the edges of the downtown and by water bodies.
- There are no cool zones in the city centre.
- The majority of day-care centres and health stations are located in the hot zone, and the walking distance to cool zones is more than two (2) kilometres.

An example of a route analysis (Figure 12) shows that the transitions along the street network and the outdoor routes to the nearest cool zone may be rather complicated. In further planning, the planning of simpler routes can shorten the walking distance in order to reach cooler conditions. Accessibility may also need to be taken into account as far as possible.

The same example shows that cemeteries, for example, can be located closer to other cool green areas. A cemetery is not suitable for the recreational activities of an entire day-care centre. However, cemeteries can be taken into account in the planning of preparing for the urban heat island as sites that can be used for walking and staying on a hot day, for example.

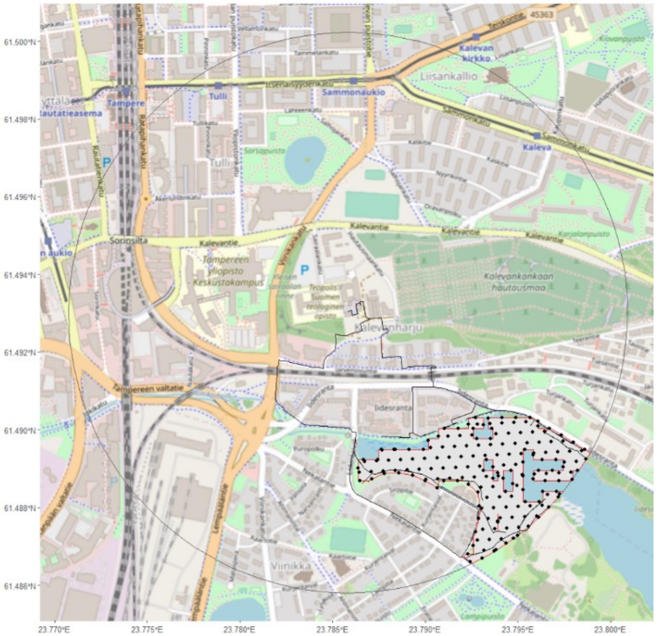
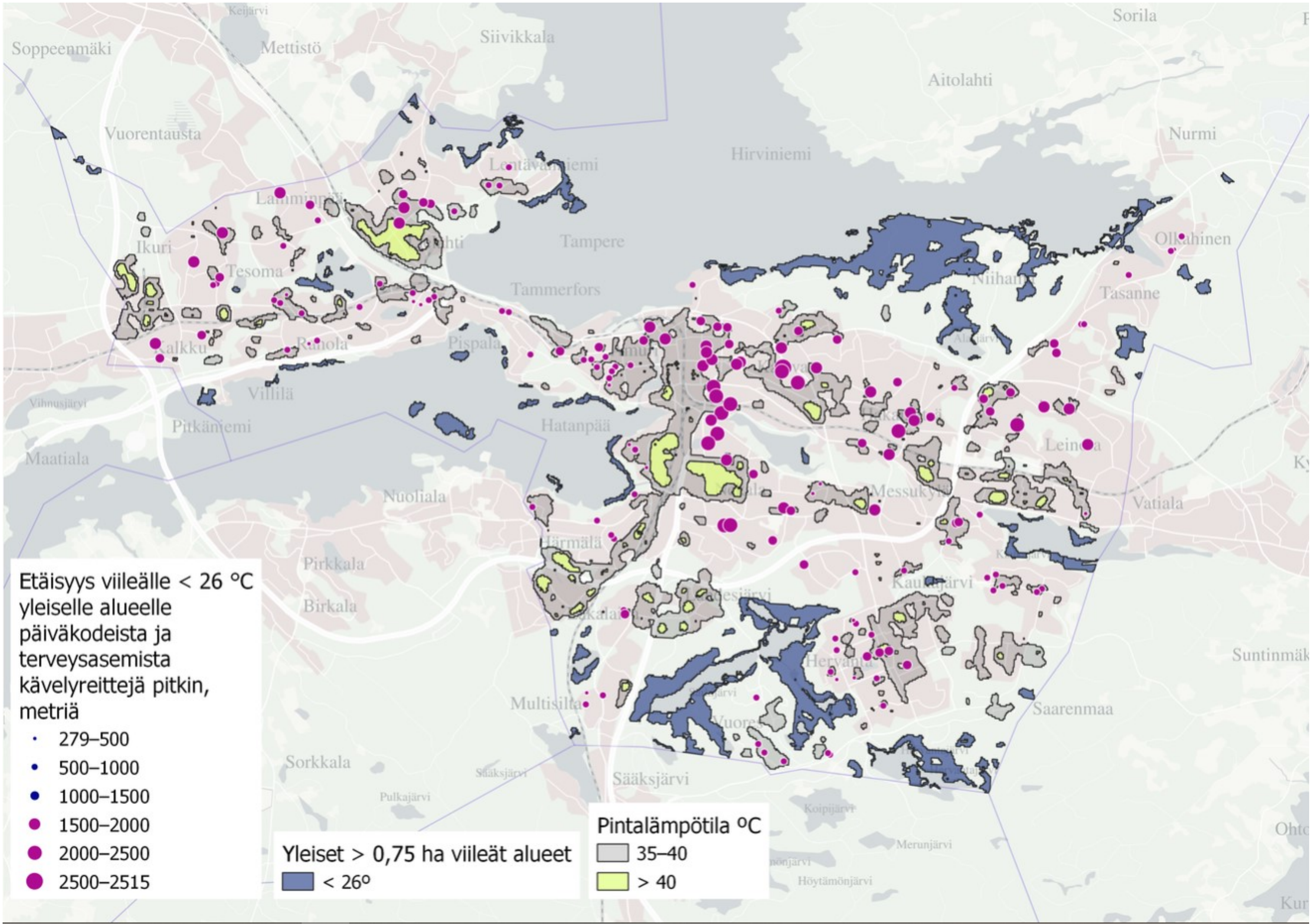


Figure 12. Route search as a spatial analysis from day-care centre to a cool zone (black lines towards black points).



Map 14. Access to cool locations: Distance from kindergartens and health care centres along pedestrian routes below +26 °C to public areas with a surface area of at least 0.75 ha.

