Mitigating the Urban Heat Island Effect in a Local Context

- How wind and vegetation regulate temperatures during summer, with an example from the grounds of Karlstad Central Hospital, Sweden.

Lokala åtgärder för att minska värmeöeffekten - hur vind och vegetation kan skapa bättre temperaturer och klimatförhållanden för utemiljön vid Centralsjukhuset i Karlstad, Sverige.

Patricia Kirkhorn

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Abstract

Climate change is the cause of more weather extremes. Cities' dense configuration, heat absorbing surfaces and low amount of vegetation leads to higher temperatures within cities known as the urban heat island effect (UHI). Mitigating and adapting to warm temperatures is of great importance to minimise the risk of people suffering from heat stress and for avoiding high energy usage for cooling. This thesis researches how vegetation, especially trees, interacts with wind and solar radiation using Geographical Information Systems and microclimate modelling, with aim for greater understanding how to use nature based solutions within cities. The study takes place at the Karlstad region hospital area in Sweden. Scenarios with different amounts of trees and respective leaf area density were modelled in a unvegetated area enclosed with buildings on two sides. The results showed that vegetation slightly changes wind speed while the wind patterns are more affected by vegetation. Air temperature reduction is highest under the trees and its near surroundings. The result showed that the amount of trees matter; more trees evens out and lower temperatures in a wider area. Thus, the overall physiological equivalent temperature (PET), which considers the heat balance of the body, air temperature, incoming solar radiation, wind movement and humidity, found that wind and vegetation best together improves thermal comfort during warm seasons. This thesis illustrates the complex challenges in cities and the many interactions leading to higher temperatures. Understanding a place's prerequisites, meteorological conditions, vegetation aesthetic and technical functions is key for providing a long term sustainable design. Further research assessing more seasons and sites is suggested to evaluate the results viability.

Abstrakt

Klimatförändringar är orsaken till fler väderextremer. Städernas täta sammansättning, värmeabsorberande ytor och låga mängd vegetation leder till högre temperaturer som orsakar den urbana värmeö effekten, på engelska Urban Heat Island (UHI). Att mildra och anpassa sig till varma temperaturer är av stor vikt för att minimera risken för att människor ska drabbas av värmestress och för att undvika hög energianvändning för nedkylning. Denna uppsats undersöker hur vegetation, särskilt träd, interagerar med vind- och solstrålning med hjälp av GIS och mikroklimatmodellering, med syfte att öka förståelsen för hur man använder naturbaserade lösningar inom städer. Studien tar plats vid Karlstad regionsjukhus i Sverige. Scenarier med olika mängd träd samt olika bladyttäthet, Leaf Area Density (LAD), modellerades i ett område omslutet av byggnader på två sidor med relativ låg andel vegetation. Resultaten visade att vegetationen ändrar vindhastighet något medan vindriktning påverkas mer av vegetationen. Sänkningen av lufttemperatur är högst under träden och dess närliggande omgivningar. Resultatet visade att mängden träd har betydelse, fler träd jämnar ut och ger lägre temperaturer i ett större område. Således fann resultatet att den övergripande Physiological Equivalent temperature (PET) som förklarar den upplevda temperaturen, vilket inkluderar vind, solstrålning och lufttemperatur, att vind och vegetation i samspel som bäst förbättrar den termiska komforten under den varma säsongen. Detta examensarbete illustrerar de komplexa utmaningarna i städer och de många interaktioner som leder till högre temperaturer. Att förstå en plats förutsättningar, meteorologiska förhållanden, vegetationens estetiska och tekniska funktioner är viktigt för att uppnå en långsiktig och hållbar design. Ytterligare forskning som bedömer fler årstider och platser föreslås för att utvärdera resultatets tillförlitlighet.

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Abbreviations

BAI	Branch Area Index
DEM	Digital Elevation Model
DSM	Digital Surface Model
GEE	Google Earth Engine
GIS	Geographical Information Systems
IPCC	The Intergovernmental Panel on Climate Change
LAI	Leaf Area Index [Leaf area (m^2) / Ground cover (m^2)]
LAD	Leaf Area Density [Portion of leaves (m^2) / Reference volume (m^3)]
LST	Land Surface Temperature
NDVI	Normalised Difference Vegetation Index [NDVI= NIR-RED/NIR+RED]
NIR	Near Infrared
Red	Refers to the Red Band from an Orthophoto IRF (out of 3; Nir, Red, Green)
SR	Solar Radiation
T	Air Temperature
UHI	Urban Heat Island
K	Kelvin [- 273,15 ^{o}C]
PET	Physical equivalent temperature
.Shp	Shapefile

Glossary

ENVI-met - a microclimate modelling tool

Shapefile - a file format in vector form for storing geographic data such as geographical placement, boundaries of an area or a group of points.

ArcMap - a software for displaying, creating, editing and analysing GIS datasets

LiDAR - Light Detection and Ranging data, elevation data in the form of laser points from airplanes or satellites.

Vector layer - A feature of lines, points or polygons in digital format that represent real features.

Orthophoto - Scaled aerial photo which is projected flat from an overhead view.

Evaporation - the process turning liquid to vapour.

Transpiration - evaporation from leaves.

Evapotranspiration - The process of absorption of water by plant roots and its subsequent evaporation from lead stomata.

Microclimate - a climatic condition in a small area differing from nearby areas.

Raster data - Consists of cells organised as a grid where each cell contains a value or represents information.

Digital elevation model - is a bare earth raster with no ground features included, which could implicate buildings and roads.

Digital Surface Model - captures both the ground surface and elevation features above earth, such as buildings and trees.

Near Infrared - refers to light with wavelengths from 800 to 2,500 nm.

Thermal band - provides temperature in Kelvin. In this work thermal bands are derived from Landsat 8 satellite data.

Thermal comfort - A term for describing the exchange of heat and the experienced temperature of the body.

Air temperature - A measure of cooling or heating provided from the air.

Mean radiant temperature - A measure of how much cooling or heating from the radiant heat transforms into the environment.

Remote sensing - Measurements and obtained data through satellites or aircrafts.

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Chapter 1

1.1 Introduction

Global climate change is induced by human activities and is affecting weather and causing more weather extremes such as drought, heatwaves and heavy precipitation. Global surface temperatures have been increasing and are expected to continue to increase to the mid century in all estimation scenarios made and presented by the Intergovernmental Panel on Climate Change, IPCC (Masson-Delmotte, Zhai, Pirani, Connors, Péan, Berger, Caud, Chen, Goldfarb, Gomis, Huang, Leitzell, Lonnoy, Mattews, Maycock, Waterfield, Yelekçi, Yu and Zhou, 2021). A substantial reduction of gas emission is needed if the global surface temperatures shall not exceed 1.5 to 2 degrees celsius during this century (Masson-Delmotte et al. 2021).

The Urban Heat Island effect, UHI, means higher land surface temperatures, and air temperatures, in cities compared to outlying areas (Weber, Haase and Franck, 2014). As such UHI is a key concern to city planners and designers and has to do with the fact that darker materials, often impervious surfaces and buildings absorb rather than reflect solar radiation. The solar radiation heats up the materials which leads to a slow release of heat that is causing higher land surface and air temperature both day and night. Light materials and vegetation reflect some of the solar radiation back through the atmosphere which can help mitigate the urban heat island effect (NASA arset 2020; Hsieh and Huang 2016).

Heatwaves are expected to occur more often in the future due to climate change (Masson-Delmotte et al. 2021). Higher air temperatures can lead to heat stress, dehydration, fatigue, higher blood pressure, cardiovascular diseases and even higher mortality rates (Weber et. al 2014). Children, elderly, pregnant women and people with different illnesses and disabilities are at particular risk of being affected by higher temperatures (SMHI, 2018). Earlier work has shown that vegetation, elevation, wind and humidity among others has an impact on land surface temperatures and air temperatures, e.g areas with vegetation often have lower land surface temperatures compared to impervious surfaces (NASA arset 2020; Wu and Zhang 2019; P. Kirkhorn, personal communication 2021). Vegetation reflects solar radiation to a greater extent and can help mitigate heat through cooling by evapotranspiration and shade (Ennos, 2015).

We face many challenges when it comes to adapting and mitigating climate change. Cities are becoming denser at the same time as the climate is becoming warmer. This places even higher demands on urban planning in order to adapt and mitigate the negative effects. Vegetation is a part of the solution when it comes to climate adaptation, it can provide many ecosystem services such as shadow, coolness together with social and recreational values. But type of vegetation, location and more can be crucial when it comes to contributing to better microclimate within the cities. Wrong placement of vegetation can obstruct the wind, especially if it has a denser crown structure (Deak Sjöman, Sjöman and Johansson, 2015). In summer, lower wind speed can affect the perception of temperatures and increase thermal discomfort causing negative effects on humans and at the same time reinforce the urban heat island effect (SMHI 2018; Errel et al. 2015).

This work is aimed at improving understanding of the issues stated above. The work is based on a literature review together with ENVI-met- and GIS modelling and analysis. A manual tree inventory within the study area was made in october 2021 (See appendix B). The general research procedure can be summarised as (a) literature review (b) tree inventory for Leaf Area Index (LAI) and Leaf Area Density (LAD) estimation (c) Data collection and the creation and visualisation of maps by using GIS-programmes (d) analysis of the data; for (e) model microclimates using GIS and ENVI-met.

1.2 Issue and research objective

Vegetation's and wind's regulatory effect on mitigating urban heat is widely acknowledged (Lehmann, Mathey, Rößler, Bräuer and Goldberg, 2014; Sawka, Millward, Mckay and Sarkovich. 2013; Dimoudi, Kantzioura, Pallas and Kosmopoulos, 2013), and vegetation is traditionally used for windbreaks in agricultural landscapes, but research has found that there are many challenges when it comes to mitigating urban heat with vegetation in cities. It can be problematic to add more vegetation in cities due to lack of space or the risk of trees obstructing the necessary ventilation. Lower wind speeds during hot summer days leads to higher air temperatures, it may increase thermal discomfort and increase experienced heat stress (SMHI, 2018; Brown and Brown, 2010). Shade on buildings from trees can contribute to better indoor climate during summer while during winter it may increase energy usage in buildings (Weber et al. 2014). Higher surface temperatures during summer may also lead to trees experiencing heat stress which leads to decreased evapotranspiration and cooling provided from the tree itself (Hirons and Thomas, 2018) This in turn may prevent certain tree species to function accordingly with inevitable loss of ecosystem services.

The objective with this research is to analyse vegetation and in particular deciduous trees, wind and solar effects on temperatures in cities in the context of the hospital area in Karlstad, Sweden, by analysing and visualising it using ArcGIS and ENVI-met. The objective is to analyse how wind is modified by the amount of vegetation and its placement, and if different leaf densities, which might arise from different kinds of species choice, are more or less effective for mitigation of high air and land surface temperatures. This topic is complex since many factors interact and impact cities' climates and temperatures. The factors that are affecting vegetation and wind which can cause higher temperatures in cities need to be investigated and considered as well for understanding the prerequisites for mitigating urban heat island with vegetation. Part of this objective is to develop understanding and skills in using the ArcGIS and ENVI-met programmes.

Research question

How does leaf area density and numbers of trees affect temperatures and wind?

Sub question

What are the thermal comfort conditions with regard to changes of leaf area density and number of trees?

1.3 Case study - Karlstad central hospital

Figure 1. Orthophoto over Karlstad city X 59°22'45.48" N 13°30'12.85”E. *Orthophoto 0.5 m (2018) © The National Land Survey (Lantmäteriet).*

Karlstad city (59°22'45.48" N 13°30'12.85) is an urban area in Värmland, located north of lake Vänern, Sweden. Karlstad central hospital was chosen as the study site and is the largest one in the Värmland region. The hospital is for the inhabitants of Karlstad municipality as well as a county hospital with specialised health care (Region värmland, 2021). Cultivation zones are an indicator of growing conditions for plants from mild (1) to severe (8). Karlstad is in cultivation zone 3 (Svensk trädgård, 2021) but within cities the local microclimate can correspond to lower climate zones due to the city configuration (Deak Sjöman et al. 2015). Prevailing winds in Karlstad come from the south or southeast (SMHI, 2021a), with a mean wind speed of 3,5 m/s (SMHI, 2006)

In earlier studies focusing on the urban heat island effect and vulnerabilities, the hospital area in Karlstad was found to be one of them (see Kirkhorn 2019, appendix F, can be supplied on request). The hospital area is more likely to be vulnerable for experiencing the urban heat island effect due to lots of dense buildings, extensive impervious surfaces and lower amount of vegetation. This combined with the fact that the patients in hospitals are often from groups vulnerable to heat stress and have additional health problems (SMHI, 2018). Outdoor environments have an importance for recovery from illness and contribute to wellbeing. It is therefore important to mitigate heat where it might be a barrier to patients accessing greenspace safely. This also makes the central hospital in Karlstad a priority area for attention and a good place for this study.

Figure 2. Karlstad central hospital area seen from above, facing south. River Klarälven runs next to the study area. (Reprinted with kind permission by Jens Magnusson, Region Värmland, 2016).

1.4 Delimitation

This paper focuses on wind and vegetation as adaptation tools and a mitigation method for urban heat island effects. The causes of climate change are many and there are challenges to mitigating and adapting to these; hotter climates, more densification, lack of space and an increased need for multiuse. It has to do with competing priorities for urban configuration, with densification and that the amount of impervious surfaces are likely to increase, which leads to increasing air temperatures (Masson-Delmotte 2021). Vegetation can be used to mitigate heavy rainfalls and provides many ecosystem services (EPA 2021), but these are not further investigated in this project. This all matters as regards mitigation of and adaptation to hotter climates and should ideally all be included in this research. The social aspects and vegetation's positive effect on health had to be delimited in this research but its importance should not be diminished. Considering the winter season is important, but this project had to be delimited and focuses mainly on the summer season due to time considerations in this project.

Chapter 2 - Literature review

2.1 Climate Change and the Urban Heat Island Effect

Climate change is expected to increase the frequency and intensity of heat waves (Weber et al. 2014; Pörtner, Roberts, Poloczanska, Mintenbeck, Tignor, Alegría, Craig, Langsdorf, Löschke, Möller, Okem, 2022). The urban heat island effect is defined by an increase of temperatures in urban areas compared to outlying, rural, areas (Oke, 1987). Urban heat island is mostly apparent during nighttime due to buildings- and surface characteristics which materials release heat slowly. Asphalt, stone, brick, concrete have a high heat storage capacity from incoming solar radiation. In rural environments, the ground is able to cool down, which lowers air temperatures (Erell, Pearlmutter and Williamson, 2015).

The urban heat island effect (UHI) can occur all year round but its occurrence during the summer months is of most concern since heat and higher temperatures leads to an increase of energy use by an higher demand for air conditioning, together with heat stress related illness and mortality (Rosenzweig, Solecki, Parshall, Gaffin, Lynn, Goldberg, Cox and Hodges, 2006; Kleerekoper, van Esch and Salcedo, 2012) UHI is not as severe in Sweden yet compared to southern latitudes but in the future, with expected climate changes and higher temperatures, the UHI effect will have a greater impact in Sweden and the need for cooling in cities is expected to increase. How strong the urban heat island effect becomes depends on weather conditions, solar radiation, materials and on wind. In cities wind speed can be lower due to urban configuration (Dimoudi et al 2013). Clouds prevent some of the solar radiation from hitting the ground which leads to a lesser increase of surface temperatures compared to days with clear sky (Deak Sjöman et al. 2015).

Heat and humidity rates vary across cities and in comparison to rural areas. Building configuration, water bodies, infrastructure and vegetation creates different structures and networks within the city (Wu and Zhang 2019; Deak Sjöman et al 2015). Higher population enhances heat emittance (Schneider dos Santos 2020; Hsieh and Huang 2016**)**. The near surrounding landscapes also affect the climate within cities. Topography, altitude and water bodies nearby have an effect on temperatures (Schneider dos Santos, 2020). The interaction between surface heating and local meteorology impacts and determines the intensity of the urban heat island effect (Rosenzweig et al. 2006), together with geographical location (Deak Sjöman et al. 2015). Land surface temperatures influence air temperatures and they are strongly correlated, but not equal in temperature. Land surface temperature is generally higher than air temperatures during summer (Weber et al. 2014).

Urban heat islands occur due to impervious surfaces, buildings dense formation and infrastructure absorbs solar radiation and releases the heat slowly leading to higher temperatures. Impervious surfaces tend to be water resistant which reduces the amount of evaporation and cooling provided by soil. In urban areas where naturally vegetated structures are reduced, less natural cooling is provided (Rosenzweig et al. 2006; Hsieh and Huang

2016). In addition to solar radiation and meteorology, industries and cars emit heat and further contribute to the urban heat island effect. The amount of sky view visible in the city affects temperatures; the less amount of sky visible from ground the higher temperatures can be measured (Deak Sjöman et al. 2015). All these factors add up which contributes to hotspots with warmer microclimates which adds up to the urban heat island effect (Rosenzweig et al. 2006).

2.2 Vegetation's Impact on City Climate - Positive and Negative Ecosystem Services and Effects

Vegetation is an important element in cities. It provides many ecosystem services for cooling like shade, evapotranspiration and reflecting of solar radiation (Ruefenacht and Acero 2017). Vegetation influences microclimates and can be used as a nature based solution for mitigating heat in cities. Trees affect temperatures and can provide better comfort by shading, evapotranspiration and by altering wind flows and humidity (Sawka et al. 2013). Wind flow is needed in cities for coolness during hot summer days (Ruefenacht and Acero 2017). By using trees and other vegetation and cultivating natural systems within cities, energy can be saved. Vegetation can be used for cooling, and especially trees reduce heating of buildings in summertime by shading and cooling of its near surroundings. In cities, where buildings are closely spaced, the energy used for cooling indoors can be reduced by adding trees (Sawka et al. 2013).

The quantity of trees and shading provided is determined by species, canopy volume, crown shape, leaf area, foliation and location (Sawka et al. 2013; Ruefenacht and Acero 2017). The tree's placement relative to the building affects the cooling effect provided by the tree (Sawka et al. 2013; Nikoofard, Ugursal and Beausoleil-Morrison, 2011). Trees contribute with more shade and obstruct wind better with age, as other ecosystem services grow (Deak Sjöman, Hirons and Sjöman, 2016).

There are challenges when it comes to adding vegetation to cities. The benefits from trees are many, but the desired effect from trees during summer, such as shade, can give less desired effects during winter. Shaded facades during winter may cause cooling with more energy used for heating as a result (Sawka et al. 2013). The need for planning and consideration for both summer heat and winter coolness is necessary when it comes to adding trees in cities (Deak Sjöman et al. 2015). Although Sawka et al. (2013) found that in mid latitude cities the amount of electricity saved during summer by shading from trees outweighs the increased amount of energy used to heat the building during winter. Trees placed west of the building provide lengthened shadows and most indoor cooling. Trees placed east of buildings have the second most significant effect on indoor cooling. Placement south of, especially close to, buildings shadows buildings well during daytime, but the shaded area is limited. Trees placed north of buildings provide no shadow and have no cooling effect on buildings in the northern hemisphere (Sawka et al. 2013).

Providing good thermal comfort during summer and winter is challenging in temperate climates. Sjöman et al. (2016) investigated how trees and their crown density affects temperature and wind in an urban area. They found that the more branches a tree has, the better it obstructs wind and raises temperatures during winter by lowering wind speed. This is an important aspect to consider during wintertime when cold winds are likely to create an unpleasant climate in cities. During summer wind is needed to provide cooling and trees that provide shadow and evapotranspiration are of importance to mitigate urban heat (Ennos, 2015).

Sawka et al. (2013) emphasises the difficulties of adding more vegetation in cities due to competition of space. There are challenges to add vegetation in narrow streets, near buildings and already existing vegetation needs to be taken into consideration. Finding the right placement for new trees is important in the long term, but existing trees should at the same time be protected so they can age. Older trees provide more ecosystem services than young ones. They therefore outweigh the advantages of removing old trees and planting new trees in the considered "right" place. Further on they argue that it is more important to plant trees where they can thrive and be long lived and not have to compete with other vegetation or be stressed to provide as many eco services as possible (Sawka et al 2013).

The distribution of vegetation matters when it comes to influencing and lowering temperatures. Group plantations, single trees, surface plantations and alleys have different effects on air temperature (Ruefenacht and Acero, 2017). Larger group plantings with trees have a higher cooling effect, and the effect can be measured on the treestands surroundings. Single trees and alleys provide shadow and have a cooling effect in its closest surrounding. The differences in surface temperatures of the shaded area, differs more than non shaded surfaces, compared to air temperatures in sunlight exposed and shaded areas (Ruefenacht and Acero 2017). Single trees as well dense canopies can improve thermal comfort but at the same time, depending on placement, it can actually increase the urban heat island effect by decreasing the windflow and leading to higher temperatures (Ruefenacht and Acero 2017; Deak Sjöman and Johansson, 2020)

Tree characteristics, leaf size, leaf and branch density affects the microclimate (Ruefenacht and Acero 2017; Deak Sjöman et al. 2016). It affects the microclimate by affecting windflow and it matters when it comes to shading. Placement also matters because of its ability to shadow and protect from solar radiation (Ruefenacht and Acero 2017). The tree's potential cooling effect is also determined by its ability to evaporate and its leaf period duration. A tree sensible to heat stress loses its leaves and is no longer able to provide coolness. The knowledge about, and choice of, tree species is thus very important. The right hardiness, provenance and site tolerance is essential for the ability to provide cooling and other ecosystem services. Other factors affecting trees such as wind, conflicts of space and microclimate conditions should be considered for a long term sustainable design (Sjöman, Hirons and Deak Sjöman, 2017).

There are challenges when it comes to establishing and growing trees long term within the city. The conditions vary depending on site, on wind, if it is a warm street or a cooler park and on ground conditions. Some trees need heat to be able to establish but other, often native species experience heat stress in dry and warm climates. Tree placement in relation to buildings also matters due to wind and that these places are more shadowed. Considering trees' ability to adapt to shadow and heat must therefore be considered. Placement and species used have to be considered for a long term sustainable treestand. (Hirons and Thomas, 2018).

Vegetation has an impact on surface cooling through evaporation. Vegetation, urban forestry, green roofs and light surfaces due to its high albedo values can be used to mitigate heat islands (Rosenzweig et al. 2006; Deak Sjöman et al. 2015). Preserving the existing and increasing amount of vegetation is one of the best ways to mitigate the urban heat island effect (Deak Sjöman et al. 2015)

2.3 Wind

Wind corridors are one of the main mitigation strategies for the urban heat island effect (Hsieh and Huang 2016). Wind provides cooling and thermal comfort during summer. It modifies urban microclimates by affecting water vapour and thermal energy transportation (Sawka et al. 2013). Wind evaporates perspiration from the human body, soil, water bodies and from vegetation (evapotranspiration) during hot summer days leading to better thermal comfort and lower temperatures (Theeuwes, Solcerová and Steeneveld, 2013.; Sciencing 2018). Higher wind speeds accelerate the evaporation from the body leading to the feeling of lower body temperature (Sciencing 2018). For instance, wind affects the cooling provided by evaporation and evapotranspiration, and it affects the wind chill during the winter season. These phenomena affect thermal comfort and how temperature is perceived, but is not equal to actual air temperature.

Wind chill index was developed by Steadman (1971) and describes how wind speed and temperature affects the perceived temperature of humans in temperatures below 10°C. The perceived temperature lowers when increased wind speeds enhance heat loss from the body (Steadman 1971). For instance when the air temperature is 0°C and wind speed is 2,7 m/s, the apparent temperature is -3°C, according to a calculated wind chill index (Bergfreunde. n.d). Wind chill is not linear but exponential and is mostly dependent on wind speed (Steadman 1971). The same effect from wind is given during the summer season when evaporative cooling increases with higher wind speeds (Roshan, Moghbel and Shady Attia, 2020).

By this, it can be concluded that wind provides cooling for all seasons and that the cooling effect is dependent on wind speed (Steadman 1971). An issue is that high wind speeds can be undesirable during winter season due to thermal discomfort and increased energy usage (Sawka et al. 2013), while during the hot summer season wind is desirable due to its ability to enhance cooling effect by evaporation and evapotranspiration (Hsieh and Huang 2016; Sawka et al. 2013).

2.3.1 Wind movement and porosity

The urban heat island effect, the amount of air pollution and air temperature distribution within cities is related to urban geometry e.g the urban configuration impacts the thermal comfort and microclimates within cities due to its ability to impair the airflow's ability to circulate (Krüger, Minella and Rasia, 2011). Vegetated areas in cities, such as parks, contribute to air inflow due to temperature changes (Deak Sjöman et al. 2015).