6.5.1 Limitations of the method

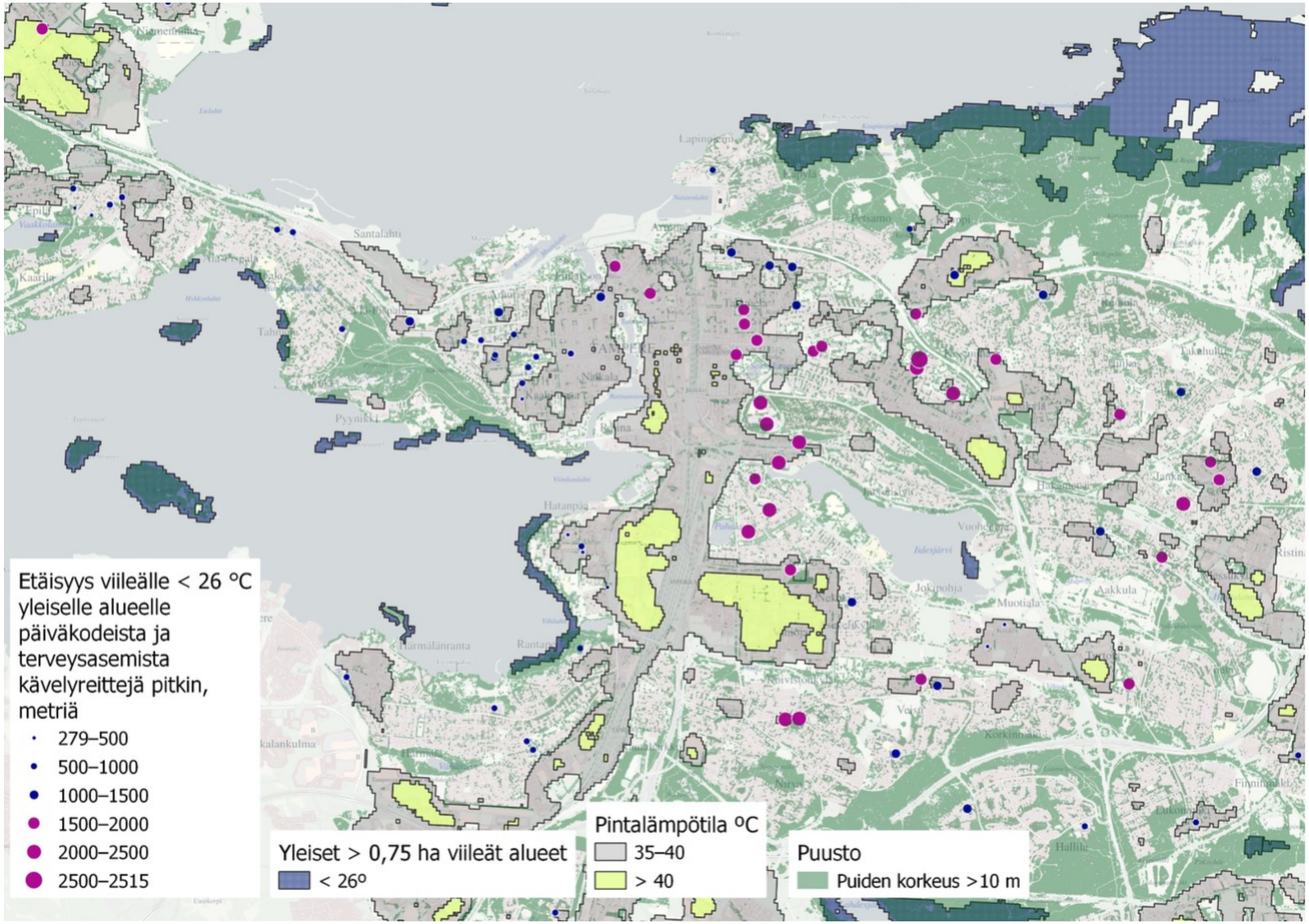
The original definition of a cool zone was to use a public outdoor space of at least 1.5 hectares. As a result, many smaller green areas in the central urban area were excluded from the examination. On the other hand, even in these areas, the land surface temperature is mostly +30°C and above in the map, so they do not appear on the map. The area requirement was dropped to 0.75 hectares on the final map, which makes it possible to stay outdoors, for example, also for small groups of people.

The tree crown cover was originally excluded from the definition of a cool zone, as its direct impact on outdoor temperature could not be verified from the data used in this report. In many public green areas, even wooded areas in the central urban area were warmer than +26°C, regardless of the tree crown cover. In wooded areas, the temperature may have been higher than in some open areas. It should be noted that the LST satellite's grid image of the land surface temperature gives an indication of the temperature of the tree crown cover. There is no reliable information on the land surface shaded by the tree under the crown.

The map also does not show cemeteries, which could be cooler and shadier than the rest of the environment, as they are not part of the public outdoor space. On the other hand, not all public outdoor spaces are a cool zone, as in sports fields, for example, the land surface temperature may exceed +30°C. Therefore, these areas are not shown on the map. Wooded areas may be cool sites close to the city centre area, even if the surface temperature is not below +26°C (Map 14).

When preparing the route analysis, the accessibility of the route could not be taken into account.

Finally, it should be noted that the same considerations apply to the mapping of cool zones in this work as to warm zones: maps describe the land surface temperature, which does not reflect the temperature of the air or take into account other factors in the microclimate nor experienced temperature comfort.



Map 15. Access to cool and trees (partial magnification): distance from day-care centres and health stations along walking routes to public areas with an area of at least 0.75 ha. In addition, the map shows areas from the Tampere land cover data where the tree height is over 10 metres.

7 Types of urban structure and modelling the local impacts of the urban heat island

7.1 Observations on the four types

In the first phase of the survey, differences in the surface temperatures of different types of urban structure were observed (section 3.2.1). In the second phase of the survey, four different types of urban structure were identified by examining the land surface temperature map and aerial photograph, each of which has a distinctive characteristic in surface temperatures: the area of single-family houses, an open apartment building, the city centre and an industrial area. Areas of detached houses are the coolest built-up areas, while industrial areas are the hottest.

An example area was selected for each type, in which the distribution of land cover was examined and windiness and solar radiation were modelled. The most significant factors affecting the urban heat island identified in sub-project 1 were used to survey the distribution of land cover: impermeable surface, buildings, trees and other vegetation (section 4.1). The results are presented in more detail in Appendix 2. On the following pages, Figures 14, 16, 18 and 20 show the oblique view aerial photo of each area of interest, an extract from the land surface temperature map and the distribution of the land cover. Figures 15,17,19 and 21 show for each survey area the following:

- hourly wind speed values at each reference point combined to annual wind conditions
- average effect of solar radiation on mean radiant temperature as the average of all hours of the hottest week in the summer
- UTCI values that combine the results of the left modelling with the hottest week's temperatures and air humidities.

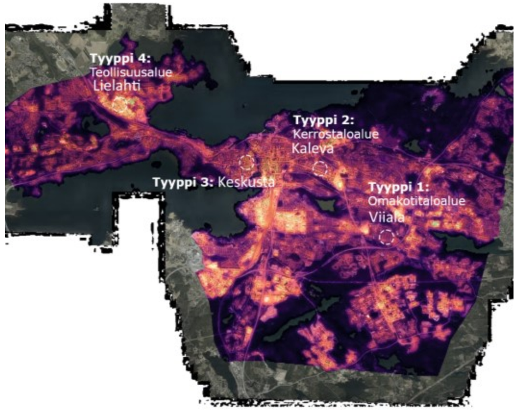


Figure 13. The locations of the four example areas on the map.

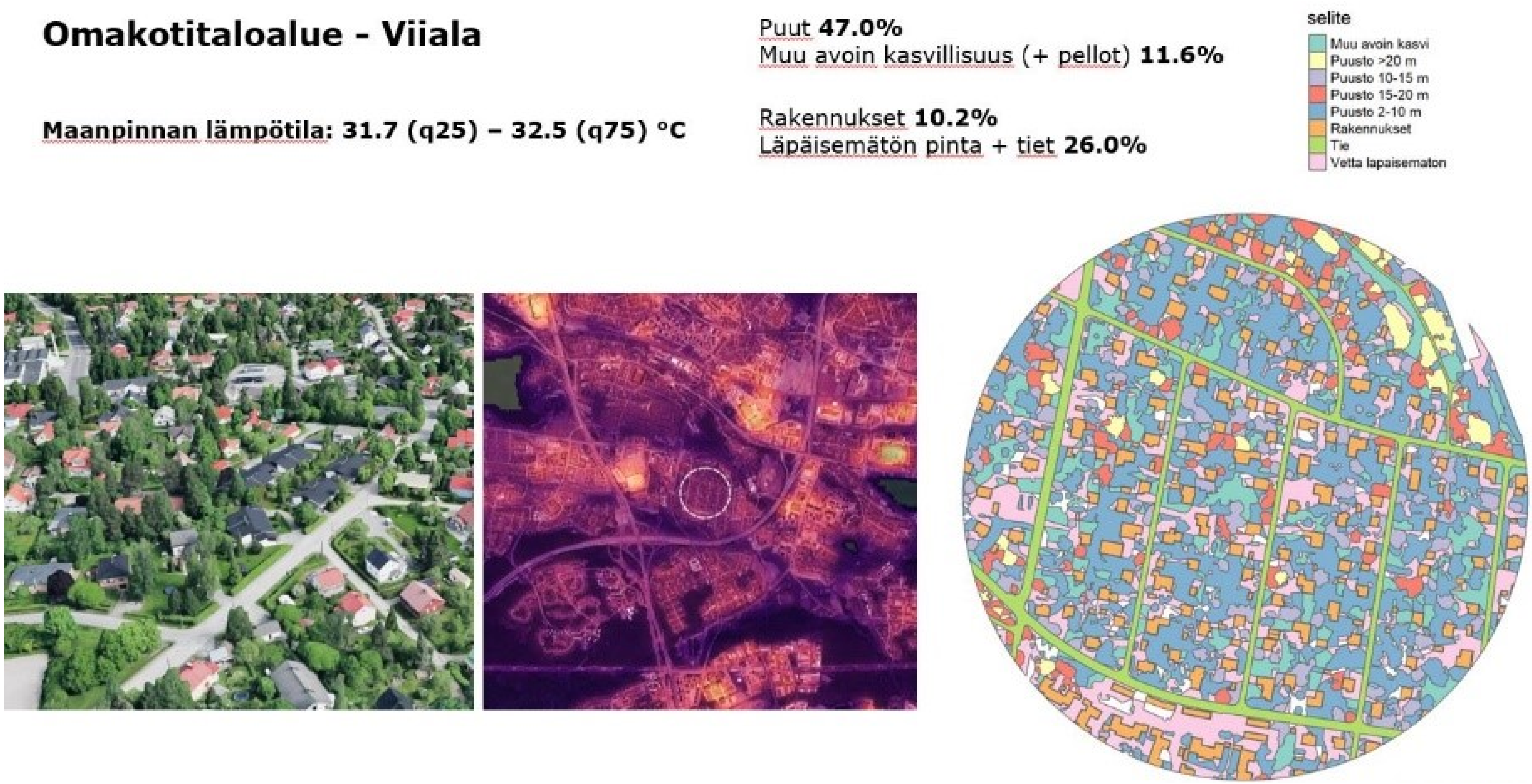


Figure 14. Aerial photograph of the Viiala single-family house area, location on the composite map of the land surface temperature and the distribution of land cover in the area.

Viiala

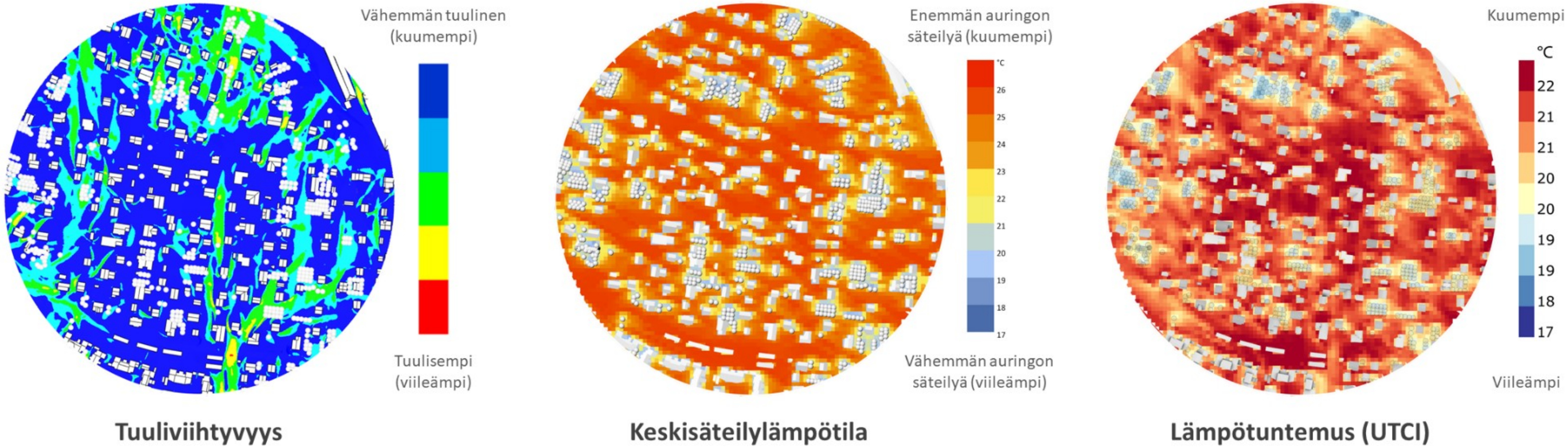


Figure 15. Windiness modelled from the Viiala single-family house area, mean radiant temperature in the hottest week of the year and thermal sensation (UTCI).

Of the areas with single-family houses, Viiala was modelled, which has a very uniform granularity. Of the ground cover, 47% is tree crown cover and 36% is buildings and impermeable surface. The land surface temperature from the composite map (lowest quartile – highest quartile) is +31.7°C to 32.5°C, and the temperatures are evenly distributed in the area.

The temperature comfort survey of the hottest week of the year carried out in Viiala (see section 7.2.2), which does not take into account the direct effects of the urban heat island, shows that the area is relatively hot. This is due to the low wind speeds in the area and the fact that the low buildings in the area do not provide shade in outdoors. However, the wooded sections of the area are clearly cooler, so based on modelling, it can mainly be stated that abundant trees are a critical factor when attempts are made to keep the outdoor areas of single-family houses cool.

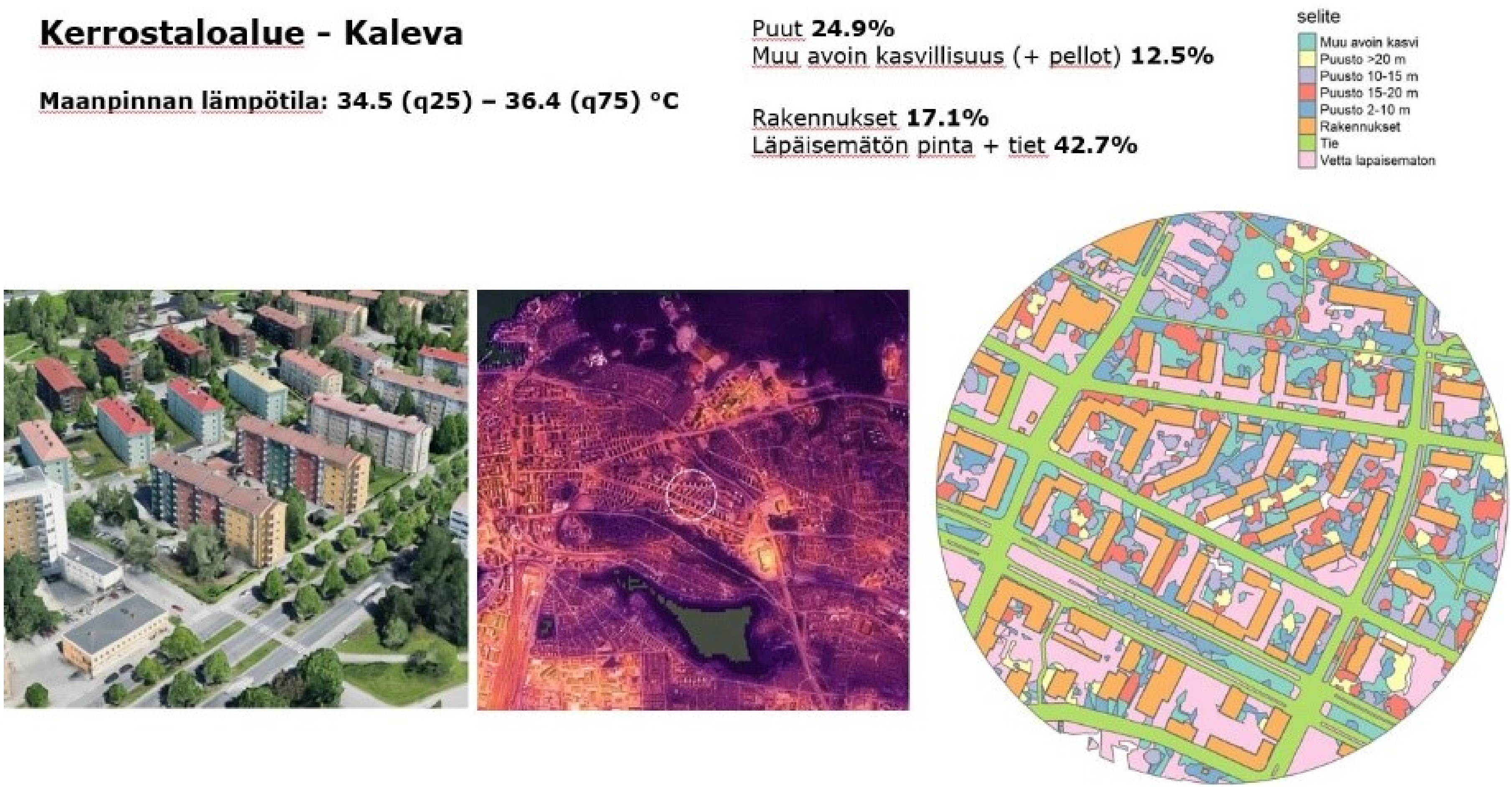


Figure 16. Aerial photograph of the Kaleva apartment building area, location on the composite map of the land surface temperature and the distribution of land cover in the area.