When buildings are even in height and formation or follow an aerodynamic profile the wind goes over it, while if the building configurations are uneven the wind is likely to go down on street level (Oke 1987). How the wind moves differs between cities and countryside. The wind speed is generally lower in cities due to dense building configurations slowering the wind speed. At the same time the wind speed varies heavily within the city, turbulent gusts of wind are more frequent. The wind speed depends on building height, street formation and width. Buildings create differential pressure on the windward and leeward side of the building which leads to higher wind speeds on the building's sides and on its backside, while closest to the building there is often lee (Deak Sjöman 2015). Wind stagnation is a risk in cities because it can cause cumulative effects such as higher temperatures and pollution hotspots (Krüger et al. 2011).

Trees affect wind and can be useful to modify wind. Their crown structure and density, Leaf area index (LAI) and branch area index (BAI) influence the wind porosity (Deak Sjöman et al. 2016) The porosity for windbreak is important for monitoring wind in cities, especially during winter season. Brown and Brown (2010) found that the porosity matters, if the porosity is too dense it tends to reduce wind only in the immediate zone behind the windbreak and rather cause wind speed to increase and become fairly quickly and strong again. On the other hand, if the porosity is intermediate, e.g 40 percent, an ameliotoring and more long lasting effect on wind reduction will occur and be prolonged for a much larger area. The height of the windbreak also plays a significant role, the higher the tree is, the better it breaks the wind (Brown and Brown, 2010).

2.4 Solar Radiations Impact on Thermal Comfort

Solar radiation has the most significant effect on thermal comfort. Solar radiation comes in several wavelengths. They can be divided into three sections; ultraviolet (UV) visible and infrared (IR), each of which has subsections. It is the total incoming solar radiation that affects the thermal comfort, rather than a specific wavelength, but the key range is IR (Hodder and Parsons, 2006). Shade minimises the amount of solar radiation received on the human body and prevents solar radiation from warming surfaces and temperatures from rising (Rosenzweig et al. 2006). When the incoming solar radiation and land surface temperatures are high it is suitable to add trees for shade and evapotranspiration, but only when soil and water conditions are good enough so the trees can thrive, otherwise they can not evapotranspirate (Sjöman et al. 2017). In places where ground conditions are poor and can not provide enough space, nutrients and water for the vegetation to thrive, the evapotranspiration is likely to decrease and the cooling effect from trees can be lost (Sjöman et al. 2017). Artificial shade is then better to use to shield from solar radiation and at the same time ensure wind corridors for cooling to mitigate the heat (Hsieh and Huang 2016). The height and density of buildings determines how much incoming solar radiation that remains or returns to the atmosphere. Denser building areas tend to get warmer due to preventing solar radiation from returning to the atmosphere (Sjöman et al. 2017).

2.5 Literature review conclusion

The phenomena of the Urban Heat Island effect was first mentioned in 1818 by Luke Howard (Howard 2012) and have been confirmed in many studies (Oke, 1982; Voogt, 2002; Rosenzweig et al. 2006; Theeuwes, 2017) and means higher temperatures within cities compared to outlying areas. It is often most prominent during nighttime (Weber et al. 2014). Urban heat islands affect thermal comfort, moreover it can alter local climatology, wind patterns, humidity, pollution (Dimoudi et al 2013), and potentially affect wildlife through longer growing seasons (Zipper, Schats, Singh, Kucharik, Townsend and Loheide, 2016) It is caused by complex interaction of land cover usage, vegetation, water bodies, topography, building configuration, humidity, impervious surfaces heated by solar radiation and human activities affecting thermal indices (Wu and Zhang 2019; Dimoudi et al. 2013; Weber et al. 2014).

Vegetation, including trees, greenery, green roofs and urban forestry is a topical issue for mitigating Urban Heat Island effects together with other climate change related issues (Pauleit, Zölch, Hansen, Randrup and Konijnendijk van den Bosch, 2017). Reduced vegetation within cities has led to less cooling provided by shade and evaporation (Rosenzweig et al. 2006; Hsieh and Huang 2016). Nature based solutions is a modern term first mentioned around 2008 (Sowiriska-Sweirkosz and Garcia 2022) and includes several related concepts, such as ecosystem services, ecological engineering, ecosystem based adaptation and green infrastructure, to highlight the importance of biodiversity. Nature based solutions focus on integrating nature in urban environments for mitigation and adaptation to climate change and for achieving resilience and sustainability (Pauleit et al. 2017).

Human induced climate change has accelerated and become noticeable since the middle of the last century (Masson-Delmotte et al. 2021). The evidence and understanding for using nature to mitigate environmental changes has increased the interest for nature based solutions (Pauleit et al. 2017).

The complexity and issues presented in this chapter lead to a desire to research trees' function, mix, crown structure, density and number in relation to air temperature change and wind changes, while also considering the urban pattern. Microclimate modelling is a tool for predicting variables affecting temperatures, wind and thermal comfort and enables modelling realistic sites. There are several microclimate modelling tools such as Envi-met, Rayman, Ladybug, Honeybee and more (Albdour and Baranyai, 2019). Envi-met was selected as it provides detailed vegetation modelling and considers variables of interest in this study (Helge 2016). Monitoring the urban environment through Geographical information systems (GIS) provides insights about spatial structures, thermal environments and periodic changes in landscapes. Remote sensing is a well established tool for assessing the Urban Heat Island effect (Wang, Liu, Tang and Wang, 2019).

2.6 Summary of chapter two

- The Urban Heat Island effect means higher surface and air temperatures within cities compared to rural areas.
- Heatwaves are expected to occur more frequently in the future and are a risk for people’s health.
- Materials absorb solar radiation and have different heat storage capacity, darker materials absorb more heat and release it slowly and enhance the Urban Heat Island effect.
- Solar radiation has a significant effect on thermal comfort and on temperatures.
- Cooling provided by vegetation can come from evapotranspiration and shade.
- Vegetation can be used as a windbreak and is useful to minimise unpleasant cold winds during winter.
- Wind provides cooling and is important for mitigating heat, but can also be problematic, especially during cold winters.
- Wind speed and temperatures are strongly affected by the urban configuration.
- Tree height and structure, placement and numbers of trees and total vegetation matters on the proportion of cooling.
- Shade from trees can benefit thermal comfort and energy usage during summer, while during winter it may enhance energy usage. This suggests that tree placement and the effect thereof have to be considered to achieve desired result.

Chapter 3 Material and method

3.1 Introduction

Recognising the potential to mitigate urban heat island effect with vegetation led to the method of spatially analysing the study site with GIS and creating a microclimate scenario in Envi-met for testing tree pattern effects on thermal comfort.

3.2 Field data - Tree inventory

A manual tree and bush inventory (see appendix B) in the Karlstad hospital area (59°22'29.1"N 13°28'48.1"E) were made in november 2021. Tree species, their habitus and ground conditions were assessed. The coordinates were established by using Google maps and the data was inserted in an Excel-file. The coordinates were then converted from WGS 1984 to Sweref 99 TM. Due to the Covid-19 situation a visit inside the hospital to reach inner courtyards was not possible and some trees have therefore been excluded from the inventory. Trees and bushes over three metres were assessed and documented in the inventory as well in the GIS-analysis. Bushes with a height under three metres were partly delimited in the inventory due to difficulties to separate them as individuals and because difficulties to investigate them using Lidar data in GIS. Bushes and trees under three metres were taken into account in the Envi-met model, but in a more generalised manner due to the limited range of shrubs and grasses to add in the model. The Excel-file (see appendix B) with the tree species was imported to ArcMap. Leaf Area Index, LAI, were estimated using working material from the doctoral thesis by Deak Sjöman (2016), Deak Sjöman et al. (2021) and Breuer et al. (2003). In the area of interest, the leaf area density, LAD, values were estimated as matching the default trees in Envi-met.

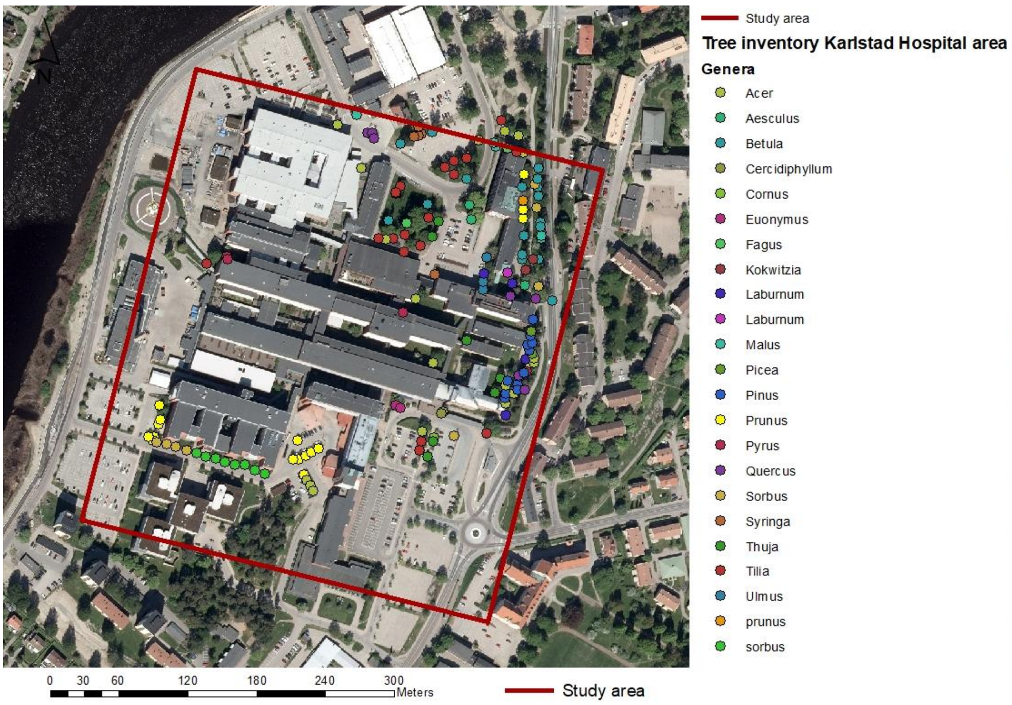


Figure 3. Tree inventory categorised by genera. Basemap orthophoto (2018) © The National Land Survey (Lantmäteriet).

3.3 GIS-analysis

Geographical information systems (GIS) can be used to analyse and visualise different types of data from a location (ESRI, n.d). Coordinate system Sweref 99TM was used since it is the official reference system in Sweden (National Land survey, n.d). There are many programmes that can analyse and visualise data. In this research ArcMap version 10.7.1 has been used the most. Google Earth Engine has also been used for easier data management and remote sensing analyses.

Geographical data come in several formats and often has to be converted or being processed before being used in GIS - programmes. Data accessed mostly come from The National Land Survey (Lantmäteriet) except from data from the tree inventory and Landsat data used in Google Earth Engine (GEE). Java scripts were used in GEE and come from a method and open code created by Ermida, Soares, Mantas, Göttsche and Trigo (2020). One important challenge has been to derive air temperature estimation from different parameters in GIS.

3.4 Envi-met

Envi-met is a simulation modelling tool which is made to assess microclimates (Krüger et al. 2011; Helge 2016). Envi-met requires detailed data and manual input of buildings, trees and surfaces. The programme visualises the result in 2D or 3D (Deak Sjöman and Johansson 2020). Envi-met offers a holistic approach on microclimates and can calculate three-dimensional wind movement, wind speed, humidity, solar radiation, radiative fluxes, air temperature, mean radiant temperature, pollution dispersion and more. The programme offers detailed vegetation modelling. The calculations provided by the programme are based on physical properties such as thermodynamics, mechanics and atmospheric physics. The model consists of cells representing objects such as surfaces, atmosphere, buildings or vegetation. The objects can have different properties; ground surface can for instance be asphalt, bare soil or concrete, all having different characteristics affecting the microclimate differently. Vegetation in Envi-met is represented as clusters of cells all having a leaf area density (LAD) (Helge 2016). Envi-met has several programmes and interfaces included for modelling, detailed tree modelling, simulations and so forth and they are all referred to as Envi-met in this thesis. Nine models in total were built, one over the whole hospital area and the other eight were built to simulate vegetation in the entrance area, including one only simulating wind.

3.4.1 Limitation and assumptions

The Envi-met programme seems to have some issues in accuracy when it comes to the near surface temperatures, especially in more complex model areas. Other limitations in the model area are the limits of boundary conditions, which in turn affect the simulation outcome (Helge, 2016). The need for empty cells at the border or nesting grids in the model is of importance for making the model stable (Envi-met n.d). The number of cells needed is dependent on the resolution (the higher resolution the more cells) and the model area. (Helge 2016). The need for empty cells means that some buildings had to be cut or that nearby buildings were excluded in the model area. By own experience, the more cells, larger model area and more elements in the model extends simulation time substiantally and one simulation can take days, even weeks, to finish. The long simulation times led to a tradeoff between fewer and simplified simulations over a larger area or more and detailed smaller model area where more scenarios could be tested.

3.4.2 Envi-met microclimate modelling

Envi-met version 4.6.6 and 5.0.2 have been used with a personal Envi-met Student Licence. A model over the Karlstad Central hospital area was created in Envi-met (see fig. 4). All surfaces were set as asphalt to get a baseline and to see how wind moves without vegetation within the study area. Later on a study area was chosen within the main study area. The main entrance to the hospital was surveyed with more detailed surface materials, trees and other vegetation were selected based on acquired data from the tree inventory, and buildings were created in a more general manner. The required input data for a simulation in the Envi-met model are climatic specific data such as date and duration, latitude and longitude, wind direction, air temperature at 2 metres height, wind speed at 10 metres height, humidity and roughness length (Helge 2016). Input parameters used are following; date 2019-07-30, time 24h start 5:00, Wind direction 225°, Wind speed 2,9 m/s (SMHI 2021b), Lowest air temp 14°C, Highest air temp 26°C (SMHI 2019**)**. Latitude (59.37), Longitude (13.47)**,** Humidity and roughness length were set as defaults, low 45% and high 75%.

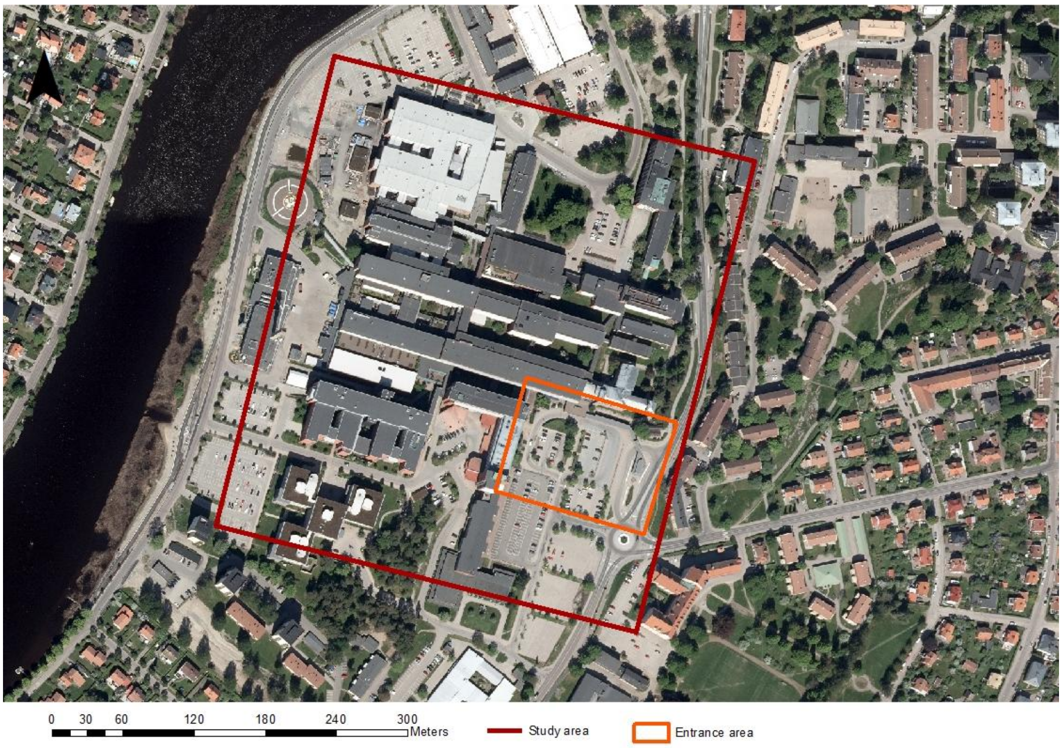


Figure 4. Model area for the hospital and entrance area in Karlstad. Basemap orthophoto (2018) © The National Land Survey (Lantmäteriet).

Based on the model over the hospital area in Envi-met, seven vegetated models and scenarios were set in the entrance area to explore how wind flow, different distribution of vegetation and leaf area density affect microclimate and air temperatures. An example of high leaf area density is a value more than 1.5, while more intermediate (mentioned as regular) values would correspond to values between 0.5-1.5 and low values are below 0.5. All comparison of results have been measured at a pedestrian level at 1,4 metre above ground. The first model with no vegetation was only used as a control map and was not included in the comparisons. First wind speed change was compared to the area's current vegetation. Secondly the scenarios were compared to that for the current vegetation in terms of air temperature change. Thirdly the physiological equivalent temperature (PET) change was compared.

The two first comparisons (wind and air temperature) were made to solely analyse the effect of the vegetation distribution, i.e how it affects wind speed and air temperature. The third comparison examines the impact on PET, how the body responds to its surroundings. PET can be calculated using Biomet, a programme included within the Envi-met programme, and includes air temperature and mean radiant temperature which have a strong influence on thermal comfort (Deak Sjöman and Johansson, 2017), solar radiation, wind speed and humidity (Höppe 1999).

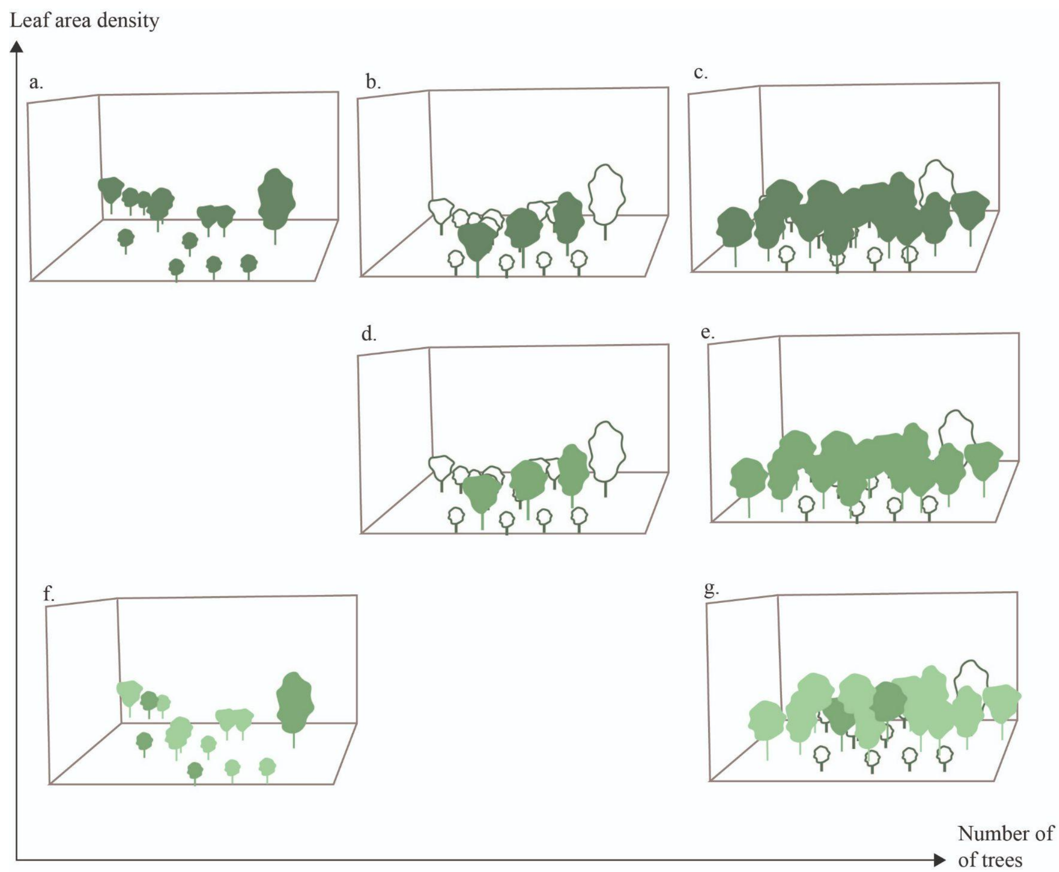


Figure 5. A visualisation diagram over tree modells in Envi-met. Existing grass, shrubs and trees are included in all models.

The vegetation models were divided into seven scenarios (fig. 5) within the same study area; current vegetation with extended leaf area density (fig. 5a), three new trees with high leaf area density (fig. 5b), twelve added trees with high leaf area density (fig. 5c.) three added trees with regular leaf area density (fig. 5d), twelve added trees with regular leaf area density (fig. 5e), current vegetation (fig. 5f), and current vegetation with a mix of twelve added trees with a low and regular leaf area density (fig. 5g). All scenarios have included existing grass, shrubs and trees.

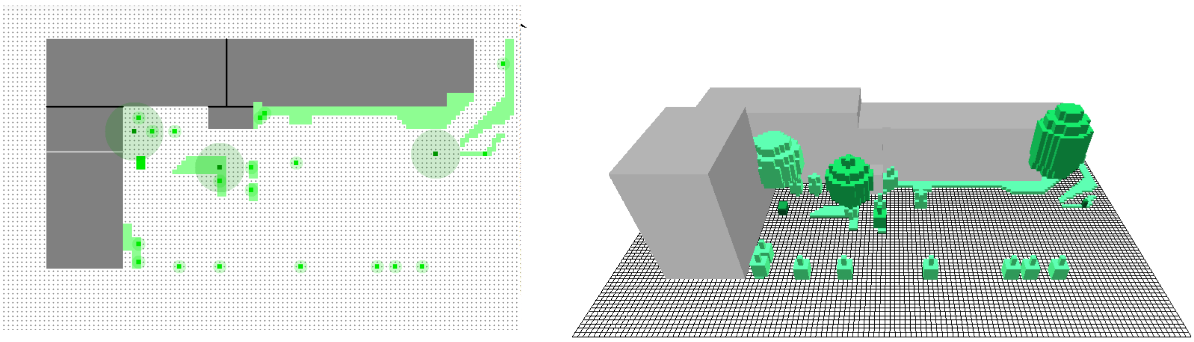


Figure 6. Screenshots over the Envi-met model seen from above and from the side, over the main entrance of the hospital area in Karlstad. The model includes existing vegetation including grass, shrubs and trees. Ground surface is set as concrete.

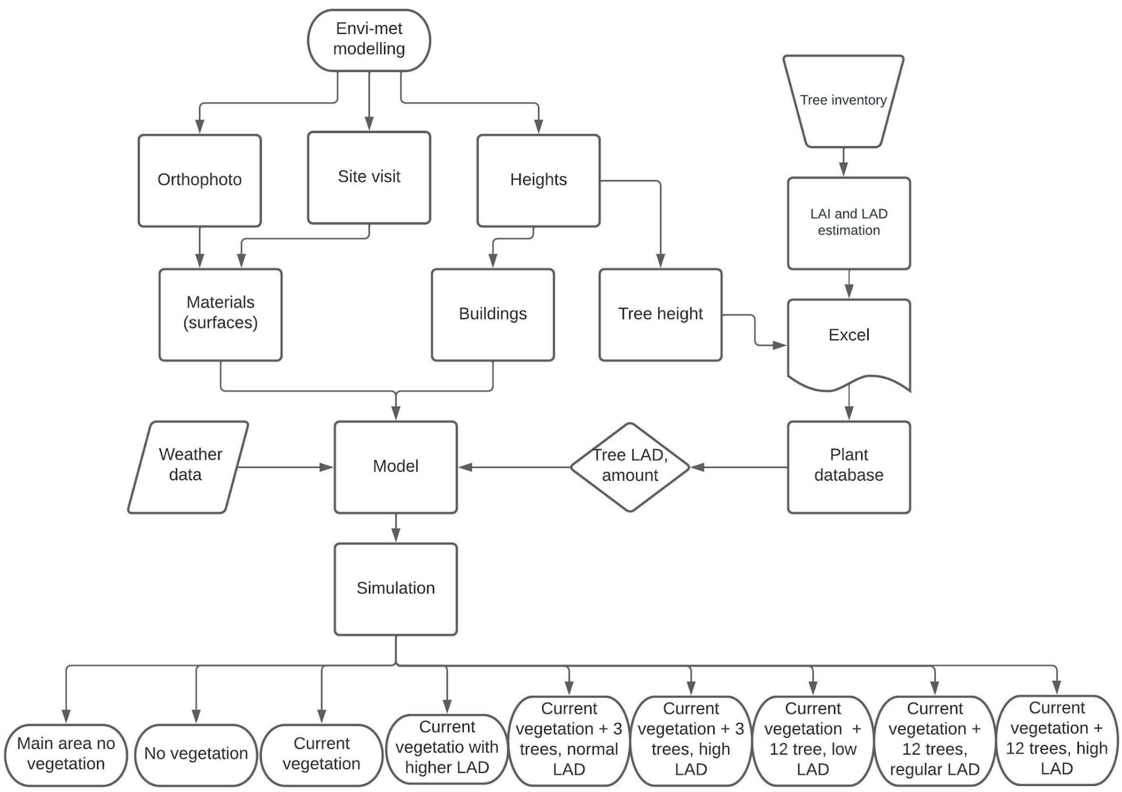


Figure 7 . Process flow diagram of the Envi-met process.