Kaleva

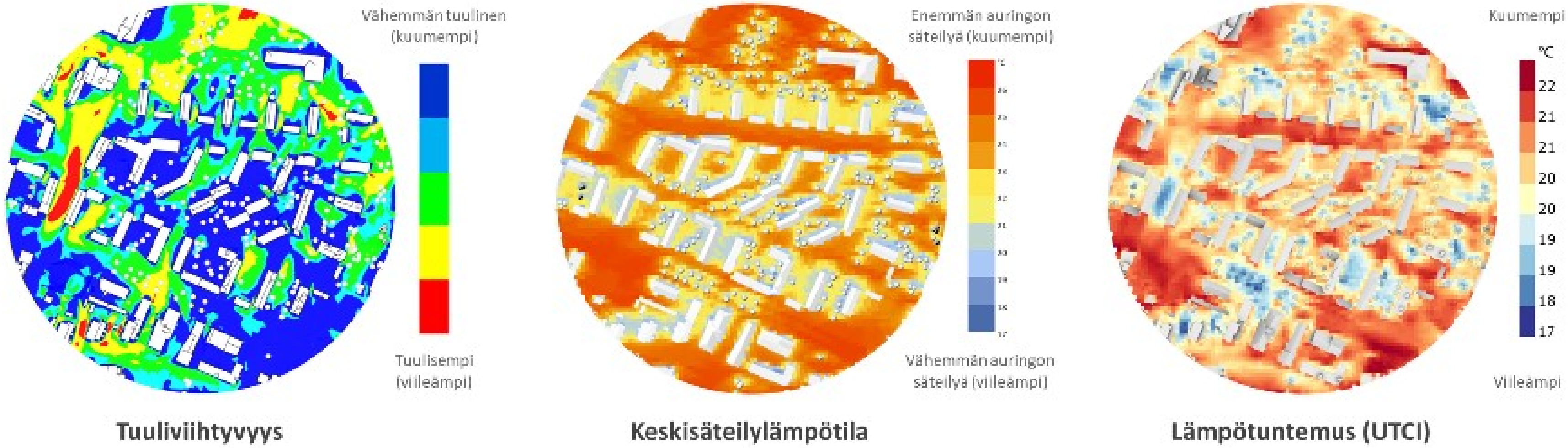


Figure 17. Windiness modelled from the Kaleva apartment building area, mean radiant temperature in the hottest week of the year and thermal sensation (UTCI).

Part of Kaleva, which has an open apartment building block structure, was modelled from the **apartment building areas**. Of the ground cover, 24 % is tree crown cover and 60 % is buildings and impermeable surface. The land surface temperature from the composite map (lowest quartile – highest quartile) is +34.5 to 36.4°C. The hottest surfaces are roads and car parking areas, and the cooler parts are plant-covered courtyards.

The temperature comfort analysis of Sampola shows that the open courtyards in the area, which are mainly oriented towards the prevailing south-west winds, provide a variety of leisure areas. The windier and more wooded yards are cooling oases. The modelling also shows that the temperature comfort in street areas varies greatly, mainly depending on the wind. The windier places stay cool, while the more sheltered ones are scorching.

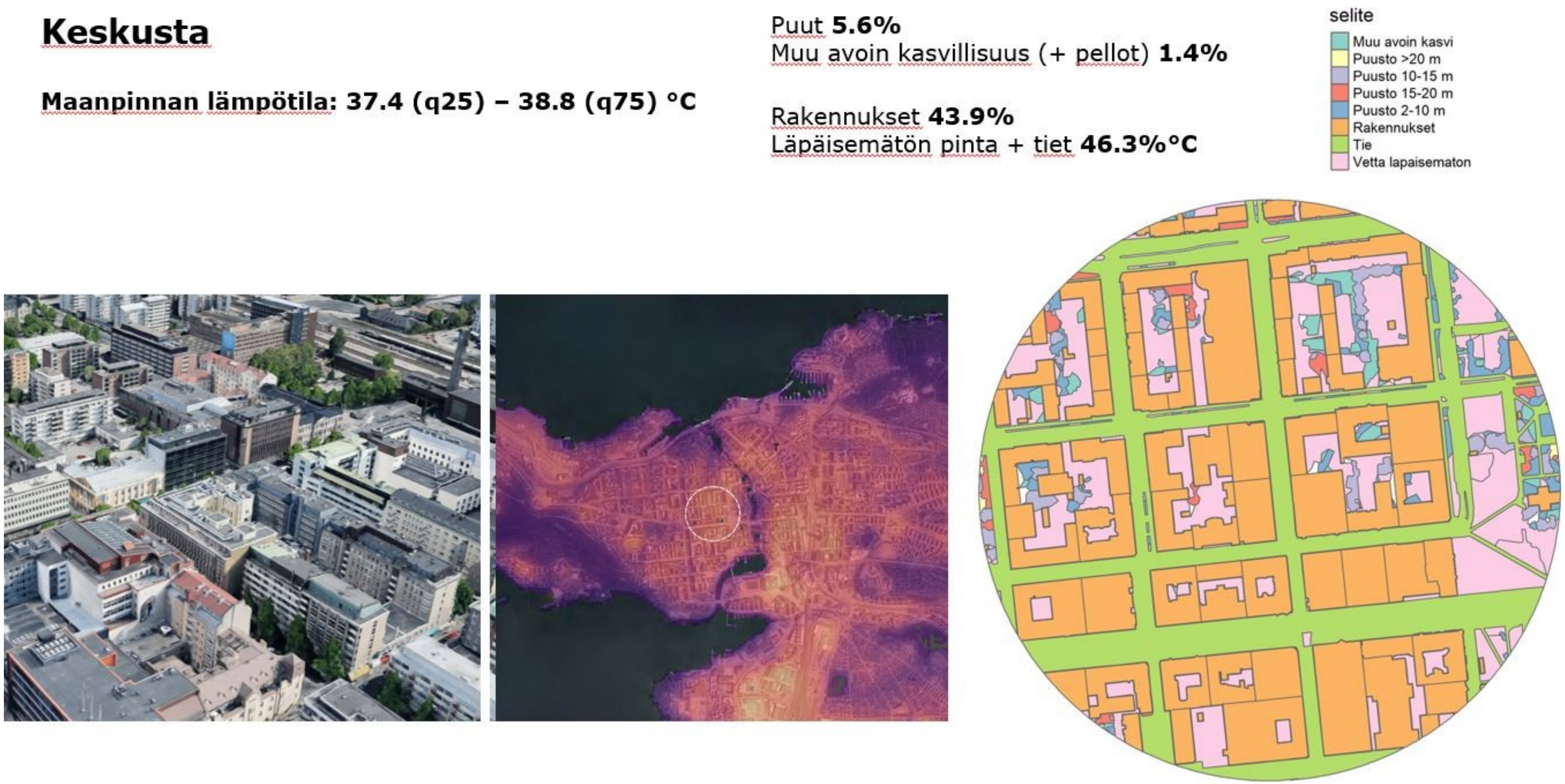


Figure 18. Aerial photograph of the city centre, location on the composite map of the land surface temperature and the distribution of land cover in the area.

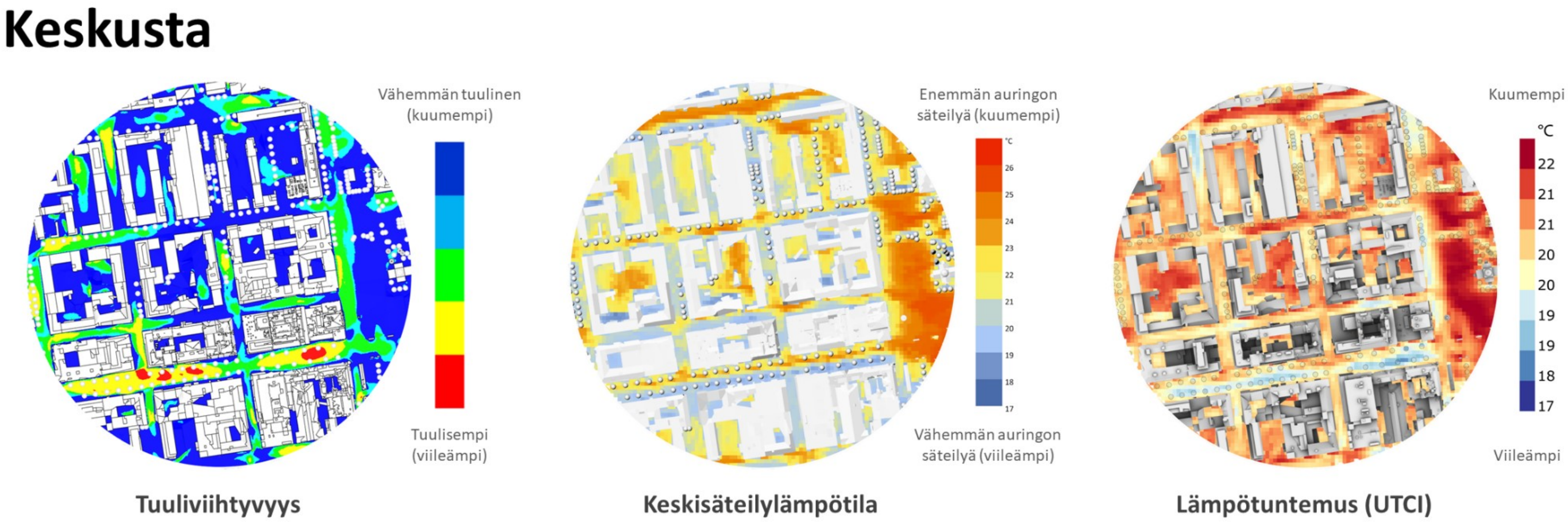


Figure 19. Windiness modelled from the city centre, mean radiant temperature in the hottest week of the year and thermal sensation (UTCI).

From the city centre, a block structure between the central market and Hämeenpuisto was modelled. Of the ground cover, 5 % is tree crown cover and 90 % is buildings and impermeable surface. The land surface temperature from the composite map (the lowest quartile – the highest quartile) is +37.4 to 38.8°C. The temperatures are evenly distributed in the area, but in open areas it is warmer and cooler in the shadow of tall buildings.

In the city centre's temperature comfort modelling, streets stand out clearly from the market squares and courtyards as cooler than average. This is due both to the shading effect of buildings and trees and the cooling effect of winds blowing through the area. This is particularly evident on Hämeenkatu, which is very windy and has a shady southern edge. The inner courtyards of the blocks are very hot in places. This is because, on the one hand, buildings do not offer significant protection against the summer sun and, on the other hand, because they have little wind. However, the central square is the hottest area because it offers the least shade and is not exposed to significant wind.

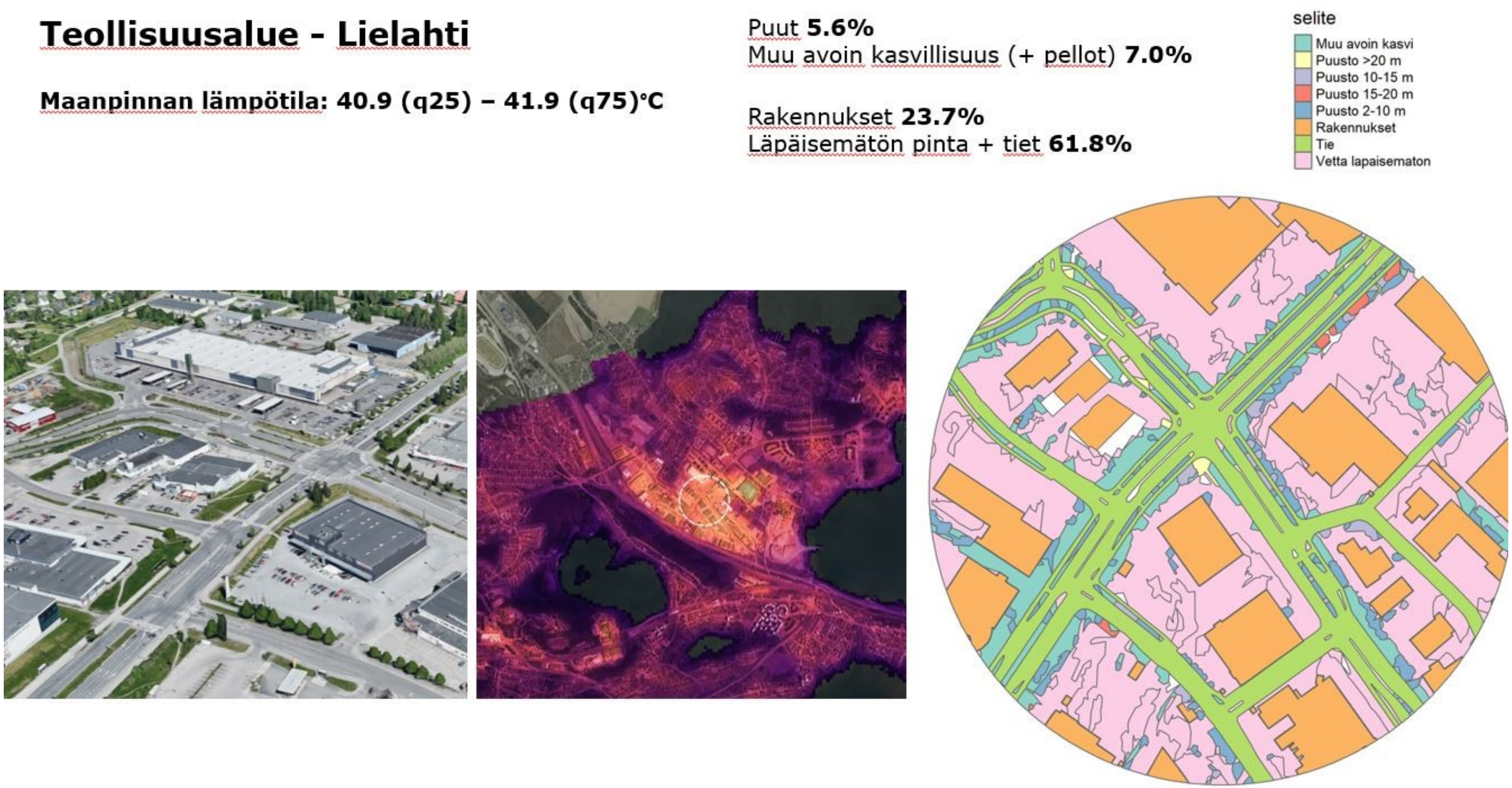


Figure 20. Aerial photograph of the Lielahti industrial area, location on the composite map of the land surface temperature and the distribution of land cover in the area.

Lielahti

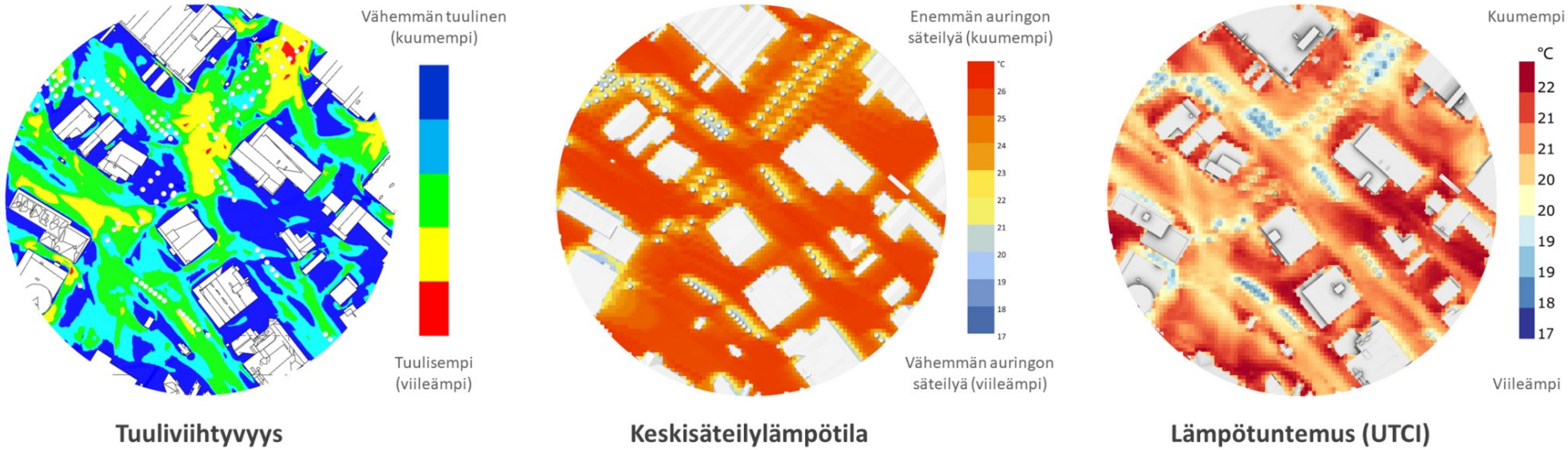


Figure 21. Windiness modelled from the Lielahti industrial area, mean radiant temperature in the hottest week of the year and thermal sensation (UTCI).