3.5 Data description

Lidar data from National Land Survey (Lantmäteriet) (2019). LiDAR (Light Detection and Ranging) data is elevation data in the form of laser measured points. The data is divided and classified in four categories, water, ground, uncategorised and bridges. The dataset used also came in categories of first hit, second hit, last hit etc. Point density is 0.5-1 points per square metre (Lantmäteriet, 2009). LiDAR data was used for the building- and tree height assessment. A Digital Surface Model and Digital Elevation Model was created from LiDAR.

Orthophoto (2018) and Ortho IRF (2012) were acquired through the National Land Survey (Lantmäteriet). NDVI and LAI were derived using ortho IRF in ArcMap by using the near infrared and red bands. Data format: Raster - Geotiff. Cell Size - 0.5 m.

Land Surface Temperature maps was created in GEE by using open-source code by Ermida et al. (2020) which then was rewritten to fit this research objectives and site. Data originates from Landsat using its thermal bands. Format: Raster - Geotiff. Cell size - 30 m.

Estimated air temperature An estimated air temperature map was created after Schneider dos Santos (2020) method for estimating air temperature (T) through a regression model. Regression models describe the relationship between certain variables to a set variable, in this case air temperature. NDVI, LST and Julian day (7.807) data were used in ArcMap because they have the highest correlation (r) to T. Other factors such as DEM (elevation), distance from water, longitude and latitude have an effect on the T but the correlation value is low (Schneider dos Santos 2020) and was omitted because it would not have any significant effect on the result in this particular case. A similar reasoning was made by Wu and Zhang (2019), which claims that elevation and water bodies have an effect on temperatures but also states that there is not a significant effect, and that cooling provided by water bodies is very limited to the nearby area. LST and NDVI have the biggest influence on T (Scheider dos Santos 2020; Wu and Zhang 2019).

Working area - a shape file (.shp) with the shape of the working area was defined.

Vector Layer of building geometry - Together with DSM, a Digital Surface Model, was used for calculating mean height of buildings.

Table 1.

Geodata sources used in this study with respective metadata.

Geodata	Year or Date	Projection	Collection agency	Resolution/Density	Raster/Vector
Ortophoto	2018	Sweref 99 TM	Lantmäteriet	0,5 m2/pixel	Raster
Ortho IRF	2012	Sweref 99 TM	Lantmäteriet	0,5 m2/pixel	Raster
Lidar dataset	2019	Sweref 99 TM	Lantmäteriet	0.25–1 points per m2	Point cloud
Build-up areas	2018	Sweref 99 TM	Lantmäteriet		Vector
Landsat data	2019-07-30	Sweref 99 TM	USGS	30 m2/pixel	Raster

3.6 The literature review

The literature review can be divided into two parts, the first one was done for defining the scope of the thesis, the second and in depth for examination of the specific topic. Title and abstract determined whether the literature was further examined. Search terms selected for this literature review consisted of; Urban Heat Island, Wind chill effect, Wind cooling potential, Vegetative cooling, Microclimates and nature based solutions among a few others. Terms were searched using various boolean commands to find the most appropriate articles. An indication of the importance of these topics is that each typically returns tens or hundreds of thousands of hits. Sources were chosen based on a number of criteria. Firstly, they had to align with the purpose of the literature review, objective and research questions. Secondly they had to be published and peer reviewed, and, or, published on reliable sites. Thirdly, studies made in geographical and meteorologically similar locations were primarily chosen when applicable. However, finding relevant studies with similar geographical areas were somewhat difficult, therefore research made in other climates was included but with careful considerations. Additional number of sources were found through the reference list in relevant articles together with provided literature by the supervisors of this thesis. Electronic articles were primarily searched using Primo and Google Scholar.

Chapter 4. - Results

This chapter presents the results from GIS analysis and from the simulated environment in Envi-met. Firstly the results from GIS are presented. Secondly the results from the simulations are presented. Multiple parameters are presented including wind speed, air temperature and physiological equivalent temperature.

4.1 GIS-results

Figure 8. Ortho IRF over the Karlstad and the hospital area. Ortho IRF 0,5 m (2012) © The National Land Survey (Lantmäteriet). Reflected near infrared, red colour in this photo, indicates vegetation (National Aeronautics and Space Administration, Science Mission Directorate 2010)

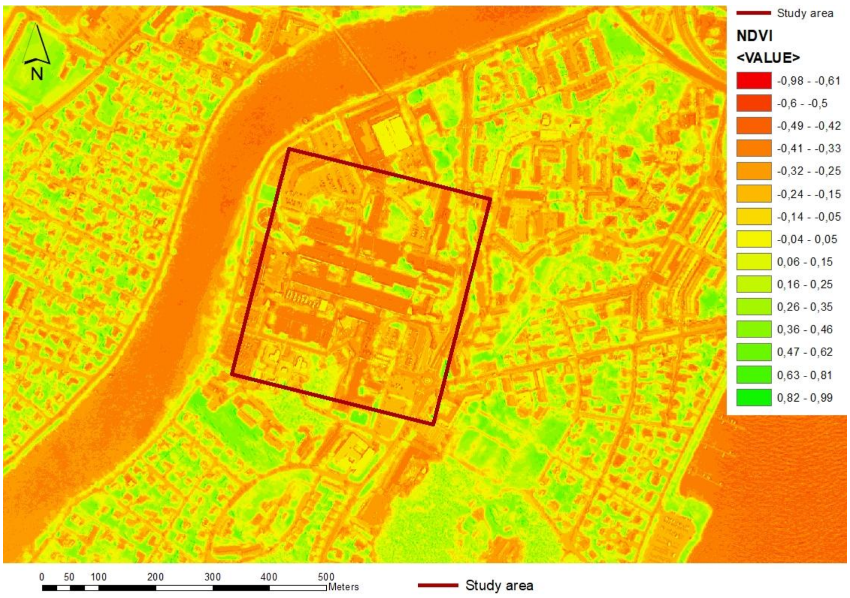


Figure 9. Normalised Difference Vegetation Index, NDVI map. Basemap Ortho IRF 0,5 m (2012) © The National Land Survey (Lantmäteriet).

NDVI (fig. 9) uses infrared to differentiate living vegetation (Klobucar et al. 2021). Values of 0.2 to 0.5 indicate sparse vegetation such as grasslands and shrubs. High NDVI values, approximately 0.6 to 0.9, indicate dense vegetation or crops at the stage of peak growth (USGS 2018). The result shows a relatively low amount of vegetation within the study area compared to the nearby surroundings.

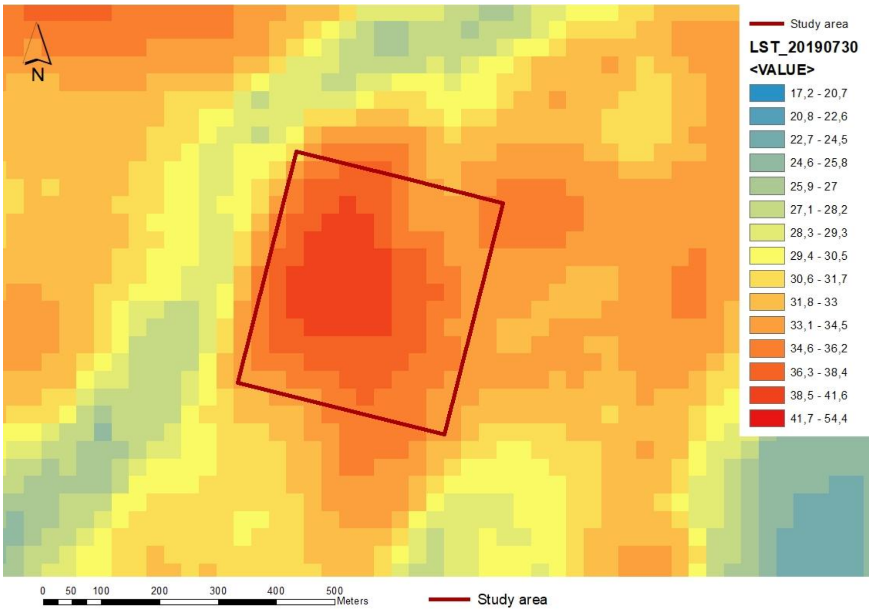


Figure 10. Land surface temperature map in °C from the date of 2019-07-30 (Google Earth Engine 2019). Highest land surface temperatures within the map can be found at the hospital area. Klarälven (the river in yellow and blueish colour indicates lower LST).

The result shows that land surface temperatures (fig. 10) are significantly higher within the study area, compared to the nearest surroundings. Nevertheless similar high temperatures can be seen in other places within the city centre. The substantial temperature differences are partly due to the water surrounding the city. Land surface temperatures are generally higher than air temperature during summer (Weber et al. 2014), which explains the high temperatures going up to 54 °C. As described earlier, the relation between vegetation and land surface temperatures are correlated (Schneider dos Santos 2020; Wu and Zhang 2019). This is also clear within this study area, a dense configuration and a lot of hardened surfaces with low amount of vegetation enhances the land surface temperatures.

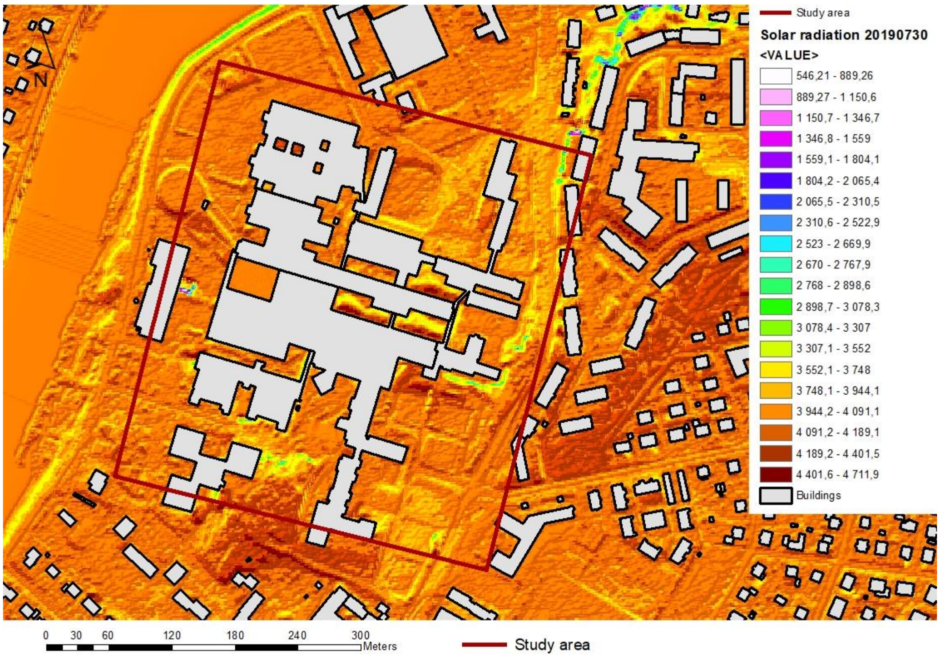


Figure 11. Incoming solar radiation (watt/m²) 2019-07-30 created with DSM based on Lidardata © The National Land Survey (Lantmäteriet). A property map of Build-up areas © The National Land Survey (Lantmäteriet) were added because only incoming solar radiation on ground surfaces was of interest and for increased readability.

Incoming solar radiation (fig. 11) rate is generally even within the study area. Slightly lower amounts of incoming solar radiation (yellow and green in the map) are seen in some areas and are likely due to shade from elevated areas. The entrance area investigated within Envi-met (see 4.2) has a particularly high incoming solar radiation near the buildings.

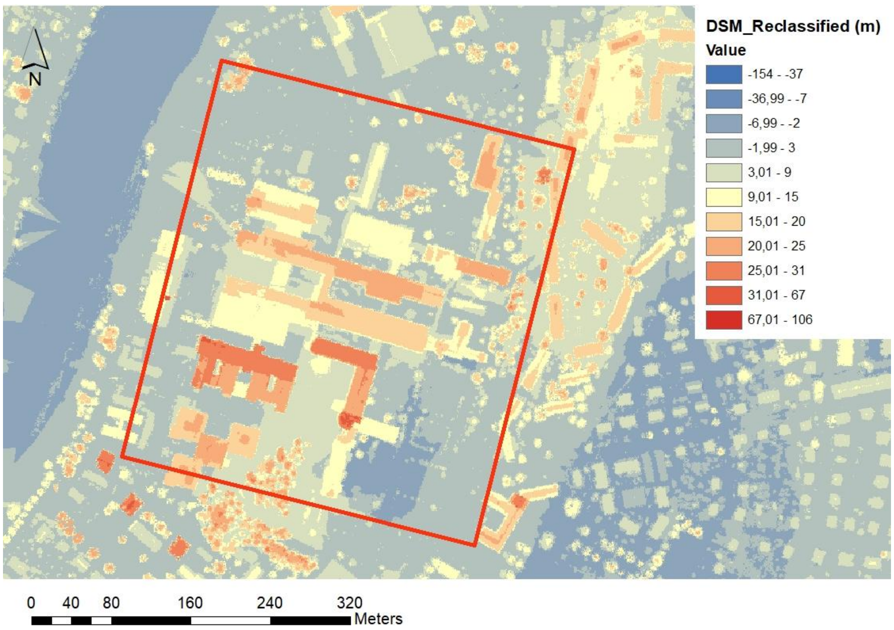


Figure 12. Digital Surface Model, DSM, derived from Lidar data (2018) © The National Land Survey (Lantmäteriet). The map has been reclassified to remove noise and for increased readability.

Estimated air temperature (fig. 13) results show that the hospital area shows a significantly higher estimated air temperature compared to its nearest surroundings. The result reflects the correlation of air temperature, LST (fig. 10) and NDVI (fig. 9). Mean air temperature in Karlstad for date of interest 2019-07-30 was 14.0°C (SMHI 2019).

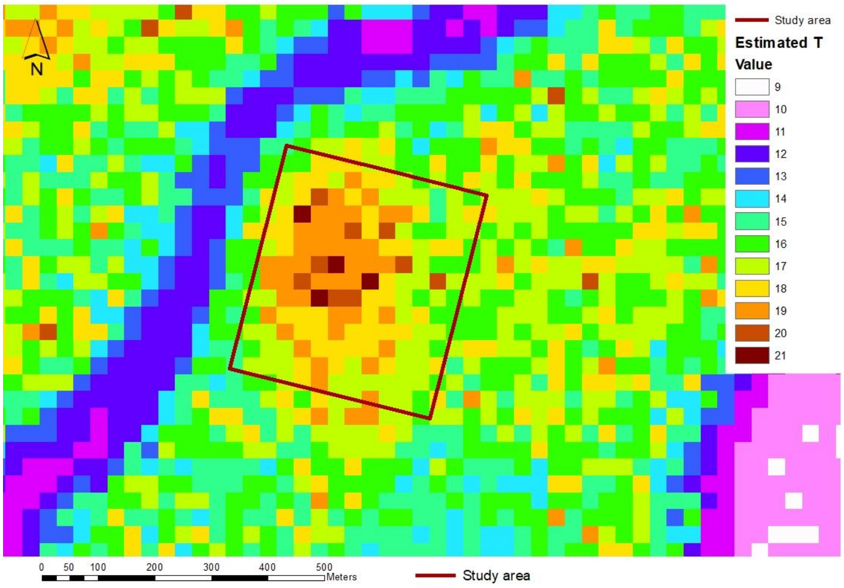


Figure 13. Estimated air temperature map 2019-07-30 a regression model created with NDVI, LST and Julian date.

4.2 Envi-met simulation results

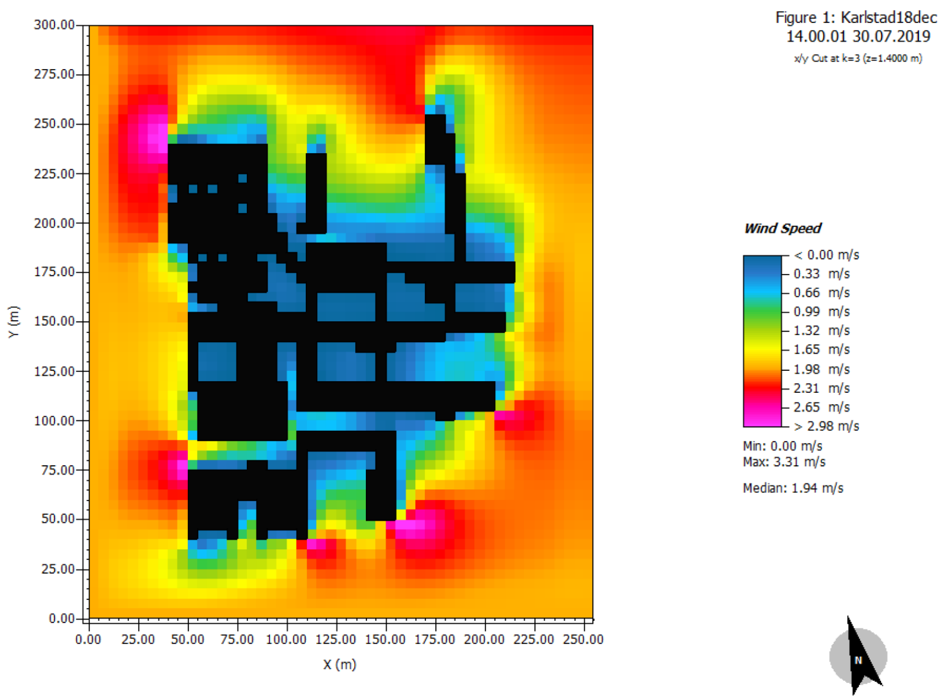


Figure. 14. Wind Speed at the hospital area without vegetation at the simulated date of 2019-07-30, measured at a pedestrian height of 1.4 metre above ground (K=1.4m). Black = buildings.

The result shows that the hospital area has low wind speed, even zero in some areas when modelled at a pedestrian level of 1,4 metre, particularly near and in between the buildings. The wind accelerates around the building corners but does not reach the inner courtyards due to building configuration.

4.2.1 Result of wind speed change

The area with current vegetation was compared to the other scenarios. The result from the simulations showed that trees lower average wind speed slightly in the area (fig. 5), less than first anticipated, at most a reduction of -0.59 m/s could be seen (See fig 15 below) At the same time, there is no overall significant change of wind speed within the whole area compared to no vegetation (See appendix A, 1a). However the pattern and distribution of the wind changes when trees are added. The higher LAD values the more changes in wind speed pattern and distribution can be seen (See appendix A).

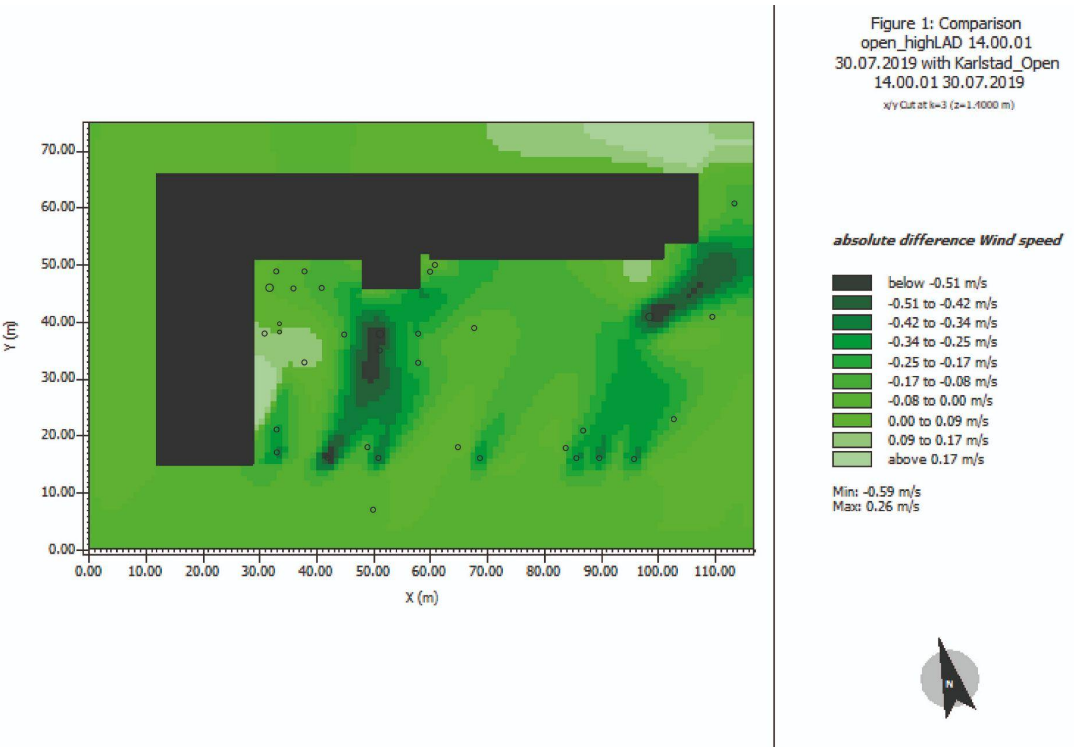


Figure 15. Comparison of wind speed. Dense vegetation slows the wind down but the result is only visible in the near surroundings. Overall the wind speed numbers are the same.

Around the building's corners, where wind speed accelerates due to building configuration, the wind speed reduces the most when vegetation is added. This can positively affect thermal comfort during winter when strong winds are unwanted. At the same time, the wind pattern and PET conjunction shows that wind has a positive effect on thermal comfort in warm temperatures. Closest to the buildings, wind speed is low with a speed of 0.56 m/s. Simultaneously higher PET and air temperature is seen which indicates the importance of incoming wind for reducing temperatures.

In general wind speed is partially slowed by vegetation and wind movement patterns changes were evident. Some results (See figure 16; appendix A; 5f, 6f, 7f, 8f) showed an opposite result with rising wind speeds in the middle of the main area. One explanation to this phenomena can be due to cooling provided from trees, which alter temperatures and increase windflow (Sawka et al. 2013).