Of the industrial areas, Lielahti was chosen to be modelled. Of the ground cover, 5 % is tree crown cover and 85 % is buildings and impermeable surface. The land surface temperature from the composite map (lowest quartile – highest quartile) is +40.9°C to 41.9 °C, and the temperatures are evenly distributed in the area.

Lielahti is the windiest of the modelled areas. This is explained by both the location between lakes and the open and largely treeless structure of the area. Although the area as a whole is hot, there are also cool spots where trees provide protection from the sun and wind provides cooling. The modelling therefore suggests that, overall, even a hot area can have cooler parts if these are relatively windy and are adequately shaded. Of course, this will not solve the wider problem of heat in the region. It should also be borne in mind that it may be calm for a long time during a heat wave.

7.2 Method

7.2.1 Land cover

An analysis of the sample areas was carried out for circle area having with a diameter of 500 metres. The following map layers of land cover data from Tampere were used as land cover data:

- Number of trees (Tampere's land cover data)
- Other open vegetation (Tampere's land cover data)
- Roads & other impermeable surface (Tampere's land cover data)
- Buildings (land area, Tampere’s land cover data)

The proportion of the area of each circle covered by these land covers was calculated and reported.

7.2.2 UTCI microclimate modelling

Microclimate modelling was carried out for the same sites that were used in land cover assessments.

UTCI is a mathematical model that describes the human body's reactions to various thermal stimuli outdoors. The modelling consists of four elements: air temperature, humidity, average radiation temperature (based mainly on the effect of solar radiation in the modelling performed) and air speed (i.e. wind). The UTCI model also takes clothing into account: people are expected to seek adaptation to conditions by increasing or reducing their clothing.

The result of UTCI modelling is expressed in degrees Celsius. The idea of UTCI corresponds to the "feels like" temperature indicated in the weather data. The modelling was performed 1.5 metres above the ground, which describes the thermal sensation of a person standing. The modelling was carried out for the hottest week of the year, calculating the required values for each hour of the week. The principles of UTCI microclimate modelling are described in more detail in Appendix 2.

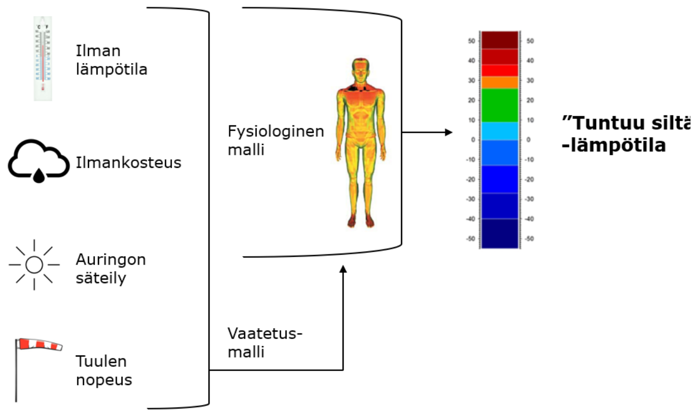


Figure 22. Illustration of the principle of UTCI low-impact climate modelling.

The UTCI modelling carried out does not directly reflect the urban heat island, but its components are linked to it. The wind cools materials in the urban environment by convection. Thus, higher wind speeds reduce the effect of the urban heat island, if other factors remain unchanged.

The mean radiation modelling performed does not take into account the warming of the land surface (or other structures), but only the direct solar radiation that targets the human body. In practice, the amount of solar radiation on the land is very close to the radiation effect shown here at a height of 1.5 metres. The effect of radiation on the land surface on the urban heat island is naturally dependent on the surface material. Areas of the land surface that are coated (especially with dark materials) and exposed to more radiation contribute most to the urban heat island.

To create a picture of the effect of wind and solar radiation on temperature comfort, a comparison was made in which the effect of wind and solar radiation was removed from the modelling results in the city centre one by one, and then the averages were compared for the whole week and the entire area. Removing windiness raises the perceived UTCI by 0.34°C on average, while removing the solar radiation effect lowers the UTCI by 6.67°C on average. The solar radiation effect is therefore clearly the more important factor, but wind also plays an important role, especially in the windiest regions.

7.2.3 Limitations

When assessing factors affecting the urban heat island, it is important to remember that the microclimate of each area is influenced by many factors, starting with the geographical conditions of the area and the surrounding areas. The results are indicative and can be used to compare different types of urban structure. However, the microclimate of a single-family house area located in one location is not identical to the single-family house area on the other side of the city centre.

Variable	WINDINESS	MEAN RADIANT TEMPERATURE °C the hottest week of the year	LAND SURFACE TEMPERATURE °C lowest 25% highest 25%	DOMINANT LAND COVER
Data source	Performed simulation	Performed simulation	Satellite images, composite map	Geospatial data of the City of Tampere
1. Area of single-family houses **Viiala**	Low wind speeds	+22–26	+31.7–32.5	**Trees 47 %** Buildings 10% Permeable surface 26%
2. Apartment building area **Kaleva**	Quite windy. However, some of the yards are sheltered.	Streets and parking +24–26 yards +22-23	+34.5–36.5	Trees 16% Buildings 17% **Impermeable surface 43%**
3. City centre	Streets are quite windy, inner courtyards are mainly very calm	Street in shade +19–20°C Street in the sun +22–25°C Marketplace +24–26°C Strongly varies based on shade.	+37.4–38.8	Trees 5 % Buildings 44% **Impermeable surface 46%**
4. Industrial zone **Lielahti**	The windiest of the areas reviewed	+24–26 tree rows +21–23	+41–42	Trees 6% Buildings 24% **Impermeable surface 62%**

Table 1. Summary of UTCI modelling of urban structure types.

8 Recommendations for the comprehensive plan

Based on the above analyses, recommendations have been created for relieving the urban heat island effect and preparing for it in the comprehensive plan of Tampere (Table 1). The recommendations take into account the level of the local comprehensive plan and also include recommendations related to more detailed further planning that is carried out based on the local comprehensive plan.

The recommendations include actions to mitigate the urban heat island and to prepare for it. The main focus of relieving is on responding to the needs for actions in existing areas, while preparedness focuses on proactive planning and actions.

There are a number of ways in which urban planning and design can be used to relieve and prepare for the urban heat island effect. For example, the orientation of streets and the ratio between the height of buildings and the width of the street space affect the exposure of buildings and outdoor spaces to solar radiation. Many of these tools relate to more detailed levels of planning than the comprehensive plan, such as neighbourhood and block planning.

In particular, the comprehensive plan can be used to influence urban structure density and thus population density, as well as to the network of green spaces and water management at a general level, and to the location of infrastructure and services critical to the functioning of society. These form the overall picture of the city.

One of Tampere's strengths in reducing the urban heat island and preparing for it is a comprehensive and versatile network of green structures and the connection of the green network to numerous small lakes. The mixed urban structure contributes to relieving the effects of the urban heat island. In the thematic map of urban structure, existing heat islands are located in particular in "areas or sites with mixed services and employment" and in centre areas . As urban structure density increases in the coming years, especially in these areas, it will continue to be important not only to take account of the urban heat island, but also to promote a functionally mixed urban structure, and to ensure adequate green areas, stormwater management, sustainable mobility and many other issues that are important in city centres.

Many of the presented recommendations relate to the use of green infrastructure, which is a widely used tool for relieving and preparing for the urban heat island effect. Green infrastructure can be used to regulate microclimates, and the significance of vegetation for controlling urban heat islands is obvious. Mixing urban green with other urban structures mitigates heat islands more effectively than large separate green areas.

Paying attention to the surface materials used in cities and their properties can also help to mitigate the urban heat island. The most effective way to mitigate the urban heat island is to combine and implement a number of different actions.

Table 2. Recommendations for relieving the urban heat island effect and preparing for the it in the Tampere downtown comprehensive plan and in more detailed further planning based on it.

Relieving or preparedness measure	Justification	Other observations	The theme to which it relates
Smooth and pleasant walking and cycling routes will be designed from the central areas and warmer zones to green areas and cooler zones and swimming places. The treecrown cover of the routes will be taken into account. The length of the routes can be assessed on the basis of geospatial information by means of route analysis and a limit value can be defined for the maximum length of the route.	Allows access to cooler areas, eases heat stress and prevents health hazards. Moving in the shade is more pleasant.	High surface temperatures in the strategic sub-area comprehensive plan of the city centre, especially around the railway station and in the Ratina area. Land surface temperatures above +40°C in Kyttälä area of the city centre and in the Nalkala and Tammerkoski areas. Hot areas also in Haukiluoma, Lentävänniemi and a small part of Vuores, as well as in the Kauppi campus area and middle parts of Hervanta.	Urban structure Green environment and leisure services Environmental Health
Placement of / allocation of space for urban green in the urban fabric Adequate green spaces will be planned, even in dense urban areas, and space will be set aside for tree planting in street space. It is recommended that urban parks are added to hot areas.	The cooling effect of large individual green areas on the edge of the city does not effectively extend to the interior of urban structures.	In some places, heat islands overlap with "indicative green network connectivity areas". There are few district parks in hot areas.	Urban structure Green environment and leisure services

Designing cool places or cooling centres for industrial areas and for dense old blocks, and for outdoor sports facilities (outdoors or indoors). Prioritise the warmest areas.	In the urban structure already in place, there is often a long distance from the hottest areas to the cool zones.	In over +40°C zones, urban structure is almost without exception industrial areas and other large units.	Urban structure Green environment and leisure services
Facilitate access to the shoreline, waterfront and swimming places. Good connections for pedestrian and cycle traffic and for public transport will be planned.	Evaporation of waters and access to water will cool down and alleviate heat stress.	-	Urban structure Green environment and leisure services
Designing an urban structure that is "through ventilating" but avoiding "wind tunnels" (green areas interlinked with neighbourhoods; building placement, avoiding long straight streets).	Helps to cool down the climate in hot weather, curbs uncomfortable conditions in the cold season.	-	Urban structure Green environment and leisure services
The current areas of high trees and abundant vegetation will be cultivated and their development and well-being will be supported. Keep green areas as uniform as possible.	Forests and integrated uniform urban tree areas cool the city's microclimate most effectively. Uniform green areas are more resistant to heat stress than fragmented green areas.	The majority of unified green and forest areas are located on the edge of the central urban area. It would be good to have cool zones, such as green areas with trees, in the central urban area.	Urban structure Green environment and leisure services
In the further planning of dense construction areas, consideration will be given to factors affecting microclimates and to preparing for the urban heat island (wooded areas, air directions of buildings and streets, windiness).	The placement of buildings and the design of street spaces have impacts on the microclimate (width-height ratio, so-	-	Urban structure Sub-area surveys of the comprehensive plan

	called "sky view factor").		
Minimise the construction of large dark and impermeable surfaces (roads, routes, car parking areas).	Dark impermeable surfaces accumulate heat and increase the urban heat island.	This applies in particular to industrial areas and street environments, as well as the city centre.	Urban structure Urban technical maintenance
Along the ditches of urban streams, shading trees are preserved and, where possible, green areas are planned along the stream.	Shading trees prevent the warming and evaporation of minor waters and improve water bodies as habitats and their ecological status.	Of the urban water bodies, the Härmälänoja, the central parts of the Pyhäoja and the lower reaches of the Vihioja along Lahdenperänkatu pass through particularly hot areas. Also Tauskonoja and a drainage ditch from Iidesjärvi to Pyhäjärvi.	Sustainable water management Green environment and leisure services
Massive brick buildings in the city centre and other concentrations of older buildings will be taken into account in the planning of preparedness and relieving for the urban heat island.	The buildings do not necessarily have air conditioning, so the significance of outdoor space and urban structure is emphasised.	There are older apartment blocks in the city centre in areas that are clearly warmer than the surrounding area. Most of the elderly population is located in hot areas in Hervanta, around Linnainmaa health care centre and	Cultural environment Urban structure

		in the centre of Tampere. The building stock built before the 1960s was mainly built in single-family house areas.	
Replace impermeable surfaces (stone, etc.) with vegetation.	Vegetated surfaces store less heat.	Renovation sites in particular, rebuilding demolition sites. Renovation of street areas.	Sub-area surveys of the comprehensive plan
Planning nature based stormwater management and reducing impermeable surfaces.	Supporting the natural water cycle and vegetated surfaces safeguards minor water bodies and cools the microclimate. Impermeable (dark) surfaces store heat.		Sub-area surveys of the comprehensive plan
The space needs of street green and tree planting are taken into account in the space reservations for street areas and routes.	Trees, and in particular uniform tree crown cover, cool the street space.	-	Sub-area surveys of the comprehensive plan
Light tones are preferred on roof surfaces.	Dark surfaces store heat, increasing the effect of the urban heat island and heating up buildings.	-	Sub-area surveys of the comprehensive plan
Wherever possible, green roofs are preferred, e.g. on carport roofs and other low structures.	Green roofs located close to the ground cool down the outdoors microclimate of the blocks. In low-rise buildings,	-	Sub-area surveys of the comprehensive plan

	green roofs do not pose major structural requirements.	

8.1 Recommended further surveys

The map-based assessment is based on current and past data for land surface temperatures and vulnerabilities. It is necessary to regularly update analyses related both to thermal conditions and to vulnerabilities, as the urban structure changes.

Despite its name, the land surface temperature map does not, for example in crown-covered areas, provide information on the land surface temperature in the shade of a tree. To get a better idea of temperatures in different parts of the city, it would be useful to observe a measurement series of air temperatures. This could also cover the winter months and highlight the effects of the winter heat island.

In addition to the recommendations for the comprehensive plan, the topics and surveys listed below can increase understanding of the urban heat island, vulnerabilities to it and the need for adaptation and the means of relieving heat. The topics are roughly divided into the comprehensive plan phase and the local comprehensive plan phase, i.e. into scale of downtown and scale of block:

COMPREHENSIVE PLAN (scale of the central urban area)

- Specification of the definition of hot zones
- Monitoring and mapping of air temperatures
- Examination of winter heat islands
- Deepening of social vulnerability analysis (common indicator)
- Modelling population change in relation to thermal conditions as urban structure evolves
- The warming effect of traffic and how to predict it
- The effect of the urban heat island on groundwater
- The impact of windiness at the scale of the central urban area and airflows in the urban structure
- Typification of green areas and the potential of blue-green structure

LOCAL COMPREHENSIVE PLAN (block scale)

- Impact of albedo
- Accessibility of cool places
- Sky view factor with 3d modelling
- Microclimate modelling for individual developments (comprehensive plan, local comprehensive plan)
- Adaptive potential of street space – brainstorming solutions
- Assessment of risks in the cultural environment (building stock, valuable vegetation)

In addition to the above, the expert work of the survey also highlighted risks related to security of supply (e.g. power cuts, heat stress) and to cultural and historical environments. Preparedness is not primarily within the sphere of influence of urban planning, but it is recommended that the results of this survey be communicated to other sectors as well. These include group administration, social and health services, rescue services, water supply services, electricity services, facilities services, the City Museum, and nature management and infrastructure (maintenance).