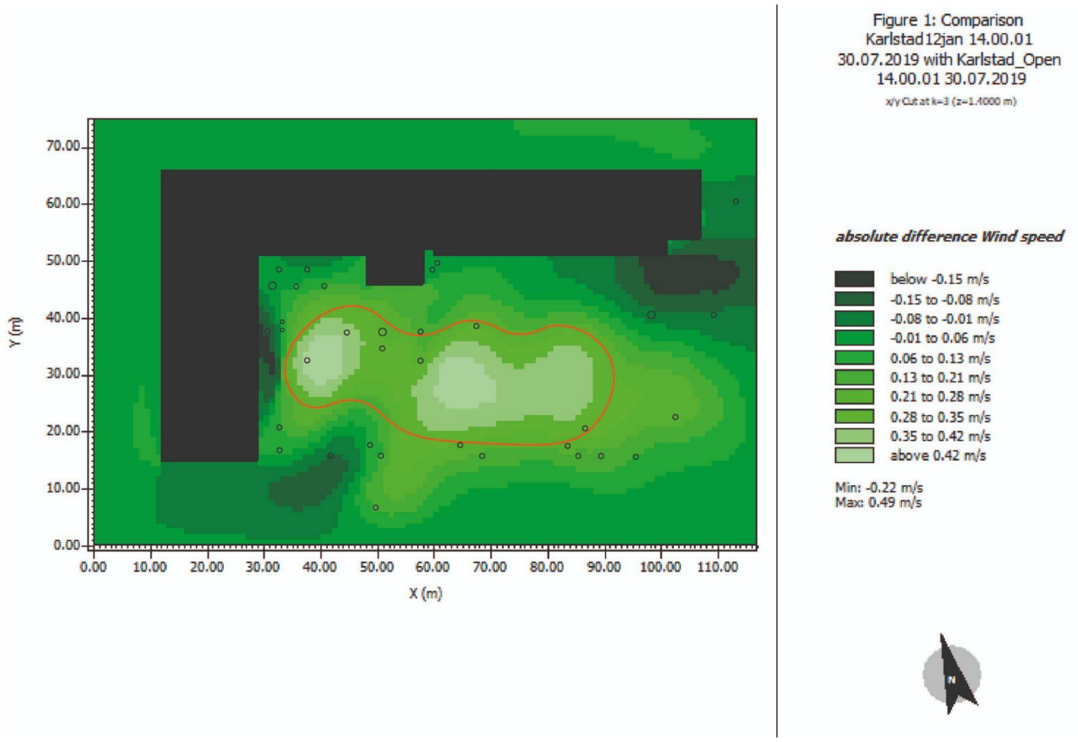


Figure 16. Results from a comparison of wind speed showed an increase of wind speed with more trees added. An explanation can be that a greater temperature change differential increases windflow. The red line frames where wind speed increased compared to current vegetation.

4.2.2 Result of air temperature

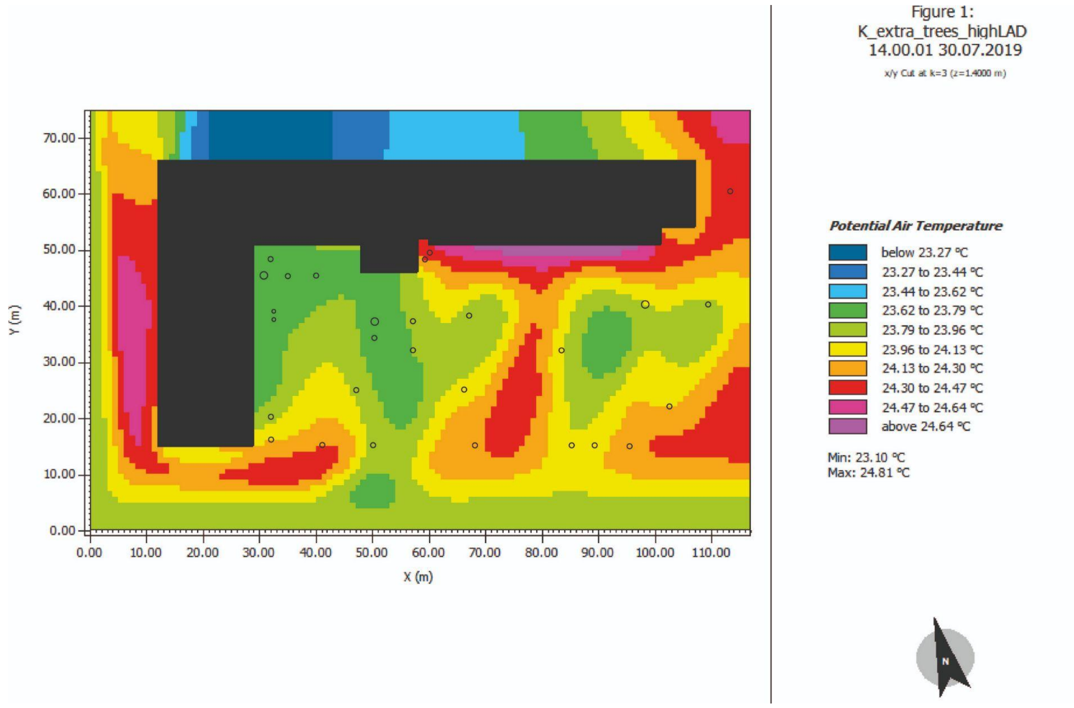


Figure 17. Potential air temperature map with twelve added trees with high leaf area density. The circles mark the locations of the trees in the model.

The area with current vegetation was compared to the other scenarios. Air temperature results were higher than the estimated air temperature in GIS (see fig. 14). The overall result confirms the literature within this thesis and it shows that vegetation has an effect on lowering air temperatures. The result of the different simulations showed that the cooling effect from trees differs depending on the numbers of trees and their leaf area density. Higher leaf area density in general is better for lowering the air temperature under the tree itself and its nearest surroundings. However, results from simulations with higher LAD (see fig 17) temperature differences are various in the study area. Tree mixes with low to intermediate leaf area density (see appendix A fig. 6c,6d) evens out the air temperature distribution.

Simulations with a mix of added trees with a relatively low LAD (See appendix A 6e, 7e) were found to have the highest impact on air temperature change in the whole area. The results show that the number of trees is more important for air temperature reduction, rather than using a few (irrespective of their tree shape and LAD). On the other hand, the consideration of trees' effect on wind as described (see 4.3) needs to be taken into account when adding new trees.

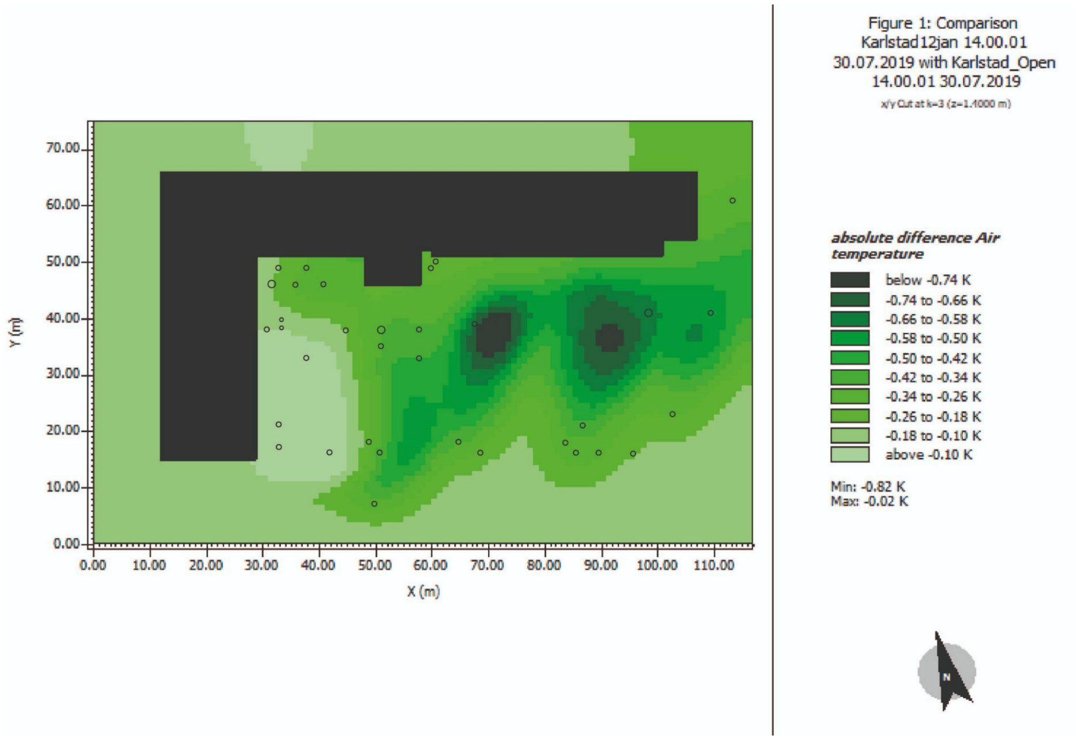


Figure 18. Comparison figure from Envi-met, comparing current vegetation and a mix of twelve trees into the area with same height (15m) but with different shapes; heart-shaped, spherical and cylindrical. The result shows a reduction of temperature within the whole area. At the same the best reduction can be found under denser trees, i.e the darker spots on the map. The result is shown as absolute difference Air temperature in Kelvin. Kelvin and Celsius have the same magnitude and the result can be read as a change in celsius temperature. All comparisons are made on a pedestrian level of 1.4 m above ground.

4.2.3 Result from physiological equivalent temperature, PET

Physiological equivalent temperature results overall show improvement of thermal comfort indices and a better improvement of temperatures compared to air temperatures only. The changes in temperature are greater. An interesting result shows the best improvement of PET can be seen where wind speed accelerates and/or near and under vegetation, which confirms research on the importance of vegetation and wind for mitigating heat. The placement is also important for direct cooling and shade (Sawka et al. 2013; Nikofaard et al. 2011). Near the buildings where wind speed is very low (around 0.5 m/s) the PET shows increased temperatures and vegetation does not seem to manage to provide enough cooling by themselves. However, the results do not tell the cause of the high temperatures near the buildings. Lack of shade, heat absorbing materials together with incoming solar radiation might cause higher temperatures through emitting latent heat.

Chapter 5. Discussion

This work objective has aimed for better understanding and to investigate vegetation and wind's cooling potential in cities, by investigating different tree leaf area densities and numbers and on how wind affects thermal comfort and how vegetation can be used to adapt and mitigate warm climates in the context of the hospital of Karlstad.

5.1 Tree inventory

There are many methods used for tree inventories. The method is dependent on purpose and varies for purpose, to in this case, analytical aims. Data from tree inventories can contain parameters such as height, age, vitality, geographical location, art, crown coverage and more (Östberg, 2015). A full inventory of trees over three metres was made, and vegetation below was included but not less thematic detail. Tree inventories where only trees worthy of protection are included seems to be a common and manageable method for a larger geographical area (Edekrans and Nilsson 2011; Borås stad 2017). Tree height assessment was an important variable for this study and height assessment from Lidar was used. Lidar has a high accuracy but the beam can be shadowed by buildings. This led to difficulties to assess height of some trees and in particular, lower vegetation. The tree coordinates from Google maps have a precision of 10 metres which lead to some tree heights having to be adjusted and compared to the orthophoto (fig. 1).

The initial intention was to model the whole hospital area which explains the extensive tree inventory made. As mentioned earlier the model had to be cut due to long simulation time (See 3.4.1). Vegetation below a height of three metres was not included in detail in the tree inventory due to the intention to increase understanding of trees' effect on temperatures and wind. However, the cut in model area into a smaller one made it possible to model grass, shrubs and other vegetation in more detail. The significance of including vegetation such as grass, shrubs and small trees became more evident after more research. The exclusion of smaller vegetation was questioned and improved in the models made.

5.2 Envi-met and GIS

The analysis made using GIS showed that the highest land surface temperature and estimated air temperature were found in the dense building configuration that the hospital area consists of. Air temperature was estimated based on aerial and satellite data, which showed that the temperature within the study area was significantly higher (fig.13) than the average temperature measured by SMHI (2019; 2021b). More available air temperature data for this kind of research would extend the ability to assess actual temperatures but is currently lacking.

GIS is a useful tool for geographical analysis and planning. The spatial information provided from GIS analyses have been useful for understanding the areas' current conditions and where mitigation measures to improve thermal comfort might be prioritised. Estimating leaf area index and leaf area density have been challenging and the precision of the estimation is difficult to assess. Direct measuring methods such optical measurements or leaf collection can be used (Envi-met 2017). These methods are more time consuming and were not suitable for the season when the tree inventory was made. Retrieving LAI through remote sensing is possible and is a useful method for monitoring forests. Methods used are often for a landscape to a regional level which in this research would cause a scaling issue, the data retrieved would not be precise enough to provide LAI data for single trees. Long term monitoring of LAI by using GIS is more useful for understanding changes in vegetation systems (Zheng and Moskal 2009).

Envi-met provides detailed tree modelling and many default tree models (Helge 2016), which in this case have been used in the simulations, together with new trees with same shapes but other LAD values in between the default ones used. Trees specific characters vary and affect their ability to provide shade, minimise wind and evaporate. These characteristics have not been further researched and modified within the Envi-met model due to time limitation. The modelled trees are set as default soil conditions, which may give a different result compared to actual ground conditions. Extra trees added in the model were all 15 m which means that they are well grown or fully grown. The desired shade and cooling provided by these trees will not reflect a new plantation but rather many years in the future. The tree's dynamic changes are not taken into account within the model which is an important aspect to consider when planning and designing these kinds of areas.

A substantial constraint with the Envi-met programme is the calculation time for simulations. The model area had to be simplified and cut into a smaller area to shorten calculation time. Even then the simulations could take days to finish. A short period of simulation, i.e calculation data for a few hours or days, is still a relatively short time on a meteorological scale. To fully appreciate vegetation's effects on meteorological changes to mitigate urban heat, a wide variety of urban areas should be included and other factors be considered (Ambrosini, Galli, Mancini, Nardi and Sfarra, 2014). The envi-met simulations were based on meteorological data and actual wind conditions. Simulations under calm wind conditions (0.05 m/s) were not assessed, by doing this it would have been possible to evaluate wind's cooling potential within the study area (Roshan et al. 2020).

5.3 Result discussion

The result showed that the entrance area could benefit from more trees to improve thermal comfort, and likely to lower energy usage during summer (Sawka et al. 2013). The result from estimated air temperature (fig. 13) together with meteorological data (SMHI 2021b), does not indicate heat wave temperatures for the date studied but the significantly high air temperature within the study area makes this vulnerable in several aspects. Mitigation measures should be taken, especially concerning the expected warmer temperatures in our future (Masson-Delmotte et al. 2021). The differences in temperatures from Envi-met (See appendix A), near estimated air temperature map (fig. 13) and data from SMHI (2021b) are dependent on several factors, which is difficult to compare. Data used in estimated air temperature differs in both scale and in temporal aspect. The NDVI (fig. 9) data which was included in estimated air temperature, does not exactly tell when the photo was taken. Leafing and peak growth, which NDVI is an indicator of by measuring reflecting near infrared from vegetation (Klobucar, Sang and Randrup, 2021), matters in this case for the result. However the result from air temperature estimation (fig. 13) indicates that air temperatures are significantly higher which indicate vulnerabilities in the studied area.

Physiological Equivalent Temperatures, PET, were calculated and included cooling by wind. Lower temperatures were overall improved but it does not evaluate different factors by their own, but rather how they together interact and affect thermal comfort. Vegetation was shown to have an impact on wind speed under actual wind conditions but it overall did not reduce wind as much as expected. This indicates that buildings may affect wind speed within cities more than vegetation does. An example of that was found around the building's corners where the wind accelerates (fig. 14). When trees were added within the entrance area the wind reduced the most just around the corners. This confirms the benefits of using trees as windbreaks, especially during winter when wind chill can be very cold (Steadman 1971).

As mentioned earlier the difference in results from GIS and Envi-met are difficult to compare. The results from Envi-met should rather be looked at and analysed as relative change rather than absolute values. The response in simulations when LAD and numbers of trees as parameters were changed showed the possibility to modify microclimates. The most interesting result was that the overall improvement of PET was found when winds were able to flow through the vegetation, without too many windbreaks, i.e when lower LAD values on trees were used in the model. The results show how important the interaction between vegetation and wind is for mitigating heat and that the usage of microclimate modelling is an effective tool for examining these interactions.

5.4 General discussion

The effects of Urban Heat Island refers to a regional level. None the less the local microclimate affects air temperatures and thermal comfort. This work has mainly focused on trees and adding trees is not always possible. The effect from other vegetation such as grass, shrubs, green walls and more makes a difference and should not be forgotten and it is of great use in small places. Vegetation's positive effect on physical and mental health is widely acknowledged (Kaplan and Kaplan 1989; Grahn and Stigsdotter 2003) and is another reason why Karlstad hospital area could benefit from using trees in their surroundings, if carefully used. However the results have shown that vegetation type, density and structure affect temperatures, wind and throughout, thermal comfort, which requires knowledge about tree species and how to use them for best result possible (Deak Sjöman and Johansson 2017)

In temperate climates, like Sweden, winter season has to be considered. Less shadow and lower wind speed is desired during winter to mitigate cold temperatures and for letting solar radiation heat buildings, while the opposite is desired during summer (Sawka et al. 2013). This research on trees effect showed positive results during summer, but it does not answer whether or not the simulations made will negatively affect the hospital area during winter. Shadow from trees may possibly increase energy usage during winter season (Sawka et al 2013). The tree species used matters because their crown structure becomes crucial for how much incoming solar radiation can heat the building during winter (Sawka et al. 2013). For a long term sustainable design, trees' dynamics and aesthetic values, together with technical and biological aspects have to be carefully considered (Deak Sjöman and Johansson 2017).

The necessity for planning to adapt for and mitigate climate change is recognized (Hsieh and Huang 2016; Masson-Delmotte et al. 2021). This work has shown that thermal comfort can be improved by adding trees. It also highlights the issues with assessing microclimates. The urban climate is affected by many interactions and is not easily assessed. Modelling microclimates is a useful tool but its restrictions in accuracy concerning air temperature, boundaries (Helge, 2016) and time for simulating restrict the outcome. Using microclimate modelling for research objectives is useful but the method does not seem feasible for landscape architects and planners in their daily work due to the simulation time. Another issue with this kind of research is scale and detail in the model are dependent on the creator and will affect the results.

Due to time limitation more areas within the main hospital area could not be assessed, which leaves the question whether or not these results can be applicable to the whole area. Research within this study has highlighted the complexity of urban climates. Interactions between land cover and temperatures are acknowledged, particularly land surface temperatures, air temperatures and vegetation, but the process to describe them is very complicated. A wider research to include different areas and building configuration would have been of great use to understand the underlying causes to temperature change for better design and mitigation of urban heat.

Man-made surfaces, which can contribute to the urban heat island effect may also be part of the solution. Anthropogenic heat emittance has not been further researched in this thesis but its great impact on near surface air temperatures should not be ignored (Rosenzweig et al. 2006). In short, measures need to be taken further into planning to get to the causes of heat emittance.

There is no given answer for which type of vegetation to use and the results rather amplify that vegetation should not be generalised. The results have rather shown how important it is to increase knowledge and understanding for a site's unique conditions and growth conditions for adapting to urban heat. The results have to be contextualised to the site studied and the limitations within the model be clear. Even so, the results did show a general benefit from adding trees and the differential benefit of more trees and leaf area density differs which is an important aspect to consider when improving microclimates.

5.5 Conclusion

To answer the research questions the results have shown that the wind pattern changes by trees. The trees slightly reduced mean wind speed but it did not significantly affect the wind speeds typical numbers seen within the study area, but the distribution rather changed. Dense trees with a high leaf area density provide a lower air temperature mostly under the trees. This highlights the importance of tree placement, especially when shade is desired. The results have shown that the more trees the better the improvement of physiological equivalent temperature and lowering air temperature within a larger area. A relationship of wind speed and lower PET can be seen which highlights the importance of wind, especially when trees can not be used. Vegetation and wind improve thermal comfort best together during warm temperatures.

In further research the results should be further assessed with more study sites and seasons. This study has clarified the challenges when it comes to mitigate the urban heat island effect. Vegetation and wind's importance for strengthening resilience, improve thermal comfort can be confirmed. Although, the complexity illustrated indicates how important it is to understand a place's prerequisites, the meteorological conditions, and vegetation aesthetic, technical functions, together with knowledge about expected future changes to reach a long term sustainable design.

References

Literature

Albdour, M.S. & Baranyai, B. 2019. *An overview of mocroblimate tools for predicting the thermal comfort, meterological parameters and design strategies in outdoor spaces.*
POLLACK PERIODICA An International Journal for Engineering and Information Sciences DOI: 10.1556/606.2019.14.2.10 Vol. 14, No. 2, pp. 109–118

Ambrosini, D., Galli, G., Mancini, B., Nardi, I. & Sfarra, S. 2014. *Evaluating Mitigation Effects of Urban Heat Islands in a Historical Small Center with the ENVI-Met®* Climate Model Sustainability *6*(10), 7013-7029; https://doi.org/10.3390/su6107013

Bergfreunde n.d. *Wind chill calculator*.
https://www.bergfreunde.eu/wind-chill-calculator/ [2022-01-07]

Borås stad. 2017. *Skyddsvärda träd i Borås*. Miljöförvaltningen, Borås stadhttps://www.boras.se/download/18.2e4f2177173eb3556d44a297/1597923378762/Inventering%20av%20skyddsvärda%20träd%20i%20Borås%20Stad2017%20TA.pdf [2022-01-30]

Brown, R.D Jr. and Brown, R.D. 2010. *Design with microclimate: The Secret to Comfortable Outdoor Space.* [Electronic resource]. Island Press.

Deak Sjöman, Johanna 2016. The hidden landscape. Doctoral Thesis. Sveriges lantbruksuniversitet, Acta Universitatis Agriculturae Sueciae, 1652-6880 ; 2016:3.

Deak Sjöman, J & Johansson, E. 2020. *Nature based solutions to Urban Microclimate Regulation* I Sang, Neil (red.) (2020). *Modelling Nature-based Solutions: integrating computational and participatory scenario modelling for environmental management and planning*. Cambridge: Cambridge University Press

Deak Sjöman, J. Sjöman, H. Johansson, E 2015. Staden som växtplats. In: Sjöman, H & Slagstedt, J (red.) (2015). *Träd i urbana landskap*. 1. uppl. Lund: Studentlitteratur

Deak Sjöman, J., Hirons, A. D., Sjöman, H. 2016. *Branch area index of solitary trees: Understanding its significance in regulating ecosystem services.* Journal of environmental quality 45(1): 175-187

Dimoudi, A. Kantzioura, A. Zoras, S. Pallas, C. Kosmopoulos, P. 2013 *Investigating of Urban Microclimate parameters in an urban center* Energy and Buildings. 64: 1-9.
https://doi.org/10.1016/j.enbuild.2013.04.014

Edekrans, A. & Nilsson, T. 2011 *Projekt skyddsvärda träd i Värmland - projekt och resultat 2005-2010.* Publ nr 2011:15. ISSN: 0284:6845 Karlstad: Länsstyrelsen Värmland.
https://www.lansstyrelsen.se/download/18.26f506e0167c605d56926dc1/1549633358928/Trädrapport%202011-15.pdf [2021-12-18]

Ennos, R. 2015. *Can trees really cool our cities down?* The conversation.
https://theconversation.com/can-trees-really-cool-our-cities-down-44099 [2022-01-03]

Envi-met n.d *Nesting grids* https://envi-met.info/doku.php?id=kb:nesting [2021-12-11]

Envi-met 2017. Obtaining leaf area density data https://envi-met.info/doku.php?id=kb:lad [2021-11-21]

EPA. 2021. *Using Trees and Vegetation to Reduce Heat Islands* https://www.epa.gov/heatislands/using-trees-and-vegetation-reduce-heat-islands [2021-12-18]

Erell, E., Pearlmutter, D., Williamson, T. J. 2015. *Urban microclimate: designing the spaces between buildings*. Routledge

Ermida, S.L., Soares, P., Mantas, V., Göttsche, F.-M., Trigo, I.F., 2020. *Google Earth Engine open-source code for Land Surface Temperature estimation from the Landsat series*. Remote Sensing, 12 (9), 1471; https://doi.org/10.3390/rs12091471

ESRI n.d *What is GIS* https://www.esri.se/sv-se/what-is-gis/overview [2021-12-06]

Grahn, P. & Stigsdotter, U.A 2003. *Landscape planning and stress* Urban Forestry & Urban Greening Vol 2:1, 1-18 https://doi.org/10.1078/1618-8667-00019

Helge, S. 2016 *Modeling urban microclimate : development, implementation and evaluation of new and improved calculation methods for the urban microclimate model ENVI-met.* Diss. Mainz: Johannes Gutenberg University Mainz. http://doi.org/10.25358/openscience-4042

Hodder, S.G. & Parsons, K. 2006. *The effects of solar radiation on thermal comfort.* International Journal of Biometeorology. 51, 233-250 (2007).

Howard, L. 2012. [1818]. *The Climate of London Deduced from Meteorological Observations*. Vol. 1. Cambridge University Press. ISBN 9781108049511.

Hsieh, C.-M., Huang H.-C. 2016. *Mitigating urban heat islands: A method to identify potential wind corridor for cooling and ventilation*. Computers, Environment and Urban Systems 57: 130-143.

Höppe, P. 1999. *The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment.* - International Journal of Biometeorology 43, 71-75.

IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. In Press.

IPCC, 2022: Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press.

Kaplan, R., & Kaplan, S. 1989. *The experience of nature: A psychological perspective.* Cambridge University Press.

Kleerekooper, L., van Esch, MN Salcedo, T. B. 2012. *How to make a city climate-proof, addressing the urban heat island effect*. Resources, Conservation and Recycling, 64, 30-38.

Klobucar, B. Sang, N. and Randrup, T. 2021. *Comparing ground and remotely sensed measurements of urban tree canopy in private residences.* Trees, Forests and People. 5 , 100114 [Research article]

Krüger, E., Minella, F.O, Rasia, F. 2011. *Impact of urban geometry on outdoor thermal comfort and air quality from field measurements in Curitiba, Brazil.* Building and Environment 46(3): 621-634.

Lantmäteriet. 2009. Laserdata NH https://www.geodata.se/geodataportalen/srv/swe/catalog.search;jsessionid=EADE3B1ECF2BEEB61C3440994CCF05D5#/metadata/8f5e284e-1cff-4f38-a023-1545c501f989 [2021-11-02]

Lehmann, I., Mathey, J., Rößler, S., Bräuer, A., Goldberg, V. 2014. *Urban vegetation structure types as a methodological approach for identifying ecosystem services–Application to the analysis of micro-climatic effects.* Ecological indicators 42: 58-72

National Aeronautics and Space Administration, Science Mission Directorate. 2010. *Reflected Near-Infrared Waves. Retrieved* [insert date - e.g. August 10, 2016], from NASA Science website: http://science.nasa.gov/ems/08_nearinfraredwaves

National Land Survey. n.d. The Calculating of SWEREF 99 https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/gps-geodesi-och-swepos/Referenssystem/Tredimensionella-system/SWEREF-99/ [2021-12-06]

NASA ARSET 2020. *Land Surface Temperature-Based Urban Heat Island Mapping, Part 1/3* [video] 2020-11-20
https://www.youtube.com/watch?v=KYV2j3kwj2A [2021-10-04]

Nikoofard, S., Ugursal, V. I., & Beausoleil-Morrison, I. 2011. *Effect of external shading on household energy requirement for heating and cooling in Canada*. Energy and Buildings, 43, 1627-1635.

Oke 1982 *The energetic basis of urban heat island.* Quarterly Journal of the Royal Meteorological Society 108(455):1 - 24 DOI:10.1002/qj.49710845502

Oke, T. R. 1987. *Boundary layer climates*. 2., [expanded] ed. London: Methuen

Pauleit S., Zölch T., Hansen R., Randrup T.B., Konijnendijk van den Bosch C. 2017. *Nature-Based Solutions and Climate Change – Four Shades of Green.* In: Kabisch N., Korn H., Stadler J., Bonn A. (eds) *Nature-Based Solutions to Climate Change Adaptation in Urban Areas. Theory and Practice of Urban Sustainability Transitions.* Springer, Cham. https://doi.org/10.1007/978-3-319-56091-5_3

Region Värmland 2021. Centralsjukhuset Karlstad https://www.regionvarmland.se/regionvarmland/jobb-utbildning--forskning/jobba-med-oss/vara-arbetsplatser/centralsjukhuset-karlstad [2021-11-04]

Rosenzweig, C. Solecki, W. Parshall, L. Gaffin, S. Lynn, B. Goldberg, R. Cox, J. Hodges S. 2006 *Mitigation New York City's Heat Island with Urban Forestry, Living Roofs and Light Surfaces*. New York: 86th AMS Annual Meeting.

Roshan, G. Moghbel, M. & Shady Attia, S. 2020 *Evaluating the wind cooling potential on outdoor thermal comfort in selected Iranian climate types Journal of Thermal Biology, Volume 98, May 2021, Pages 102966.* https://doi.org/10.1016/j.jtherbio.2020.102660

Ruefenacht, L., Acero JA. 2017. *Strategies for cooling Singapore: A catalogue of 80+ measures to mitigate urban heat island and improve outdoor thermal comfort*. In Cooling Singapore https://doi.org/10.3929/ethz-b-000258216 [2021-09-27]

Sawka, M., Millward, AA., Mckay, J., Sarkovich, M. 2013. *Growing summer energy conservation through residential tree planting.* Landscape and Urban Planning 113: 1-9.

Schneider dos Santos, R. 2020. *Estimating spatio-temporal air temperature in London (UK) using machine learning and earth observation satellite dat*a. In International Journal of Applied Earth Observation and Geoinformation 88: 102066. https://doi.org/10.1016/j.jag.2020.102066 [2021-10-25]

Sciencing. 2018. *How Does Water Stabilize Temperature?* https://sciencing.com/water-stabilize-temperature-4574008.html [2021-12-11]

Sjöman, H., Hirons, A., Deak Sjöman, J. 2017. *Criteria in the Selection of Urban Trees for Temperate Urban Environments*. In: Ferrini, F., Konijnendijk van den Bosch, C., Fini, A. (Eds.) Routledge Handbook of Urban Forestry, 339-362.

SMHI. 2006. *Wind statistics for Sweden 1961-2004*. Table 2. Mean values of wind speed (m/s) 1991-2004. https://www.smhi.se/polopoly_fs/1.1895!meteorologi_121-06%5B1%5D.pdf [2022-01-20]

SMHI. 2018. *Heat wave - Possible effects and measures in health care.* https://www.smhi.se/lathund-for-klimatanpassning/stod-i-ditt-verksamhetsomrade/vard-och-omsorg/varmebolja-mojliga-effekter-och-atgarder-inom-vard-och-omsorg-1.140208 [2021-10-04]

SMHI. 2019. *JULY 2019 - AIR TEMPERATURE AND PRECIPITATION* https://www.smhi.se/polopoly_fs/1.150751!/w14_jul19.pdf [2021-12-10]

SMHI. 2021a. *Wind in Sweden*. https://www.smhi.se/kunskapsbanken/klimat/sveriges-klimat/vind-i-sverige-1.31309 [2021-10-11]

Sowińska-Świerkosz, B and García, J.2022. *What are Nature-based solutions (NBS)? Setting core ideas for concept clarification Nature-Based Solutions* Vol. 2, 2022, 100009 https://doi.org/10.1016/j.nbsj.2022.100009

Steadman, R.G. 1971. *Indices of Windchill of Clothed Persons* Journal of Applied Meteorology and Climatology. 10: 674 - 682. https://doi.org/10.1175/1520-0450(1971)010<0674:IOWOCP>2.0.CO;2

Svensk trädgård. 2021. Svensk trädgårds zonkarta över Sverige. https://www.tradgard.org/svensk_tradgard/zonkarta/zonkarta_stor.html [2021-11-04]

Theeuwes, N.E., A. Solcerová, A., Steeneveld, G.J. 2013. *Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city.* JGR Atmospheres. *118(16):* 8881-8896 https://doi.org/10.1002/jgrd.50704

Theeuwes, N. E.; Steeneveld, G.J.; Ronda, R.J.; Holtslag, A.A.M. 2017. A *diagnostic equation for the daily maximum urban heat island effect for cities in northwestern Europe*. *I*nternational Journal of Climatology. 37 (1): 443–454. Bibcode:2017IJCli..37..443T. doi:10.1002/joc.4717.

USGS. 2018. *NDVI, the Foundation for Remote Sensing Phenology* https://www.usgs.gov/special-topics/remote-sensing-phenology/science/ndvi-foundation-remote-sensing-phenology [2022-01-06]

Voogt, J.A. 2002. Urban Heat Island. In: Munn, T., Ed., Encyclopedia of Global Environmental Change, Wiley, Chichester, Vol. 3, 660-666

Wang, W., Liu, K., Tang, R., Wang, S. 2019 *Remote sensing image-based analysis of the urban heat island effect in Shenzhen, China.* Physics and Chemistry of the Earth, Parts A/B/C Volume 110, April 2019, Pages 168-175. https://doi.org/10.1016/j.pce.2019.01.002

Weber, N., Haase, D., Franck, U. 2014. *Zooming into temperature conditions in the city of Leipzig: how do urban built and green structures influence earth surface temperatures in the city?* Science of the total environment 496: 289-298.

Wu, Z. & Zhang, Y. 2019. *Water Bodies' Cooling Effects on Urban Land Daytime Surface Temperature: Ecosystem Service Reducing Heat Island Effect,* Sustainability 2019, 11, 787 DOI: https://doaj.org/article/778e7a0df8eb4220814a2437b6a11fc5

Zheng, G.& L. Monika Moskal, M.L, 2009. *Retrieving Leaf Area Index (LAI) Using Remote Sensing: Theories, Methods and Sensors.* Sensors (Basel). 9(4): 2719–2745. doi:10.3390/s90402719

Zipper, S.C., Schatz, J., Singh, A., Kucharik, C.J., Townsend, P.A., & Loheide, S.P. 2016. *Urban heat island impacts on plant phenology: intra-urban variability and response to land cover.* Environmental Research Letters, Volume 11:5

Östberg, J. 2015. *Standard för trädinventering i urban miljö v.2.* Landskapsarkitektur Trädgård Växtproduktionsvetenskap. Alnarp:Institutionen för landskapsarkitektur, planering och förvaltning. [Report series]. https://pub.epsilon.slu.se/12353/7/ostberg_j_150616.pdf [2021-11-15]

Cartographic material

Google Earth Engine. 2019. *Karlstad Region, Sweden. 59°22'45.48" N 13°30'12.85.* Landsat collection level 2 data. [Online] https://earthengine.google.com [2021-10-13]

National Land Survey 2018. *Karlstad. SWEREF 99 TM, RH 2000.* Orthophoto (Ortofoto) [Cartographical material]

National Land Survey 2012. *Karlstad. SWEREF 99 TM, RH 2000.* Ortho IRF (Orto IRF) [Cartographical material]

National Land Survey 2019. *Karlstad. SWEREF 99 TM, RH 2000.* Lidardata (Laserdata NH) [Cartographical material]

National Land Survey 2020. *Karlstad. SWEREF 99 TM, RH 2000.* Property map Build-up areas (fastighetskartan bebyggelse) [Cartographical material]

Dataset

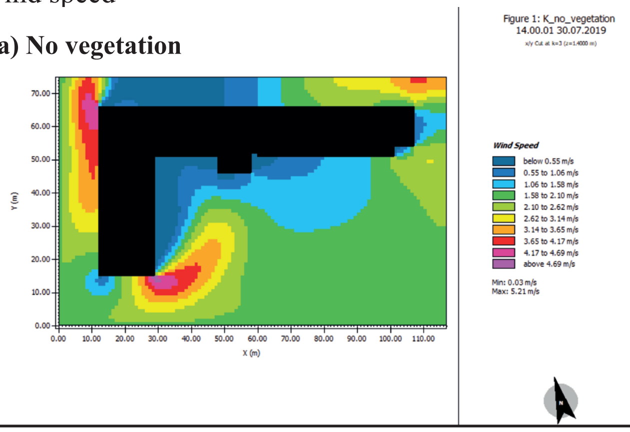
SMHI. 2021b. *SMHI open data wind, Karlstad airport*. Climate number 93220. https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer/#param=wind,stations=all,stationid=93220 [2021-12-12]

Appendix A

Envi-met results - simulation over Karlstad hostpital entrance area

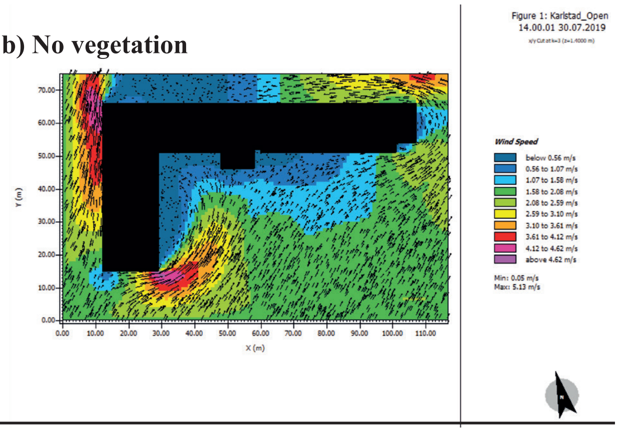
Wind speed

1 a) No vegetation

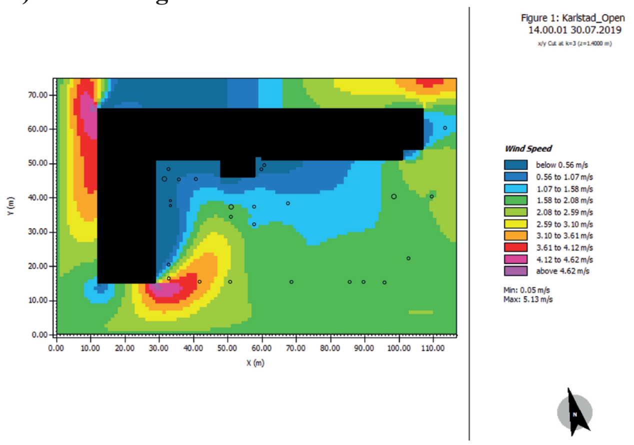


Wind direction

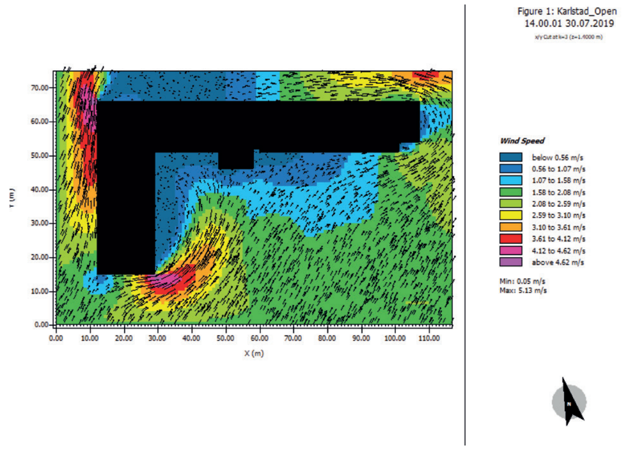
2 b) No vegetation



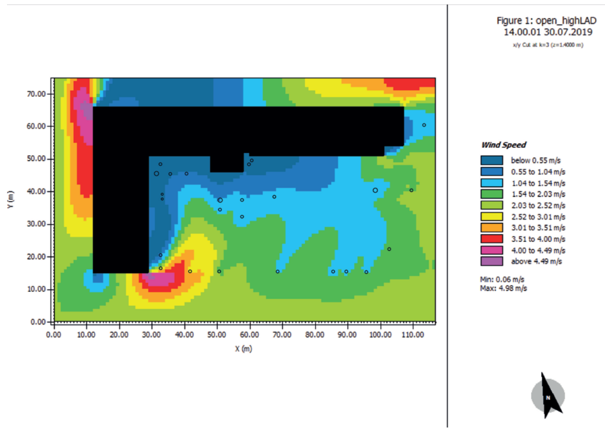
2 a) current vegetation



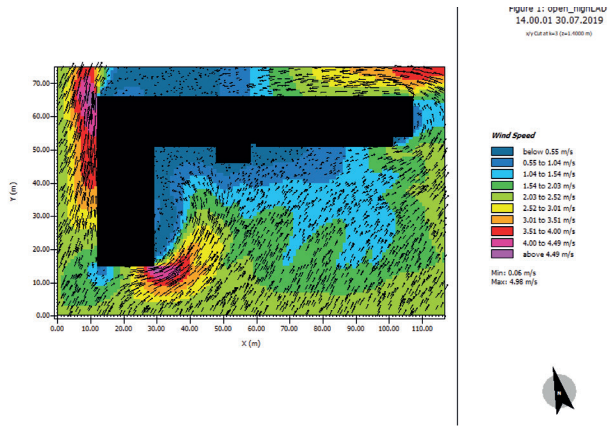
2 b) current vegetation



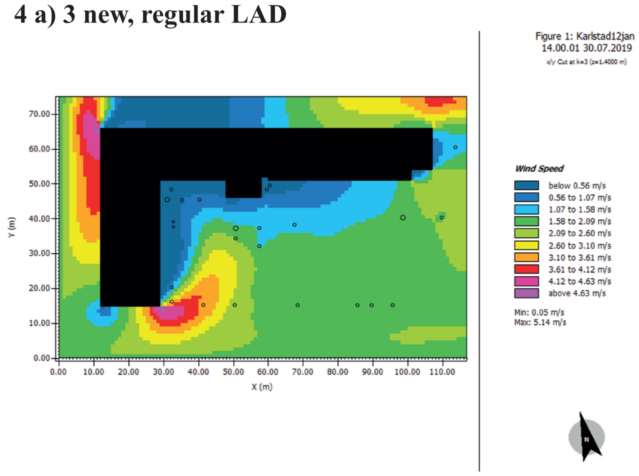
3 a) current veg. with increased LAD



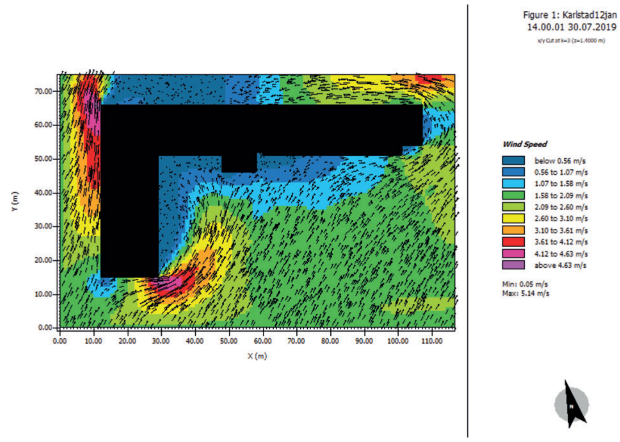
3 b) current veg. with increased LAD



4 a) 3 new, regular LAD



4 b) 3 new, regular LAD



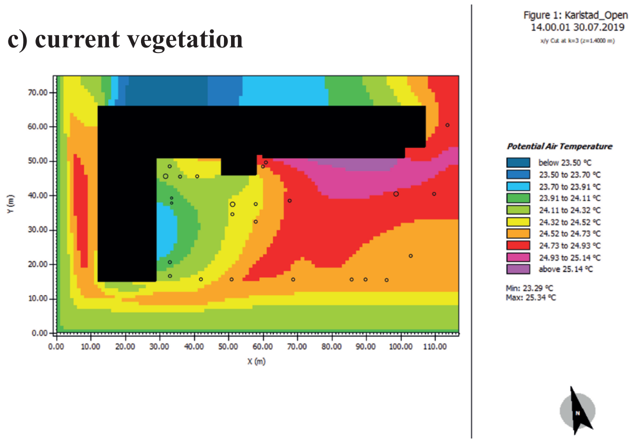
Appendix A

Envi-met results - simulation over Karlstad hostpital entrance area

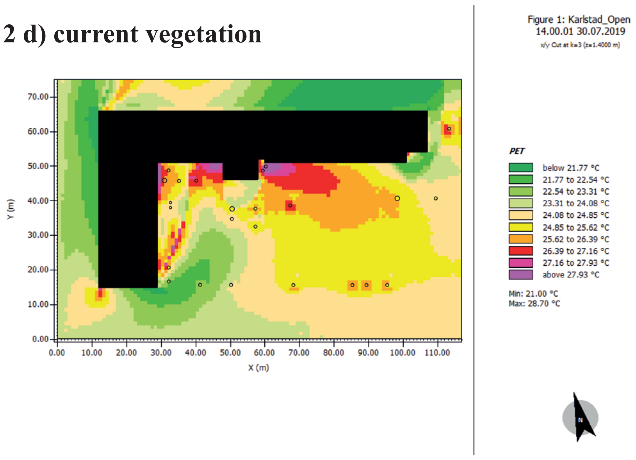
Air temperature

PET

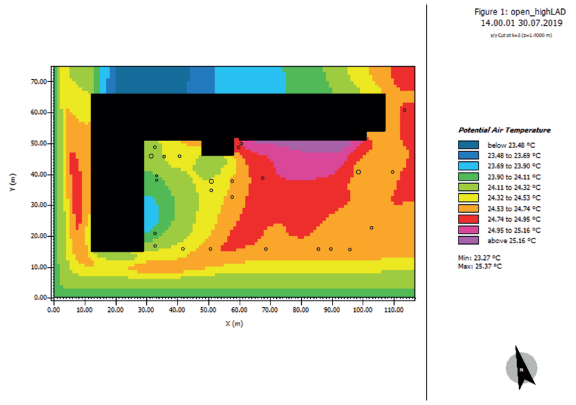
2 c) current vegetation



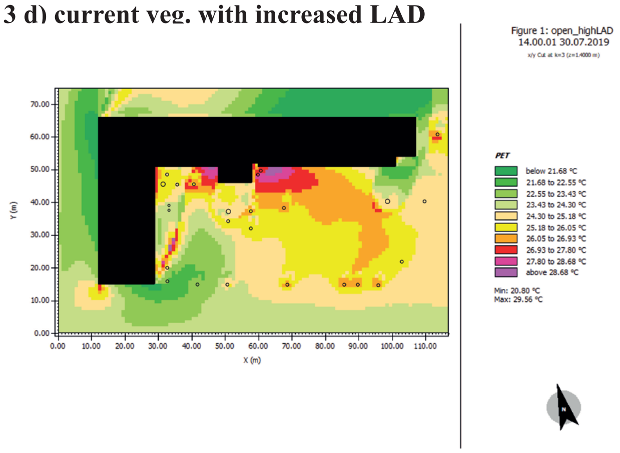
2 d) current vegetation



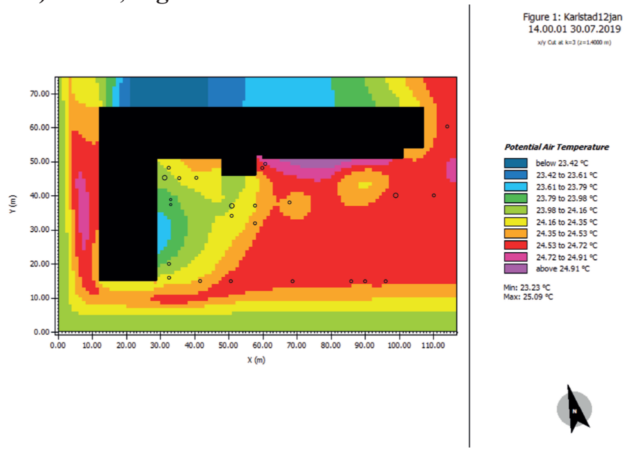
3 c) current veg. with increased LAD



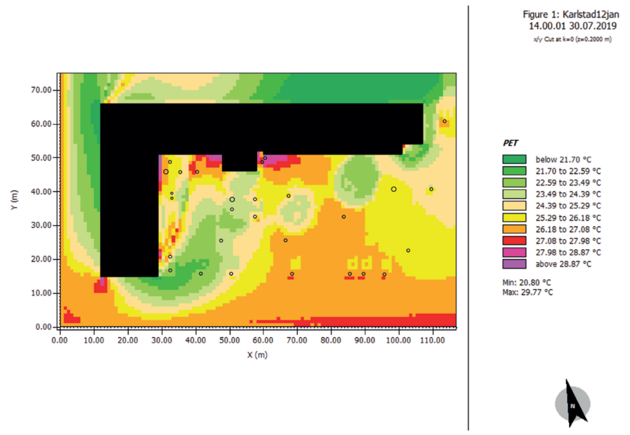
3 d) current veg. with increased LAD



4 c) 3 new, regular LAD



4 d) 3 new, regular LAD

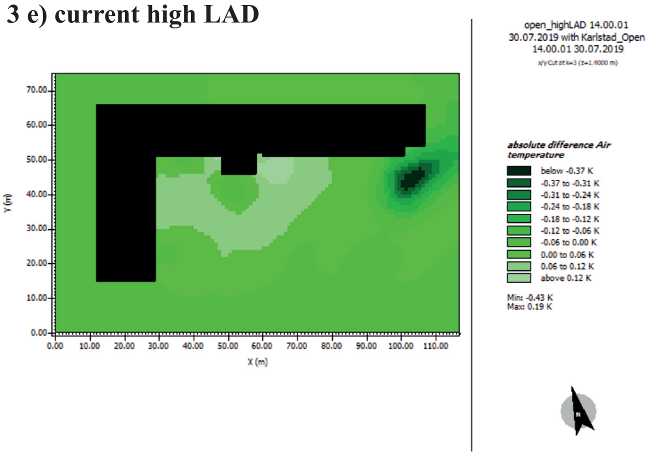


Appendix A

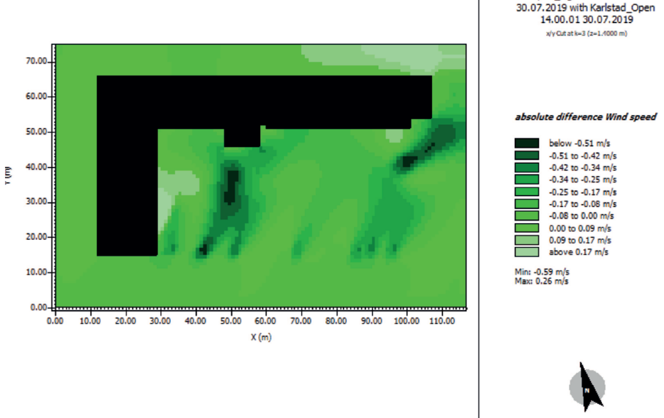
Envi-met results - simulation over Karlstad hostpital entrance area, comparison of current veg,