9 Closing remarks

Researching urban heat islands in urban planning is a new topic in Finland. On the basis of this report, preliminary conclusions can be drawn on the factors and targeting of the urban heat island and the vulnerabilities in Tampere's main city at a general level. The report can be used to identify themes and targets to be prioritised in further surveys and urban planning. It is necessary to regularly update analyses related both to thermal conditions and to vulnerabilities, as the urban structure changes.

Reducing urban heat islands and preparing for heat risk must be studied in both the short and long term. As a result of climate change, temperatures will rise in Finland, not just in summers, but also in winters. There are other risks associated with a winter heat island, such as slipperiness and ecological challenges. Proactive planning is an important part of preparedness.

The urban structure and in particular urban green spaces, including street space, affect microclimates, rising temperature and their mitigation. In addition to climate policies and communication, the comprehensive plan and local detailed plans play an important role in relieving the urban heat island effect, as they are legally enforceable means of guiding urban development. Further analysis will allow for a deeper identification of adaptation needs and the development of adaptation actions in Tampere.

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11 Appendices

Appendix 1. Selecting the dates for the surface temperature composite map

The table shows the days when the average daily temperature at the Härmälä weather unit was above +18°C, as it exceeds the average temperature in July in Tampere from 1991 to 2020 (+17.4°C) in the statistics of the Finnish Meteorological Institute.

For the previous heat wave, daily maximum air temperatures from the Härmälä station of the Finnish Meteorological Institute have been examined for the summers 2015–2021, from 1 June to 31 August.

In the Selection column, a value of 1 indicates that the time is selected for the time points on the composite map.

date	cloudiness %	Average daily temperature at Härmälä weather station °C	selection	previous heat wave
03 July 2015	**0**	**23**	**1**	**no**
11 August 2015	100	18	0	-
03 June 2016	100	19	0	-
26 June 2016	70	20	0	-
15 May 2018	5	18	0	-
18 July 2018	**10**	**24**	**1**	**yes**

27 July 2018	**5**	**25**	**1**	**yes**
03 August 2018	50	22	0	-
19 June 2019	60	19	0	-
21 July 2019	**5**	**21**	**1**	**no**
14 June 2020	**0**	**20**	**1**	**no**
21 June 2020	90	19	0	-
08 August 2020	**0**	**21**	**1**	**no**
17 June 2021	95	18	0	-
03 July 2021	**0**	**22**	**1**	**yes**
10 July 2021	100	23	0	-
26 July 2021	**15**	**22**	**1**	**no**

Translations to pictures

<u>Page 31</u>
Number of days
Temperature °C

<u>Page 32</u>
Surface temperature °C

<u>Page 35</u>
Weather stations
H Härmälä
T Tampella
Surface temperature °C

<u>Page 36</u>
3 July 2015, H: 27.1°C, T: 27.0°C
18 July 2018, H: 28.9°C, T: 29.3°C
27 July 2018, H: 29.6°C, T: 30.4°C
14 June 2020, H: 25.8°C, T: 26.1°C
8 August 2020, H: 25.8°C, T: 26.1°C
3 July 2021, H: 28.1°C, T: 25.5°C
21 July 2019, H: 25.3°C, T: 25.5°C
26 July 2021, H: 26.5°C, T: 26.9°C

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Surface temperature °C

<u>Page 41</u>
Surface temperature °C

Page 44
Surface area m^2
Surface temperature °C
Floor area
Low vegetation
Trees
Impermeable

Page 45
Impermeable surface (road + other) m^2
Tree covered area m^2
20,000
40,000
60,000
80,000
0
20,000
40,000
60,000
80,000
100,000
120,000

Page 46
Surface temperature °C
Low vegetation, incl. fields m^2
20,000
40,000
60,000
80,000
100,000

Page 49
Surface temperature °C
Older people (> 75 years)
Day-care centre
Health care station or TAYS

Page 50
Building (year of construction < 1960)
Surface temperature °C

Page 53
Playgrounds
Surface temperature °C
Temperature °C

Page 56
Spruce-dominated forest
Ditch
Spring or seepage
Pond
Surface temperature °C

Page 59
Temperature °C
Nature value clusters in streambeds
Nature value cluster
Potential nature value cluster
Streambeds
Natural
Natural-like
Other waterways
Spring or seepage

Page 61
Elderly, >= 75

Page 62
Surface temperature °C
35–40 °
>= 40 °

Page 63
Residential buildings
Surface temperature °C
35–40 °
>= 40 °

Page 64
Surface temperature °C
35–40°C
≥ 40°C
Workplace building (office and administration building, industrial building, care building)

Page 65
Surface temperature °C
35–40 °
> 40 °

Page 71
Distance to cool (< 26°C) public area from day-care centres and health care stations along pedestrian routes, metres
279 to 500
500–1,000
1,000–1,500
1,500–2,000
2,000–2,500
2,500–2,515

Public > 0,75 ha cool areas
< 26 °

Surface temperature °C
35–40 °
> 40 °

Page 73
Distance to cool (< 26°C) public area from day-care centres and health care centers along pedestrian routes, metres
279 to 500
500–1,000
1,000–1,500
1,500–2,000
2,000–2,500
2,500–2,515

Public > 0,75 ha cool areas
< 26 °

Surface temperature °C
35–40 °
> 40 °

Trees
Tree height > 10 m

Page 74
Type 4:
Industrial zone
Lielahti

Type 3:
City centre

Type 2:
Apartment building area
Kaleva

Type 1:
Single-family home area
Viiala

Page 75
Single-family home area – Viiala
Surface temperature: 31.7 (q25) – 32.5 (q75) °C
Trees **47.0%**
Other open vegetation + fields **11.6%**
Buildings **10.2%**
Impermeable surface + roads **26.0%**

legend
Other open vegetation
Trees > 20 m
Trees 10–15 m
Trees 15–20 m
Trees 2–10 m
Buildings
Road
Impermeable

Page 76
Viiala
Wind comfort
Less windy (hotter)
Windier (cooler)

Radiation temperature, average
More solar radiation (hotter)
Less solar radiation (cooler)

Thermal sensation (UTCI)
Hotter
Cooler

<u>Page 77</u>
Apartment building area – Kaleva
Surface **temperature: 34.5 (q25) – 36.4 (q75) °C**
Trees **24.9%**
Other open vegetation + fields **12.5%**
Buildings **17.1%**
Impermeable surface + roads **42.7%**

legend
Other open vegetation
Trees > 20 m
Trees 10–15 m
Trees 15–20 m
Trees 2–10 m
Buildings
Road
Impermeable

<u>Page 78</u>
Kaleva
Wind comfort
Less windy (hotter)
Windier (cooler)

Radiation temperature, average
More solar radiation (hotter)
Less solar radiation (cooler)

Thermal sensation (UTCI)
Hotter
Cooler

<u>Page 79</u>
City centre
Surface temperature: 37.4 (q25) – 38.8 (q75) °C
Trees **5.6%**
Other open vegetation + fields **1.4%**
Buildings **43.9%**
Impermeable surface + roads **46.3%**

legend
Other open vegetation
Trees > 20 m
Trees 10–15 m
Trees 15–20 m
Trees 2–10 m
Buildings
Road
Impermeable

<u>Page 80</u>
City centre
Wind comfort
Less windy (hotter)
Windier (cooler)

Radiation temperature, average
More solar radiation (hotter)

Less solar radiation (cooler)

Thermal sensation (UTCI)
Hotter
Cooler

<u>Page 81</u>
Industrial zone – Lielahti
Surface temperature: 40.9 (q25) – 41.9 (q75) °C
Trees **5.6%**
Other open vegetation + fields **7.0%**
Buildings **23.7%**
Impermeable surface + roads **61.8%**

legend
Other open vegetation
Trees > 20 m
Trees 10–15 m
Trees 15–20 m
Trees 2–10 m
Buildings
Road
Impermeable

<u>Page 82</u>
Lielahti
Wind comfort
Less windy (hotter)
Windier (cooler)

Radiation temperature, average
More solar radiation (hotter)
Less solar radiation (cooler)

Thermal sensation (UTCI)
Hotter
Cooler

Page 84
"Feels like" temperature
Air temperature
Humidity
Solar radiation
Wind speed

Physiological model
Clothing model