Comparision of Air temp	Comparison of wind speed

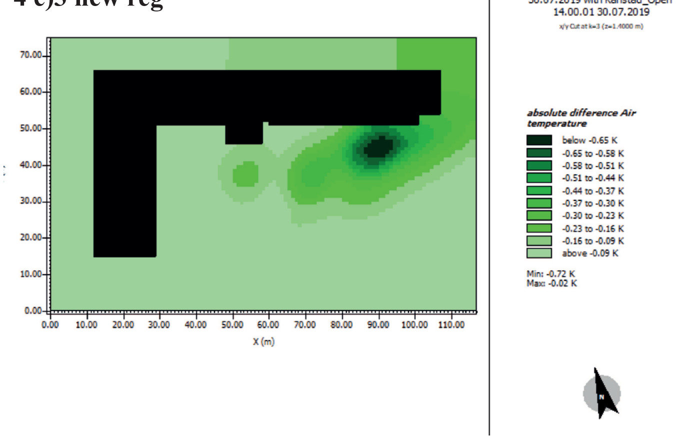
3 e) current high LAD



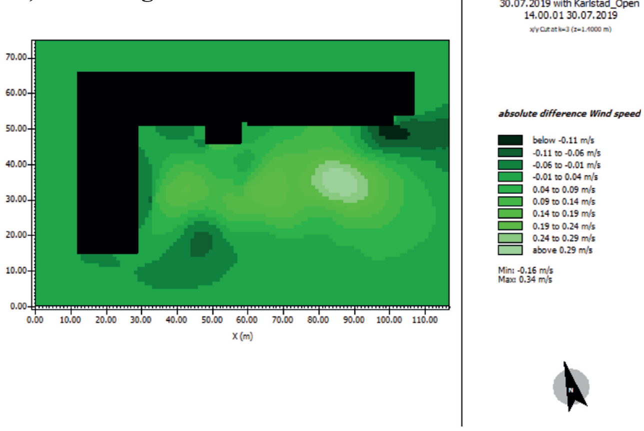
3 f) current high LAD



4 e)3 new reg



4 f) 3 new reg



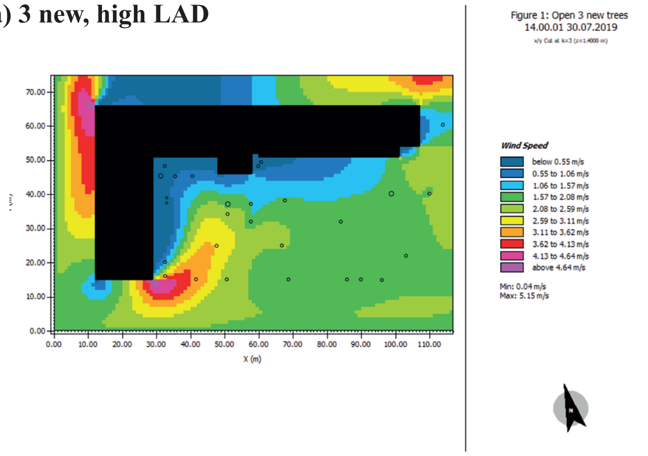
Appendix A

Envi-met results - simulation over Karlstad hostpital entrance area

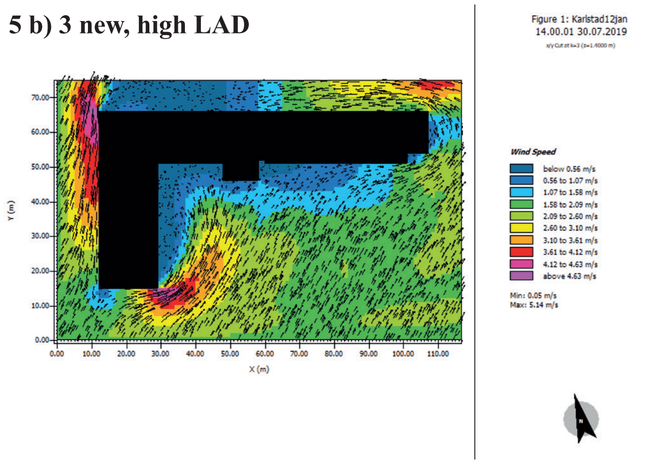
Wind speed

Wind direction

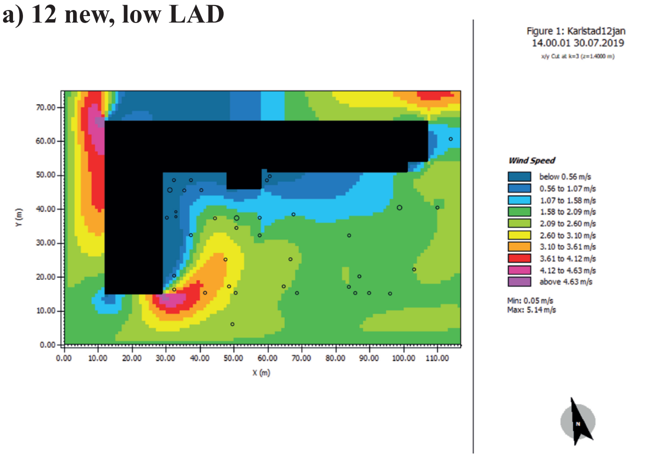
5 a) 3 new, high LAD



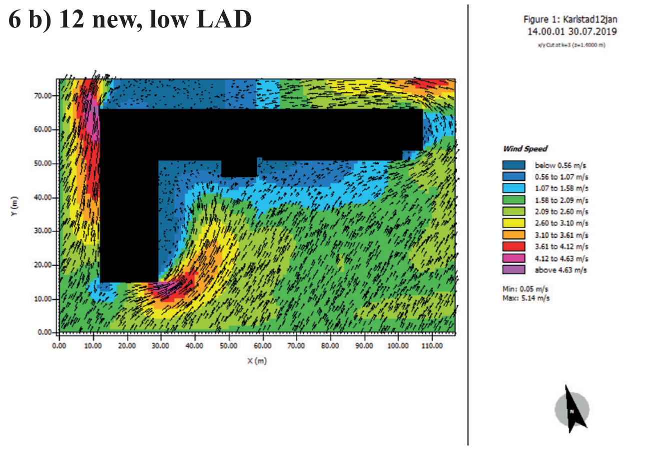
5 b) 3 new, high LAD



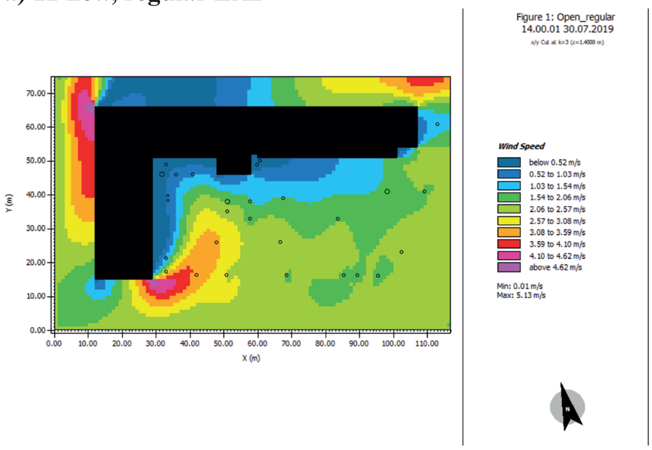
6 a) 12 new, low LAD



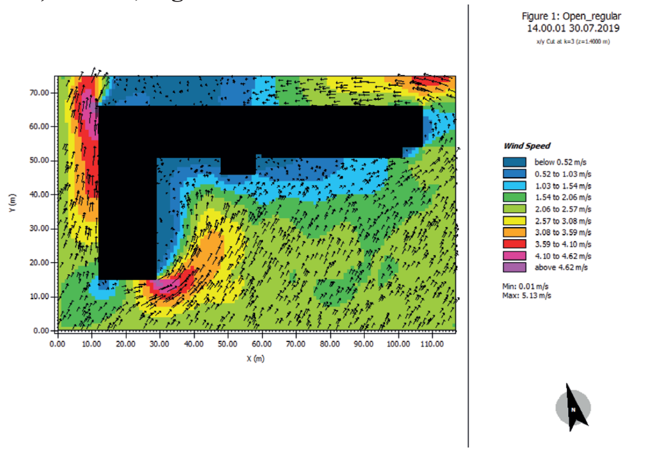
6 b) 12 new, low LAD



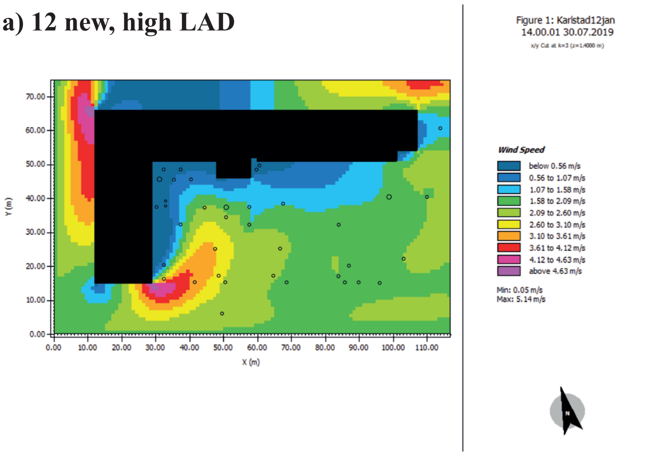
7 a) 12 new, regular LAD



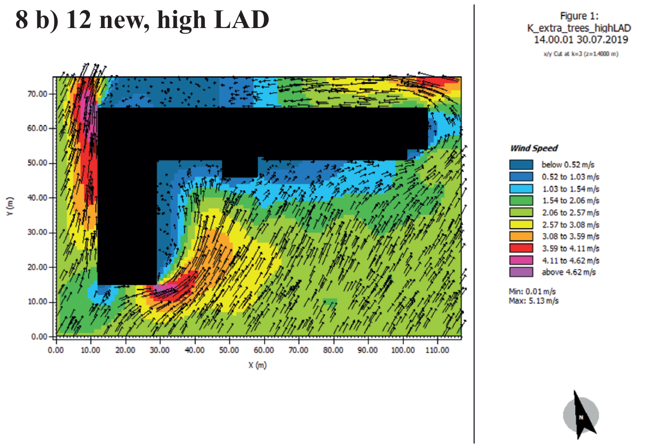
7 b) 12 new, regular LAD



8 a) 12 new, high LAD



8 b) 12 new, high LAD

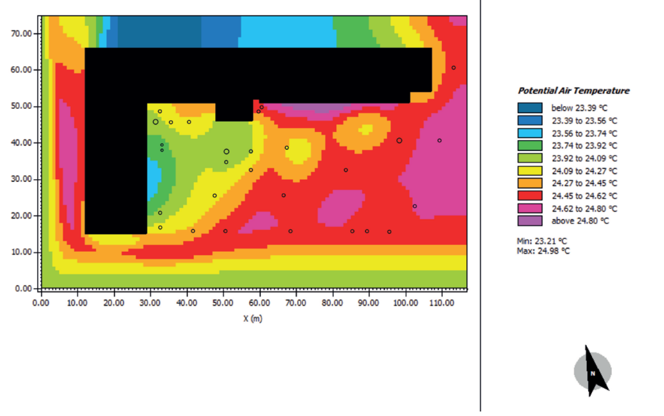


Envi-met results - simulation over Karlstad hostpital entrance area

Air temperature	PET

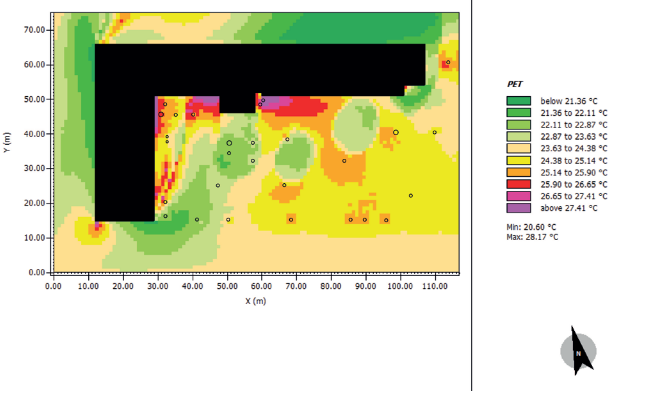
5 c) 3 new, high LAD

Figure 1: Open 3 new trees
14.00.01 30.07.2019



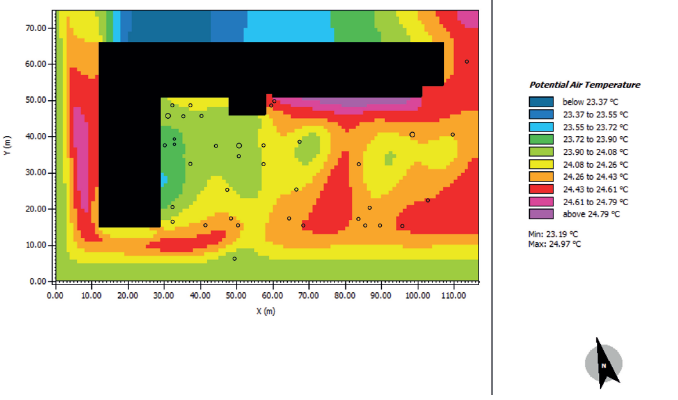
5 d) 3 new, high LAD

Figure 1: Open 3 new trees
14.00.01 30.07.2019



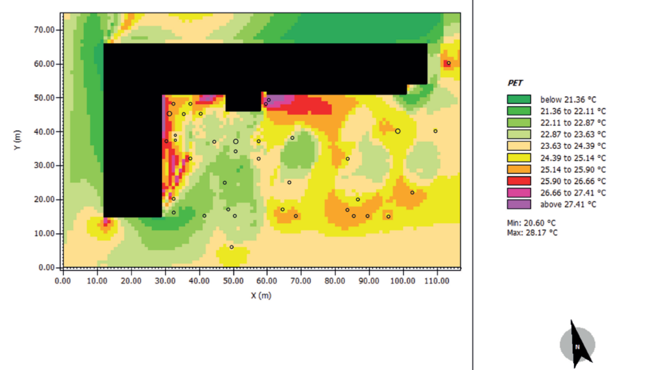
6 c) 12 new, low LAD

Figure 1: Karlstad12jan
14.00.01 30.07.2019



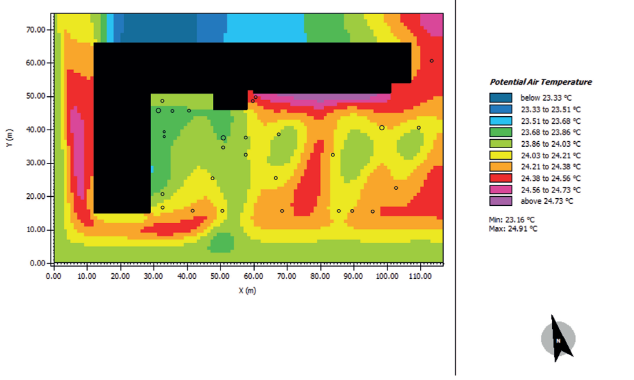
6 d) 12 new, low LAD

Figure 1: Karlstad12jan
14.00.01 30.07.2019



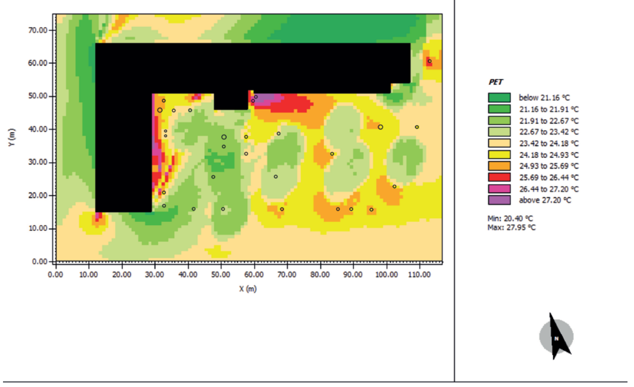
7 c) 12 new, regular LAD

Figure 1: Open_regular
14.00.01 30.07.2019



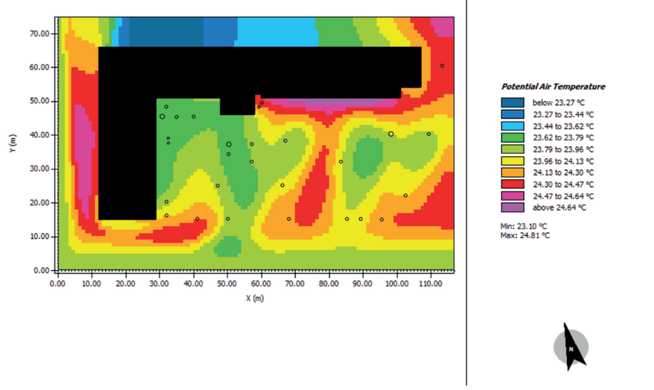
7 d) 12 new, regular LAD

Figure 1: Open_regular
14.00.01 30.07.2019



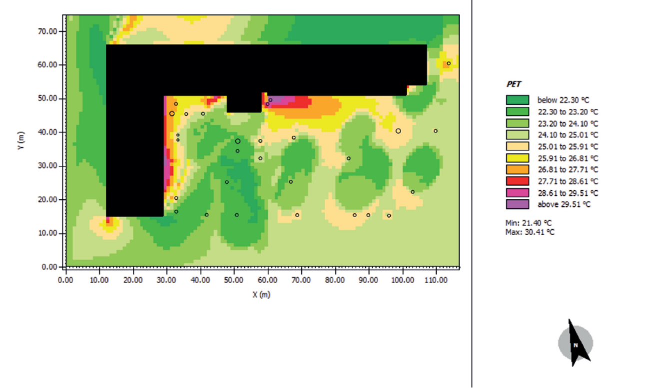
8 c) 12 new, high LAD

Figure 1:
K_extra_trees_highLAD
14.00.01 30.07.2019



8 d) 12 new, high LAD

14.00.00 01.07.2021



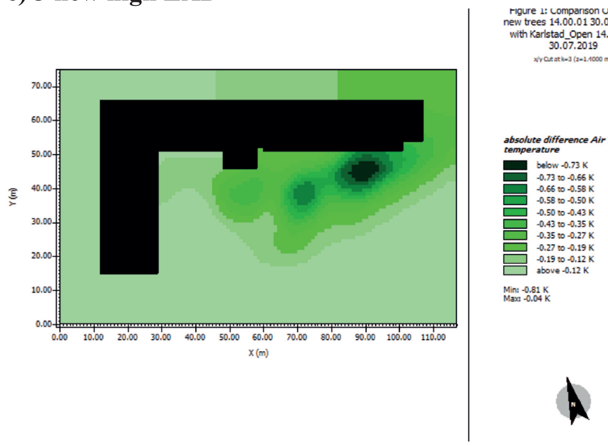
Appendix A

Envi-met results - simulation over Karlstad hostpital entrance area, comparison to current veg,

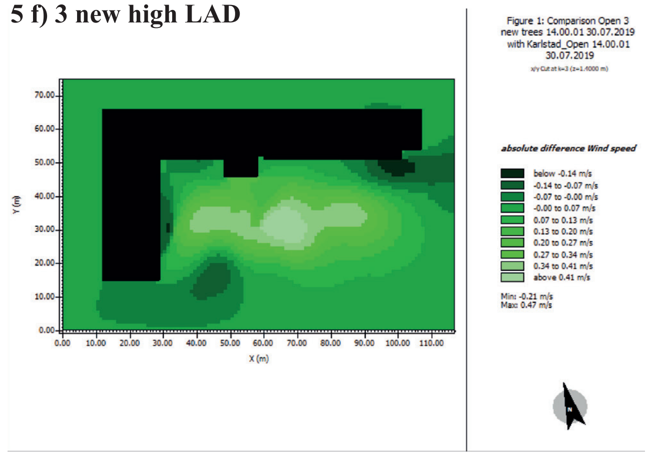
Comparision of air temperature

Comparison of wind speed

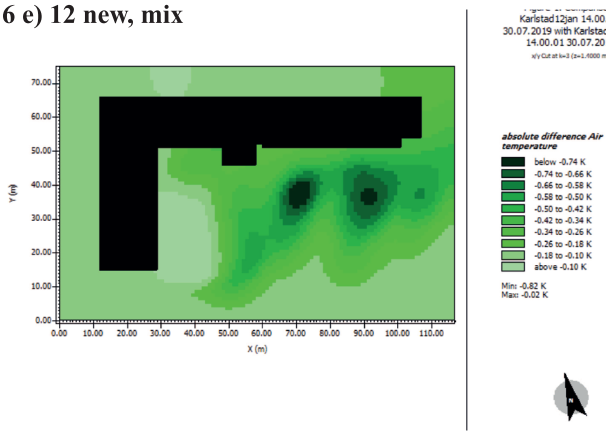
5 e) 3 new high LAD



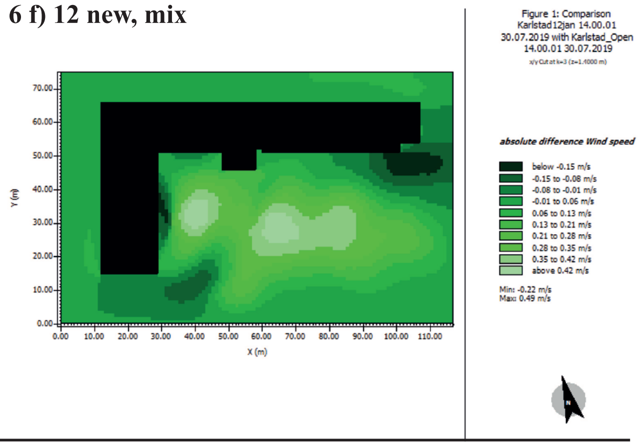
5 f) 3 new high LAD



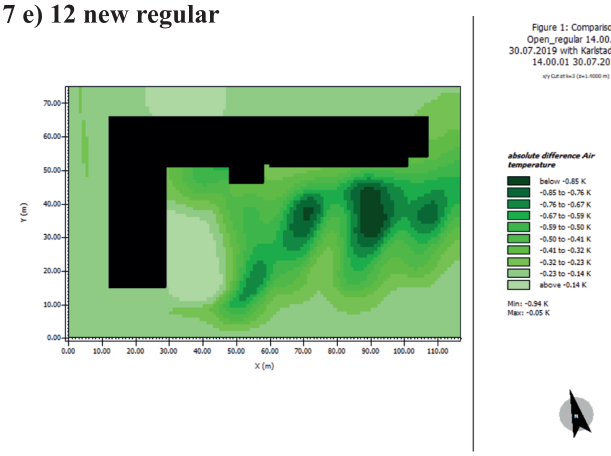
6 e) 12 new, mix



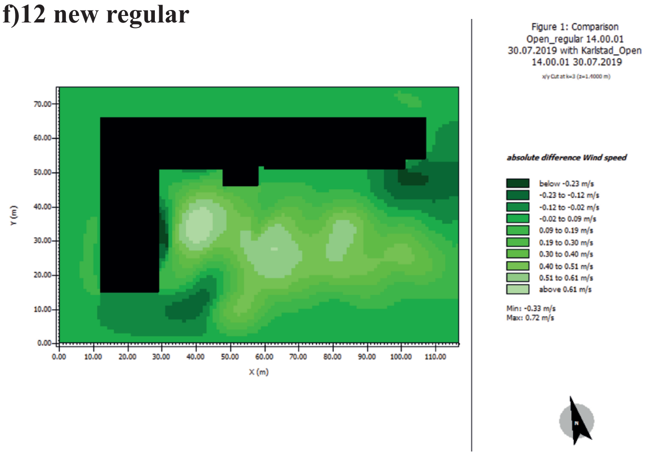
6 f) 12 new, mix



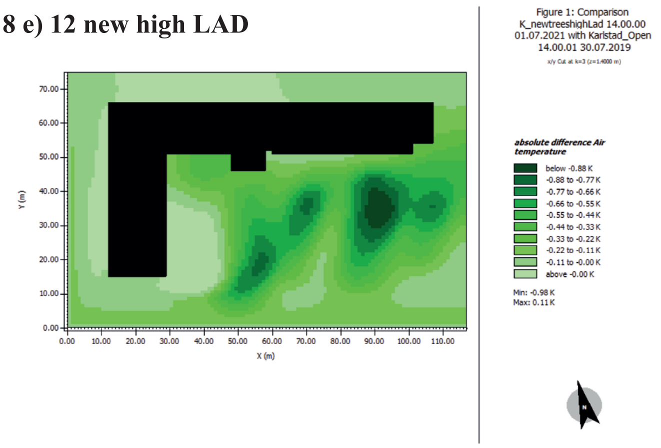
7 e) 12 new regular



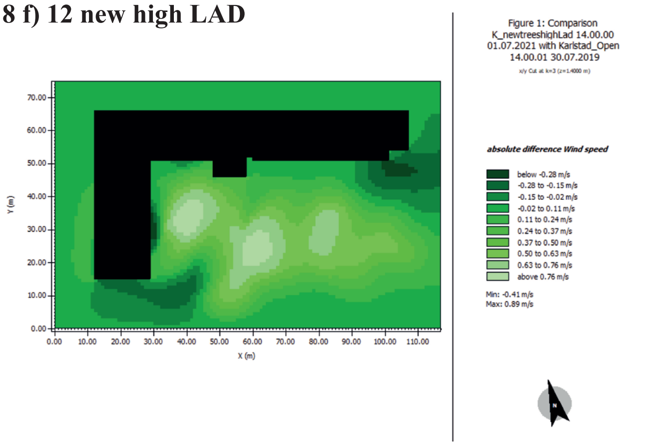
7 f)12 new regular



8 e) 12 new high LAD



8 f) 12 new high LAD



Treeinventory Karlstad hospital area

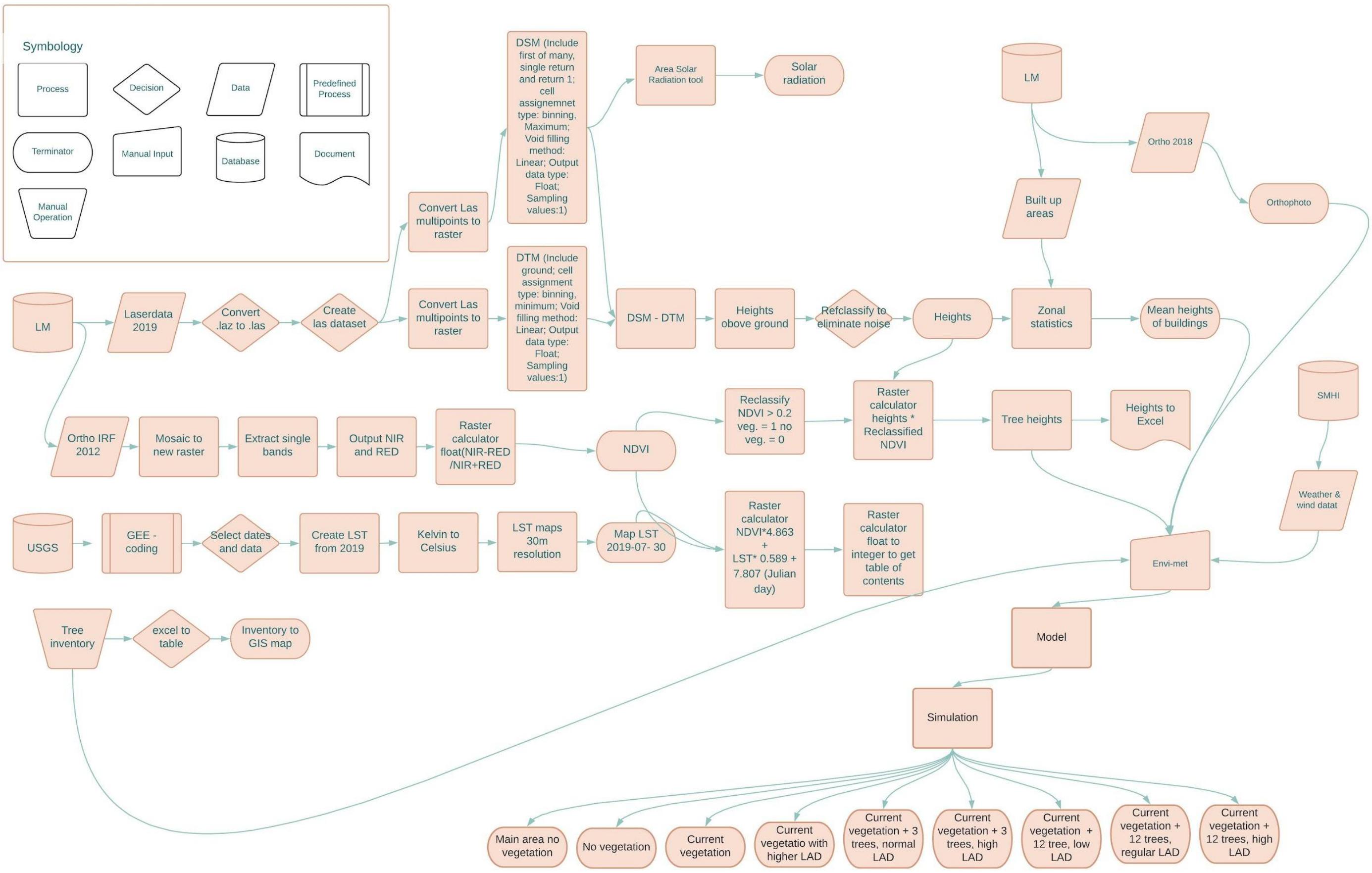
Genera	Species	Latitude	Longitude	Habitus	Comments	ground conditions, planted in:	Height from LiDAR	LAI*	Tree in Envi-met
Acer	Acer platanoides	6582781.9	413724.2	Columnar	Young	grass	3	5	
Acer	Acer platanoides	6582789.0	413716.6	Columnar	Young	grass	8	4,6	
Acer	Acer platanoides	6582993.6	413731.9	Columnar		grass	7	4,6	
Acer	Acer platanoides	6582917.6	413612.1	Columnar		grass, park	16	4,6	
Acer	Acer platanoides	6583004.6	413692.9	Columnar	Small	hardened surface	4	4,8	
Acer	Acer platanoides	6583004.6	413692.9	Columnar	Small	hardened surface	4	4,8	
Acer	Acer pensylvanicum	6582980.5	413591.0	Columnar	Small	hardened surface	3	4,5	
Betula	Betula pendula	6582900.5	413730.8	Columnar		grass	14	5	
Betula	Betula pendula	6582904.0	413731.0	Columnar		grass	20	4,9	
Betula	Betula pendula	6582920.7	413732.6	Columnar		grass	18	4,9	
Betula	Betula pendula	6582864.0	413757.2	Columnar		grass	4	5,2	
Betula	Betula pendula	6582900.0	413745.6	Columnar		grass	16	5	
Betula	Betula pendula	6582923.9	413748.0	Columnar		grass	24	5	
Betula	Betula pendula	6582932.9	413747.4	Columnar		grass	21	5	
Betula	Betula pendula	6582929.0	413746.8	Columnar		grass	19	5	
Betula	Betula pendula	6582963.6	413731.3	Columnar	Big	grass	11	5,3	
Betula	Betula pendula	6582963.7	413744.5	Columnar	smal	grass	4	5	
Betula	Betula pendula	6582955.3	413745.2	Columnar		grass	7	5,3	
Betula	Betula pendula	6582970.5	413745.0	Columnar	young	grass	4	5,2	
Betula	Betula pendula	6582980.0	413745.2	Columnar		grass	7	5,3	
Betula	Betula pendula	6582934.6	413614.9	Columnar		grass, park	6	5	
Betula	Betula pendula	6582948.7	413648.8	Columnar		grass, park	8	5,3	
Betula	Betula pendula	6582957.8	413621.1	Columnar		grass	10	5	
Betula	Betula pendula	6582971.0	413682.7	Columnar		grass	19	5	
Betula	Betula pendula	6583012.4	413652.9	Columnar		grass	18	5	
Betula	Betula pendula	6583001.5	413625.1	Columnar		grass	13	5	
Fagus	Fagus sylvatica	6582931.9	413630.5	Columnar		grass, park	21	4,9	
Pinus	Pinus sylvestris	6582784.1	413724.3	Columnar		grass	6	2,8	
Pinus	Pinus sylvestris	6582789.9	413727.1	Columnar		grass	18	3,3	
Pinus	Pinus sylvestris	6582796.6	413728.8	Columnar		grass	18	3,3	
Pinus	Pinus sylvestris	6582778.0	413716.2	Columnar		grass	20	3,3	
Pinus	Pinus sylvestris	6582782.1	413716.8	Columnar		grass	17	3,3	
Pinus	Pinus sylvestris	6582789.1	413717.3	Columnar		grass	12	3,1	
Pinus	Pinus sylvestris	6582785.2	413727.5	Columnar		grass	18	3,3	
Pinus	Pinus sylvestris	6582793.3	413718.2	Columnar		grass	13	3,1	
Pinus	Pinus sylvestris	6582813.0	413741.1	Columnar		grass	6	2,8	
Pinus	Pinus sylvestris	6582800.2	413733.0	Columnar		grass	17	3,3	
Pinus	Pinus sylvestris	6582819.6	413737.6	Columnar		grass	27	3,4	
Pinus	Pinus sylvestris	6582824.6	413736.0	Columnar		grass	21	3,3	
Pinus	Pinus sylvestris	6582826.6	413740.3	Columnar		grass	19	3,3	
Pinus	Pinus sylvestris	6582832.8	413738.4	Columnar		grass	21	3,3	
Pinus	Pinus sylvestris	6582847.2	413740.4	Columnar		grass	9	2,8	
Quercus	Quercus robur	6582867.4	413721.2	columnar		grass	17	4,6	
Thuja	Thuja occidentalis	6582919.8	413652.4	Columnar	Stemmed	grass, park	11	6	
Thuja	Thuja occidentalis	6582933.1	413657.9	Columnar	Stemmed	grass, park	11	6	
Tilia	Tilia x europea	6582747.0	413700.5	Columnar		hardened surface	19	4,6	Spherical, large trunk, dense, high LAD, small
Tilia	Tilia x europea	6582994.8	413726.4	Columnar		grass	7	5	
Tilia	Tilia x europea	6582906.2	413628.2	Columnar		grass, park	17	4,8	
Tilia	Tilia x europea	6582918.6	413618.3	Columnar		grass, park	12	4,6	
Tilia	Tilia x europea	6582918.3	413606.1	Columnar		grass, park	14	4,6	
Tilia	Tilia x europea	6582921.3	413629.0	Columnar		grass, park	19	4,8	
Tilia	Tilia platyphyllos	6582912.4	413642.2	Columnar		grass, park	20	4,8	
Tilia	Tilia x europea	6582936.4	413649.1	Columnar		grass, park	20	4,8	
Tilia	Tilia x europea	6582974.4	413671.5	Columnar		grass	12	4	
Acer	Acer saccharinum	6582773.5	413716.6	Columnar		hardened surface	11	5,5	
Quercus	Quercus robur 'Fastigiata'	6582785.4	413733.7	Fastigiate		grass	4	3,8	
Thuja	Thuja occidentalis 'smaragd'	6582739.5	413653.2	Fastigiate		hardened surface	3	6	
Thuja	Thuja occidentalis 'smaragd'	6582726.5	413648.3	Fastigiate		hardened surface	6	6	Cylindic, small trunk, dense, High LAD, small
Thuja	Thuja occidentalis 'smaragd'	6582828.4	413682.8	fastigiate		grass	9	6	
Acer	Acer platanoides	6583008.8	413727.9	Global		grass	10	4,6	
Acer	Acer platanoides	6583012.9	413716.3	Global		grass	10	4,6	
Acer	Acer platanoides	6582865.3	413638.7	Global		hardened surface	13	4,6	
Aesculus	Aesculus hippocastanum	6582947.8	413685.3	Global		grass	16	4,9	
Aesculus	Aesculus hippocastanum	6582934.8	413687.1	Global		grass	17	4,9	
Malus	Malus floribunda	6582999.6	413708.5	Global		grass	4	2,5	
Malus	Malus toringo	6583002.5	413706.4	Global		grass	4	2,5	
Syringa	Syringa vulgaris	6582887.0	413655.1	Global		hardened surface	5	3	
Tilia	Tilia x europea	6583022.6	413712.6	Global		grass	7	5	
Ulmus	Ulmus glabra	6582873.2	413696.7	Global		grass	11	5,8	
Ulmus	Ulmus glabra	6582879.9	413697.4	Global		grass	10	5,8	
Ulmus	Ulmus glabra	6582901.4	413700.5	Global		grass	11	5,8	
Acer	Acer platanoides	6582748.8	413644.0	Globe		hardened surface	10	4,6	Spherical, medium trunk, dense, high LAD medium
Acer	Acer platanoides	6582808.7	413653.8	Globe		grass	12	4,6	
Acer	Acer platanoides	6583018.7	413569.8	Globe		grass	5	4,8	
Acer	Acer tataricum ssp ginnala	6582706.0	413543.2	Globe		hardened surface	4	5	
Acer	Acer tataricum ssp ginnala	6582701.2	413546.4	Globe		hardened surface	4	5	
Acer	Acer tataricum ssp ginnala	6582696.1	413548.9	Globe		hardened surface	4	5	
Aesculus	Aesculus hippocastanum	6582877.1	413733.7	Globe		grass	16	4,9	
Malus	Malus domestica	6582920.6	413747.9	Globe		grass	6	2,5	
Malus	Malus toringo	6583026.8	413586.9	Globe		hardened surface	7	2,5	
Prunus	Prunus avium	6582935.7	413731.7	Globe		grass	12	5,5	
Prunus	Prunus avium	6582943.9	413731.8	Globe		grass	13	5,5	
Prunus	Prunus avium	6582952.0	413732.3	Globe		grass	13	5,5	
Prunus	Prunus avium	6582963.6	413731.3	Globe		grass	13	5,5	
Prunus	Prunus avium	6582974.7	413732.5	Globe		grass	11	5,5	
Prunus	Prunus avium	6582724.1	413535.9	Globe		grass, small strech between buildings and lane	4	5	
Prunus	Prunus avium	6582724.1	413531.6	Globe		hardened surface	6	5	
Prunus	Prunus avium	6582727.4	413542.5	Globe		hardened surface	6	5	
Prunus	Prunus avium	6582730.2	413547.1	Globe		hardened surface	5	5	
Prunus	Prunus avium	6582733.5	413553.6	Globe		hardened surface	6	5	
Prunus	Prunus avium	6582740.9	413535.3	Globe		hardened surface	5	5	
Prunus	Prunus avium	6582710.8	413540.4	Globe		hardened surface	10	5,3	
Quercus	Quercus robur	6582864.9	413743.2	globe		grass	17	4,6	
Sorbus	Sorbus aucuparia	6582745.0	413671.6	Globe		hardened surface	3	3	Sperical large trubj, sparse, small, low lad
Sorbus	Sorbus aucuparia	6582876.0	413745.3	Globe		grass	7	3	
Sorbus	Sorbus aucuparia	6582966.2	413742.2	Globe		grass	5	3	
Sorbus	Sorbus aucuparia	6582945.0	413743.6	Globe		grass	4	3	
Sorbus	Sorbus aucuparia	6582739.3	413411.9	Globe		grass, small strech between buildings and lane	3	3	
Sorbus	Sorbus aucuparia	6582737.2	413420.9	Globe		grass, small strech between buildings and lane	3	3	
Sorbus	Sorbus aucuparia	6582734.9	413428.8	Globe		grass, small strech between buildings and lane	4	3	
Sorbus	Sorbus aucuparia	6582731.6	413438.6	Globe		grass, small strech between buildings and lane	3	3	
sorbus	Sorbus aucuparia	6582729.2	413446.9	Globe		grass, small strech between buildings and lane	3	3	
sorbus	Sorbus aucuparia	6582726.7	413454.7	Globe		grass, small strech between buildings and lane	3	3	
sorbus	Sorbus aucuparia	6582724.4	413463.6	Globe		grass, small strech between buildings and lane	4	3	
sorbus	Sorbus aucuparia	6582721.6	413472.0	Globe		grass, small strech between buildings and lane	3	3	
sorbus	Sorbus aucuparia	6582719.4	413480.1	Globe		grass, small strech between buildings and lane	3	3	
sorbus	Sorbus aucuparia	6582719.3	413489.1	Globe		grass, small strech between buildings and lane	3	3	

sorbus	Sorbus aucuparia	6582714.3	413498.3	Globe		grass, small strech between buildings and lane	4	3	
sorbus	Sorbus aucuparia	6582711.2	413506.6	Globe		grass, small strech between buildings and lane	4	3	
Tilia	Tilia x europea	6582739.6	413643.5	Globe		hardened surface	4	5	spherical, medium trunk, dense, high LAD, small
Tilia	Tilia x europea	6582732.2	413641.9	Globe		hardened surface	6	5	
Malus	Malus domestica	6582918.3	413747.8	Globe	Smal	grass	5	2,8	
Cornus	Cornus alba 'Sibirica'	6582743.2	413654.2	Horizontal		hardened surface	3	3,4	heartshaped, small trunk, sparse, low LAD, small
Tilia	Tilia x europea	6582801.4	413735.2	Horizontal		grass	19	4,6	
Tilia	Tilia x europea	6582809.6	413739.3	Horizontal		grass	9	5	
Fagus	Fagus sylvatica	6582997.8	413718.7	Irregular	young	grass	4	8	
Pyrus	Pyrus communis	6582853.0	413627.0	Irregular		hardened surface	7	2,5	
Pyrus	Pyrus communis	6582902.3	413473.3	Irregular		grass	6	2,5	
Pyrus	Pyrus communis	6582900.5	413473.8	Irregular		grass	4	2,5	
Quercus	Quercus rubra	6583011.1	413596.4	Irregular		grass	12	4,6	
Quercus	Quercus rubra	6583011.3	413600.1	Irregular		grass	11	4,6	
Quercus	Quercus rubra	6583006.7	413602.1	Irregular		grass	13	4,5	
Acer	Acer platanoides	6582809.0	413737.8	Oval		grass	17	4,5	
Quercus	Quercus robur	6582797.8	413728.3	Oval		grass	18	4,6	
Thuja	Thuja occidentalis	6582782.8	413707.0	Oval		grass	10	9,8	
Thuja	Thuja occidentalis	6582795.7	413712.4	Oval		grass	11	9,8	
		6582811.5	413636.0	Oval	Dense. Not accessible	grass	8	5	
Acer	Acer platanoides	6582809.1	413741.3	Oval		grass	16	4,5	
Acer	Acer platanoides	6582813.2	413741.5	Oval		grass	16	4,5	
Picea	Picea abies	6582816.9	413740.3	Oval	young	grass	3	6,5	
Picea	Picea abies	6582837.0	413738.9	Pyramidal		grass	17	12,8	
Tilia	Tilia platyphyllos	6582964.5	413624.8	Pyramidal		grass, park	10	5,8	
Tilia	Tilia cordata	6582958.8	413621.1	Pyramidal		grass	10	4	
Tilia	Tilia cordata	6582980.7	413663.8	Pyramidal		grass	10	4	
Tilia	Tilia cordata	6582986.9	413671.9	Pyramidal		grass	10	4	
Tilia	Tilia cordata	6582989.3	413682.9	Pyramidal		grass	12	4	
Tilia	Tilia x europea	6582896.1	413456.0	Pyramidal		grass	6	5,6	
Cercidiphyllum	Cercidiphyllum japonicum	6582765.7	413661.9	Vase		hardened surface	5	4	heartshaped small trunk, sparse low LAD, small
Cercidiphyllum	Cercidiphyllum japonicum	6582764.5	413660.7	Vase		hardened surface	6	4	heartshaped small trunk, sparse low LAD. small
Prunus	Prunus serrula	6582771.6	413414.3	Vase		grass	4	5	
Prunus	Prunus serrula	6582755.3	413413.8	Vase		grass	4	5	
Prunus	Prunus serrula	6582758.6	413415.4	Vase		grass	3	5	
Prunus	Prunus serrula	6582743.6	413409.8	Vase		grass	3	5	
Prunus	Prunus serrula	6582741.0	413408.8	Vase		grass	4	5	
Prunus	Prunus serrula	6582743.8	413404.8	Vase		grass	4	5	
Syringa	Syringa vulgaris	6583010.3	413643.1	Vase		grass	4	3	
Syringa	Syringa vulgaris	6583009.0	413640.5	Vase		grass	4	3	
Syringa	Syringa vulgaris	6583008.2	413636.7	Vase		grass	4	3	
Syringa	Syringa vulgaris	6583016.4	413640.8	Vase		grass	4	3	
		6582774.6	413620.2	Vase	Not accessible	hardened surface	7	4	Heart shaped, medium trunk, sparse Low LAD, small
		6582768.2	413615.8	Vase	Not accessible	hardened surface	4	4	Heart shaped, medium trunk Low LAD, small
Euonymus	Euonymus europaeus	6582771.7	413620.9	Weeping	Sparse	hardened surface	4	2	Heart shaped small trunk, sparse low LAD, small
Euonymus	Euonymus europaeus	6582768.9	413625.0	Weeping		hardened surface	4	2	Heart shaped small trunk, sparse, low LAD, small
Kokwitzia	Kolkwitzia amabilis	6582890.8	413734.0	Weeping		grass	3	2,8	
Kokwitzia	Kolkwitzia amabilis	6582899.9	413741.0	Weeping	Shrubbery	grass	3	2,8	
Laburnum	Laburnum sp	6582763.0	413716.9	Weeping		hardened surface	4	2,8	
Laburnum	Laburnum sp	6582811.9	413734.2	Weeping		grass	3	2,8	heart shaped small trunk, sparse, low LAD, small
Laburnum	Laburnum sp	6582878.9	413722.7	Weeping		grass	6	2,8	
Laburnum	Laburnum sp	6582887.1	413698.2	Weeping		grass	10	2,8	
Laburnum	Laburnum sp	6582887.9	413718.7	Weeping		grass	6	2,8	

Note: Most of the trees are planted in grass but are often placed near buildings.

* LAI is estimated based on litterature from Breuer et al. 2003; Deak Sjöman et al. 2021; Deak Sjöman 2017

Appendix C



Symbology
Process
Decision
Data
Predefined Process
Terminator
Manual Input
Database
Document
Manual Operation
LM
Laserdata 2019
Convert .laz to .las
Create las dataset
Convert Las multipoints to raster
Convert Las multipoints to raster
DSM (Include first of many, single return and return 1; cell assignemnet type: binning, Maximum; Void filling method: Linear; Output data type: Float; Sampling values:1)
DTM (Include ground; cell assignment type: binning, minimum; Void filling method: Linear; Output data type: Float; Sampling values:1)
Area Solar Radiation tool
Solar radiation
DSM - DTM
Heights above ground
Refclassify to eliminate noise
Heights
Zonal statistics
Mean heights of buildings
LM
Ortho 2018
Built up areas
Orthophoto
Ortho IRF 2012
Mosaic to new raster
Extract single bands
Output NIR and RED
Raster calculator float(NIR-RED /NIR+RED
NDVI
Reclassify NDVI > 0.2 veg. = 1 no veg. = 0
Raster calculator heights * Reclassified NDVI
Tree heights
Heights to Excel
SMHI
Weather & wind datat
USGS
GEE - coding
Select dates and data
Create LST from 2019
Kelvin to Celsius
LST maps 30m resolution
Map LST 2019-07- 30
Raster calculator NDVI*4.863 + LST* 0.589 + 7.807 (Julian day)
Raster calculator float to integer to get table of contents
Envi-met
Tree inventory
excel to table
Inventory to GIS map
Model
Simulation
Main area no vegetation
No vegetation
Current vegetation
Current vegetatio with higher LAD
Current vegetation + 3 trees, normal LAD
Current vegetation + 3 trees, high LAD
Current vegetation + 12 tree, low LAD
Current vegetation + 12 trees, regular LAD
Current vegetation + 12 trees, high LAD

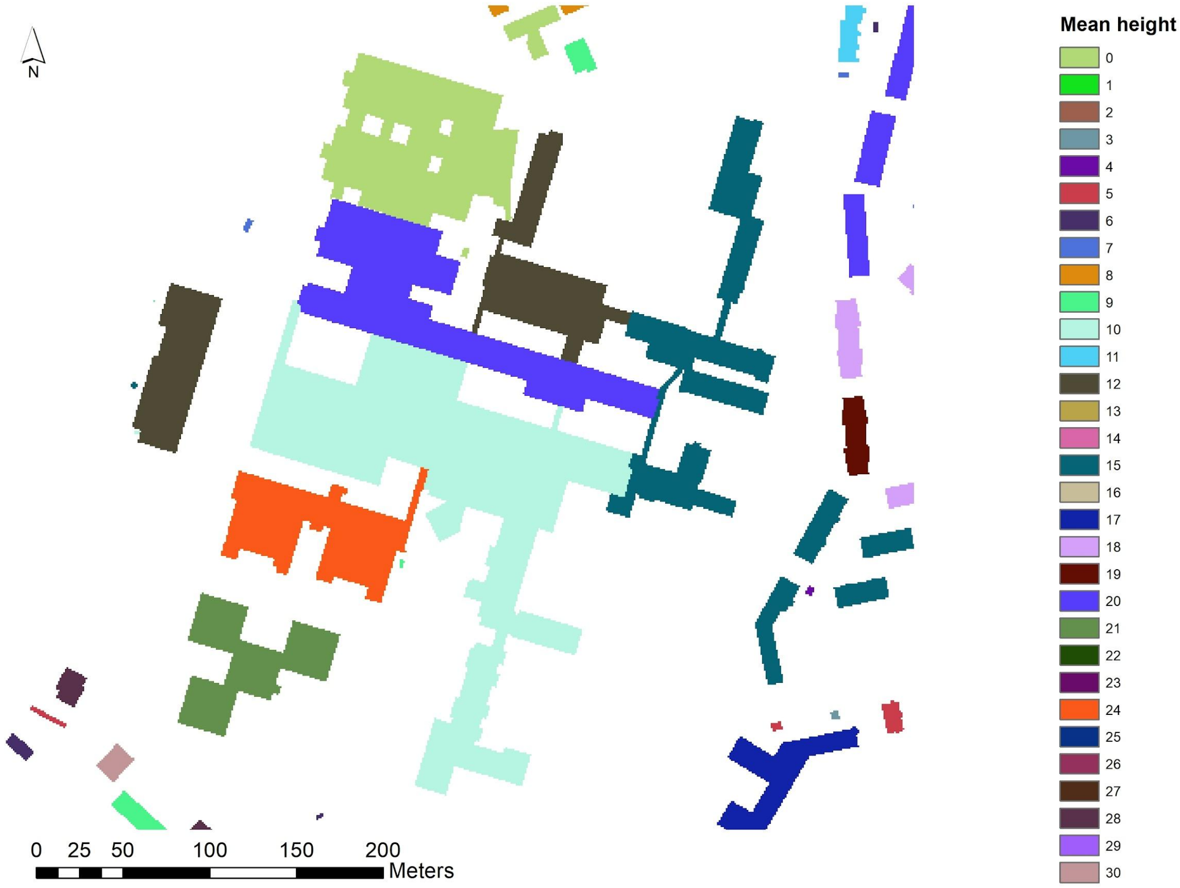
Appendix D

Code used in Google Earth Engine

By Ermida et al (2020) .

```
var LandsatLST = require('users/sofiaermida/landsat_smw_lst:modules/Landsat_LST.js')

//var geometry = geometry422
var geometry = ee.Geometry.Rectangle([12.0, 59.0, 11.5, 60.1]);
var satellite = 'L8';
var date_start = '2019-07-15';
var date_end = '2019-07-30';
var use_ndvi = true;

// get landsat collection with added variables: NDVI, FVC, TPW, EM, LST
var LandsatColl = LandsatLST.collection(satellite, date_start, date_end, geometry, use_ndvi)
print(LandsatColl)

// select the first feature
var exImage = LandsatColl.first();

var cmap1 = ['blue', 'cyan', 'green', 'yellow', 'red'];
var cmap2 = ['F2F2F2','EFC2B3','ECB176','E9BD3A','E6E600','63C600','00A600'];

Map.centerObject(geometry)
Map.addLayer(exImage.select('TPW'),{min:0.0, max:60.0, palette:cmap1},'TCWV')
Map.addLayer(exImage.select('TPWpos'),{min:0.0, max:9.0, palette:cmap1},'TCWVpos')
Map.addLayer(exImage.select('FVC'),{min:0.0, max:1.0, palette:cmap2}, 'FVC')
Map.addLayer(exImage.select('EM'),{min:0.9, max:1.0, palette:cmap1}, 'Emissivity')
Map.addLayer(exImage.select('B10'),{min:290, max:320, palette:cmap1}, 'TIR BT')
Map.addLayer(exImage.select('LST'),{min:290, max:320, palette:cmap1}, 'LST')
Map.addLayer(exImage.multiply(0.0001),{bands: ['B4', 'B3', 'B2'], min:0, max:0.3}, 'RGB')

Export.image.toDrive({
  image: exImage.select('LST'),
  description: 'LST2019-07-30',
  scale: 30,
  region: var geometry,
  fileFormat: 'GeoTIFF',
  crs: 'epsg:3006',
});
```

Appendix E



Map of mean height of buildings derived from Lidardata (2018) and property map of Build-up areas © The National Land Survey (Lantmäteriet). The building with a height of 0 is newly built and therefore not included in the lidar data.

Appendix F

URBAN HEAT ISLAND IN KARLSTAD CITY - INVESTIGATING LAND SURFACE TEMPERATURE, LAND COVER AND VEGETATION TO FIND VULNERABLE AREAS

By Patricia Kirkhorn

LK0376 Advanced digital landscape analysis with GIS
Swedish University of Agricultural Sciences

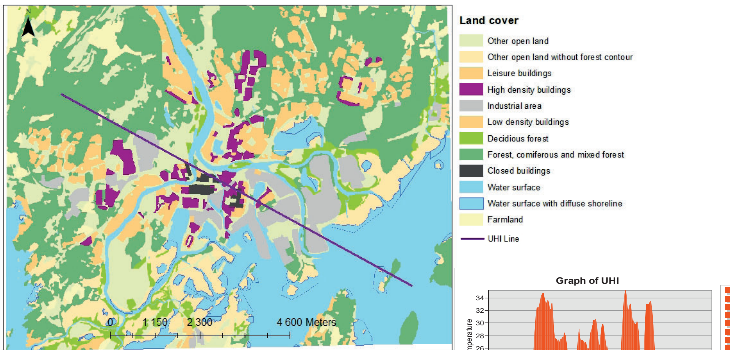
Introduction

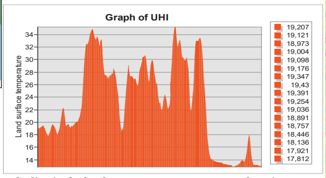
This project focuses on Karlstad city and investigates urban heat island, UHI, in the urban area. Karlstad (59.3821, 13.5025) is located north of Vänern, between Oslo and Stockholm, and is a growing city with more than 65.k inhabitants [8, 11]. Karlstad has several streams crossing the urban area.

Urban heat islands means higher temperature in urban areas than outlying areas. These temperature differences have to do with thermal and radioactive properties. Some surfaces absorb more heat, example buildings and pavements, than other surfaces like natural surfaces and vegetated surfaces. Some surfaces also release heat slowly which causes higher surface and air temperatures at night. Urban heat island can be divided into surface urban heat island and atmospheric (air) urban heat island. Land surface temperature, LST, which is mainly investigated in this project is not equal to air temperature but is an indicator on where urban heat islands occur since the air temperature is heated mostly by the ground, while surfaces are heated by solar radiation, SR. [3, 6].

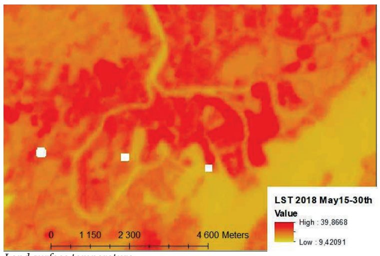
UHI is complex and there are many causes to it. Reduced vegetation in urban areas minimizes the natural evaporation, shading and cooling that vegetation provides which leads to even higher land surface temperatures. Impervious surfaces, buildings and infrastructure absorb rather than reflect SR and heat leading to higher surface and air temperatures due to their capacity to storage heat. Heat produced by humans - buildings, air conditioning, industries and cars all emit heat as well. Wind has a cooling effect. Taller buildings reduce wind and thereof the cooling effect from it. LST are influenced by slope and elevation which control the amount of solar radiation coming to the particular surface. Humidity and land use also affects the LST and UHI [3, 6, 12].

Urban heat island leads to increased heat-stress and heat-related mortality. Elderly, those with health conditions and children are at particular risk [5, 6]. UHI increases energy demand and consumption due to the use of cooling equipment. UHI degrades water quality due to thermal pollution and affects aquatic life, reproduction and metabolism. UHI causes higher levels of air pollution and greenhouse gases. [14] In the future higher air temperatures and land surface temperatures are expected. Heatwaves are expected to occur more often, up to every fifth year which makes the urban areas more vulnerable to experience UHI and heat stress [2, 5, 6]. By identifying vulnerable areas it is possible to plan for, and take measures to, mitigate where UHI is likely to appear [3, 5, 6].

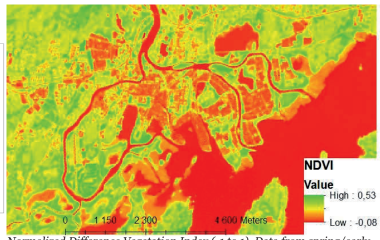




The line in the land cover map measures LST. There is a clear difference between different land covers and LST.

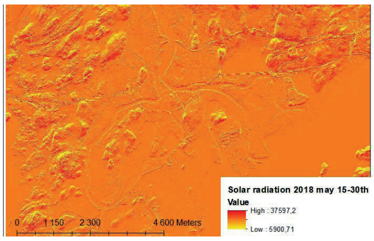


Land surface temperature

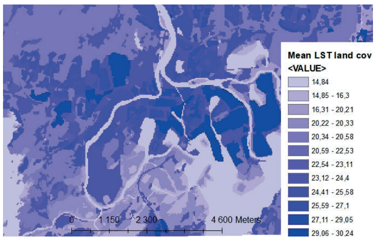


Normalized Difference Vegetation Index (-1 to 1). Data from spring/early summer therfore is the value 0,53, will assumingly be higher during summer.

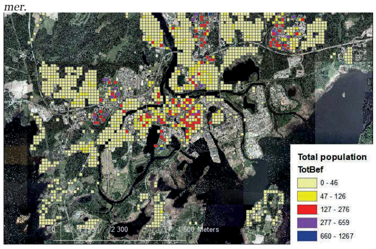
Orthophoto over Karlstad



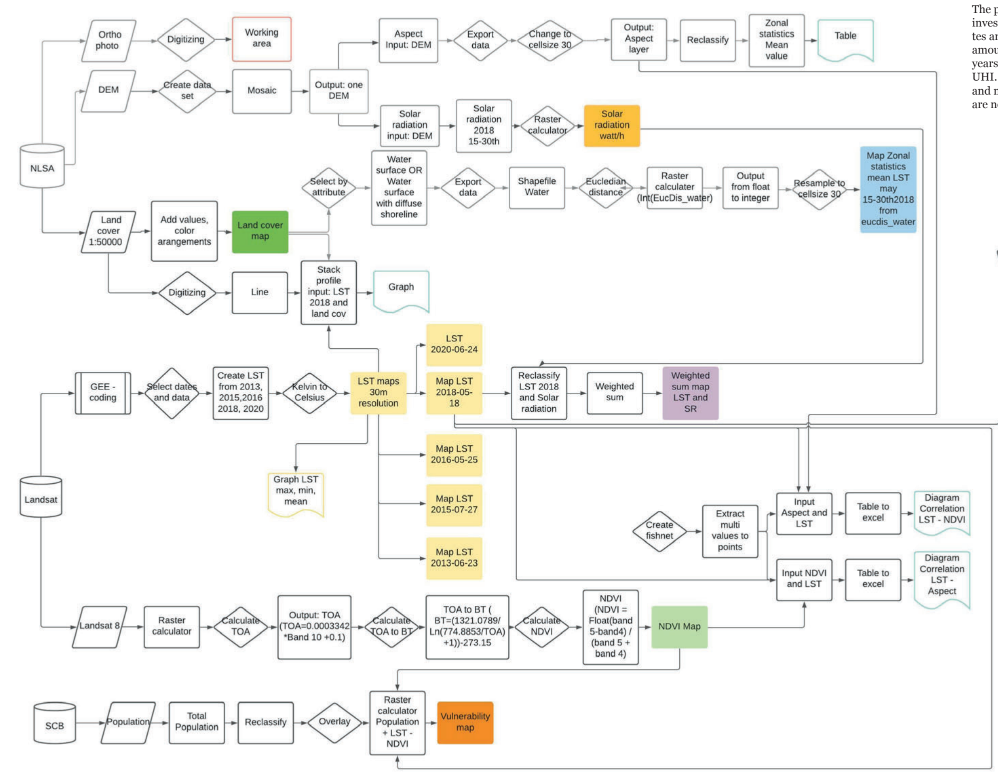
Solar radiation. Average 8 hours of sun per day. High radiation 700 = watt/h and low = 200 watt/h in may [9, 10].



Mean LST in each land cover. The map shows higher mean temperatures in industrial areas, high density areas and closed buildings. Overall higher mean LST's in the centre of Karlstad.



Population density in Karlstad.



Method

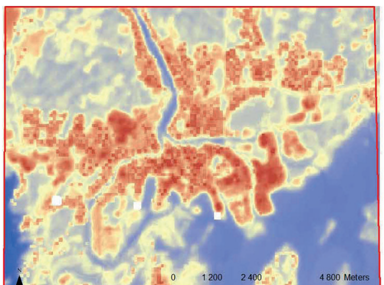
The primary purpose in this study is to characterize Karlstad city, its risk of experiencing urban heat island by investigating land surface temperature, land cover, vegetation and population to find areas with different climates and vulnerabilities. In order to do so data from Landsat, SCB and NLSA had to be collected. To minimize the amount of data being downloaded Google Earth Engine was used to create LST maps from different dates and years by using open code [3] with own written code. As described earlier many factors interact when it comes to UHI. Calculations, solar radiation, slope, aspect, euclidean distances, fishnet, reclassify, weighted overlay, overlay and manual input have been used in Arc GIS to investigate land cover and land surface temperature but all results are not presented, particularly if they were inexplicit or not accurate.

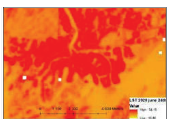
Sources of error and limitations

* Landsat data is only accessible when the transects are carried out and that has delimited the study.
* Difficulties to find data with high spatial resolution. 30x30m resolution is not very precise but a good start to investigate UHI. In a further analysis a finer data resolution is needed for a more accurate analysis.
* Satellites/optical sensors can not go through clouds and vegetation which could lead to datagaps or missing data (as seen in the LST map, may 15-30th 2018 where chosen to be the main data set because there was the least lack/gaps of missing data).
* Data from Landsat are taken at a certain time every interval (day/month/year) instead of when the surface urban heat island is at a minimum or maximum. The data would be more accurate if it showed the maximum because it is not possible to say whether the temperature is increasing or decreasing [15].
* Changed thresholds and criterias can change the result. Example when comparing solar radiation and LST. If overlay it is possible to compare them visually but this does not give any good numbers. By doing a reclassification of solar radiation and LST and looking into literature to find proper values for low-high temperatures and solar radiation [9,10] gives a better understanding but one risk by doing this is that the result will be modified and it could easily be manipulated which has to be considered during the process and analysis.
* Wrong assumptions from population data and estimation of population growth could be made and especially considering the expectancy. Many factors such as building construction rate, birth and mortality affects the population growth [11].
* There are many factors affecting UHI but not all of them are possible to measure. Wind speed can not be derived from satellite data and it is difficult to assess it even though it is known that it has an effect on experienced air temperature [7, 14]. Close to surface air temperature (1 m above ground) can be estimated using Modis data if there also are enough air temperature observations [15]. In this case there is only one temperature station in Karlstad and air temperature could not be estimated. Soil moisture, cloud cover and surfaces permeability also affect LST and air temperature but have not been deeply investigated in this work [6, 14].
* Looking at air temperature from the fixed station in Karlstad gives high accuracy but are not representable for the whole city, but gives an indication of air temperature and is therfore used in the LST graph when looking in to different dates and years [7].

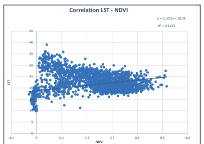
Results and discussion

High LST values are identified in non or low vegetated areas such as low density building areas, high density building areas and industrial areas. There is a positive correlation between NDVI and LST in Karlstad city. Low LST values could be identified in vegetated areas, such as parks and forests and on water surfaces. Plants reflect solar radiation, SR, and NDVI can be used as an indicator of LST. The LST values from different years measured can not be compared to eachother due to the large time difference in months, it is not accurate, but what is interesting is that the mean air temperature follows the lower LST rather than the higher LST. 2020 was a particular warm year and it shows higher LST from that date as well as the temperature span is wider. Water usually has a cooling effect on LST [14] but in this case the mean temperature is higher closer to the water than further away from water and it is not possible to assume that water has a cooling effect within the study area. This could be due to the lack of vegetation in these areas as well depending on the type of ground surface and elevation that could be more heat absorbent and more exposed to SR [6, 14]. The vulnerability map shows areas where people are more likely to experience urban heat island and heat stress. These areas are more dense, have a lower NDVI and a higher LST values and are closer to the centre of Karlstad. The population in Karlstad has grown in recent years and is estimated to continue growing [11]. This could lead to higher housing density, more impervious surfaces and lead to more areas with higher land surface temperatures and air temperatures as a result. Connecting this with the expectancy of higher mean air temperatures due to global warming and heat waves occurring more often will increase the stress on the environment, peoples health in cities during the warmer times of the year, and it can also lead to stress for healthcare as well as society overall [5]. Slope and aspect where investigated and slopes in a southeast to southwest direction shows a slightly higher mean temperature. This could be due to a higher SR. When a weighted overlay was done with SR and LST there was also a correlation, the surfaces with higher temperature had a higher SR exposure and higher SR numbers. Investigating UHI is challenging. There are many climate characteristics such as SR, wind, land cover / land use and vegetation that affects the appearance of UHI's. Time of the day and season also affects the results when investigating UHI. Heat released by humans also contributes to UHI [7]. Estimating air temperature was not possible during this study, it demands planning and many people involved to measure air temperature during a certain time [15]. By looking at LST it is possible to get an understanding of vulnerabilities and places at risk of becoming UHI's as well as it is possible to mitigate and take action when developing urban areas [7].

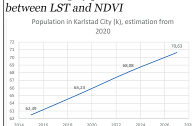




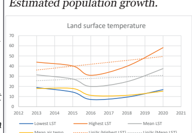
LST 2020. The map shows how the hot surfaces spread when temperatures are rising.



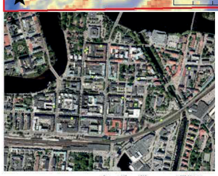
There is a slighly possitive correlation between LST and NDVI

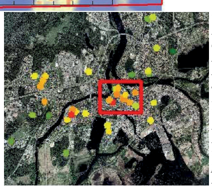


Estimated population growth.



LST from 2013-06-23, 2015-07-27, 2016-05-25, 2018-05-18, 2020-06-24.





The near environment is of importance when it comes to UHI. Preschools, health care and retirement homes where pointed out and a mean LST within 100m where measured. The centre of Karlstad is at risk and should be further investigated. It can be seen that there are a lot of impervious surfaces as well as low amount of vegetation.

Mitigation

Green space is considered effective to reduce urban heat island, through evaporation, air exchange and shading. Water bodies could mitigate higher temperature during daytime and have a cooling effect, particularly if they are larger (wider than 100m). The land cover impacts the land surface temperature. Green space and water bodies have generally a lower temperature meanwhile impervious surfaces have higher land surface temperature. Terrain height and surface roughness also affects LST. By implementing more vegetation in areas most vulnerable and considering what type of surfaces are used the UHI effect could decrease. Considering the distance to water and parks for the population to get coolness is of importance. [14].

References

[1] Climatedata.org (2019) Karlstad Climate https://sv.climate-data.org/europa/sverige/vaermlands-laen/karlstad-200/#climate-graph [2021-03-08]
[2] Darlington Mushore, T. Odindi, J. Dube, T & Mutanga, O. (2017) Prediction of future urban surface temperatures using medium resolution satellite data in Harare metropolitan city, Zimbabwe. Building and Environment. vol. 122, Sept 2017, p. 397-410. https://doi.org/10.1016/j.buildenv.2017.06.033 [2021-03-08]
[3] Ermida, S.L., Soares, P., Mantas, V., Göttsche, F.-M., Trigo, I.F., 2020. Google Earth Engine open-source code for Land Surface Temperature estimation from the Landsat series. Remote Sensing, 12 (9), 1471; https://doi.org/10.3390/rs12091471
[4] GIS Crack (2018) How to calculate Land Surface Temperature with Landsat 8 satellite images. Available from: https://giscrack.com/how-to-calculate-land-surface-temperature-with-landsat-8-images/?fbclid=IwAR-11V2qzZsMDMFXW6x4p9aeXX-wYq48P35zK08oIkwYgQtYzK2uC5nywStQ [2021-03-04]
[5] SMHI (2018) Heat wave - Possible effects and measures in health care. https://www.smhi.se/lathund-for-klimatanpassning/stod-i-ditt-verksamhetsomrade/vard-och-omsorg/varmebolja-mojliga-effekter-och-atgarder-inom-vard-och-omsorg-1.140208 [2021-03-08]
[6] NASA VIDEO (2020) NASA ARSET: Land Surface Temperature-Based Urban Heat Island Mapping, Part 1/3 [youtube] 2020-11-20 Available from: https://www.youtube.com/watch?v=KYV2j3kwj2A [2021-02-22]
[7] Rodríguez, L.R. Ramos, J.S, R. Sánchez de la Flor, F. J, Domínguez, S.Á (2020) Analyzing the urban heat Island: Comprehensive methodology for data gathering and optimal design of mobile transects Sustainable Cities and Society Vol. 55, April 2020, https://doi.org/10.1016/j.scs.2020.102027
[8] SCB (2020) Statistical urban areas 2018; population, land area, population density www.scb.se/MI0810. [2021-03-08]
[9] SMHI (n.d) Karlstad [solar radiation daily] Available from: https://www.smhi.se/polopoly_fs/1.90552!/Menu/general/extGroup/attachmentColHold/mainCol1/file/Daily_Karlstad.png [2021-02-26]
[10] SMHI (n.d) Karlstad [solar radiation hourly] Available from: https://www.smhi.se/polopoly_fs/1.91854!/Menu/general/extGroup/attachmentColHold/mainCol1/file/Hourly_Karlstad.png [2021-02-26]
[11] Sweco (2019) Population forecast 2019-2028 Karlstad municipality and sub-areas. Rapport 2019-05-10 SWECO SOCIETY https://karlstad.se/globalassets/filer/kommun-och-politik/kvalitet_undersokningar_och_statistik/statistik/befprognos-k-d-2019-2028-samt-delomr-2019-2023---rapport.pdf [2021-03-08]
[12] USGS Earth Resources Observation and Science (EROS) Center (2018) Landsat. Earth Explorer. https://earthexplorer.usgs.gov [2021-03-08]
[13] Vackert väder (n.d) Climate and temperature for Karlstad, Värmland https://www.vackertvader.se/karlstad/klimat-och-temperatur [2021-03-05]
[14] Wu, Z & Zhang, Y (2019) Water Bodies' Cooling Effects on Urban Land Daytime Surface Temperature: Ecosystem Service Reducing Heat Island Effect, Sustainability 2019, 11, 787 DOI: 10.3390/su11030787
[15] Zeng, L. Wardlow, B.D. Tsedaye, T. Shan, J. Hayes, M.J. Li, D & Xiang, D. (2015) Estimation of Daily Air Temperature Based on MODIS Land Surface Temperature Products over the Corn Belt in the US. Remote Sens. 2015, 7(1), 951-970; Available from: https://doi.org/10.3390/rs70100951 [2021-03-02]