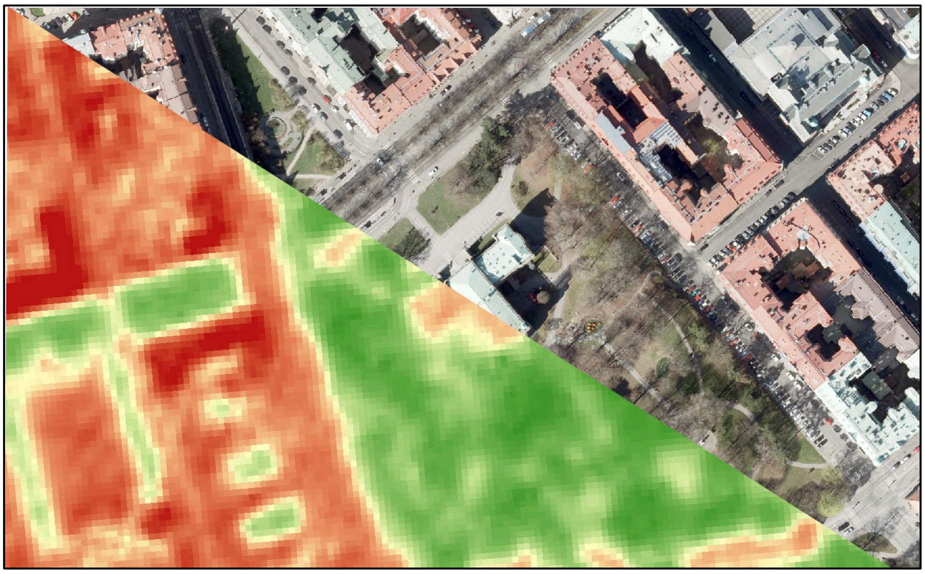
UNIVERSITY OF GOTHENBURG

DEPARTMENT OF BIOLOGICAL AND ENVIRONMENTAL SCIENCES

CHANGES IN URBAN GREENERY DURING THE 2018 HEAT WAVE – A CASE STUDY FOR GÖTEBORG USING REMOTE SENSING



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Frontpage image source: Ivan Ruzic

Abstract

Urban vegetation plays a crucial role in diverse urban microclimates. The numerous ecosystem services provided by vegetation, particularly trees, ensure greater quality of life and thermal comfort regulation. Yet, not all trees are immune to extreme weather events, such as droughts and heat waves, especially in cities. The urban heat island effect, combined with human-induced climate change, adds significant stress to vulnerable urban ecosystems, especially in species that are not used to such extreme conditions. The 2018 summer heat wave which occurred simultaneously with a long period of drought from late spring to late July caused significant tree heat stress, vitality decline and subsequent mortality in urban habitats in Sweden. This study aimed to investigate the impact of this event on urban tree health in Gothenburg, Sweden. The Normalized Difference Vegetation Index (NDVI) was used as an indicator for tree health, which was obtained through remote sensing by using satellite imagery. An overall decline in NDVI across the entire urban area of Gothenburg was identified for late July 2018 when compared to the same period in 2017. Field measurements were conducted in spring 2023 on trees in central Gothenburg to find traits correlating to NDVI differences in July 2018 - July 2017, such as tree height, tree crown surface and permeable surface percentage.

Tree height and tree crown area relatively correlated with NDVI changes in 2018, with NDVI declines being lower in larger trees. This indicates greater NDVI declines in smaller trees, implying them to be more drought sensitive. Additionally, NDVI declined x% in trees with a larger y% fraction of permeable surface under the crown. Due to a co-variance of NDVI decline with tree height, I conclude that tree size was the most important indicator for drought sensitivity, followed by area of permeable ground. Smaller trees are shown to generally have greater permeable surface fractions below the crown, due to their size alone. Hence, the advantages of larger trees compared to permeable surface fraction are a key finding. No correlation was found between tree species composition in affected vs. control areas, apart from linden trees (*Tilia Europaea*) being found more in grouped areas with no decline and less in single tree areas with NDVI decline. With linden trees being large, this confirms previously mentioned statements about tree size and drought resistance. These findings can be used as a basis for improving urban vegetation design, highlighting the importance of tree size, and improving planting design for greater tree growth, which can increase climate resilience and resistance towards extreme weather conditions that are likely to occur more frequently in the future.

Keywords: Heat wave, urban trees, NDVI, remote sensing

Popular Science Summary

Promjene u urbanoj vegetaciji tijekom toplinskog vala 2018. - studija slučaja za Göteborg pomoću daljinskog očitavanja

Urbana vegetacija, posebice drveće, igra ključnu ulogu u stvaranju raznolike mikroklime unutar gradova, nudeći mnoštvo prednosti za dobrobit stanovništva i regulaciju gradskih temperatura. Međutim, drveća nisu otporna na ekstremne vremenske uvjete kao što su suše i toplinski valovi, koji su dodatno pogoršani učinkom urbanog toplinskog otoka i klimatskih promjena. Ljetni toplinski val 2018., zajedno s dugotrajnom sušom, uzrokovao je štetne posljedice na zdravlje stabala u Göteborgu u Švedskoj. Korištenjem daljinskog satelitskog očitavanja, znanstvenici su primijetili sveukupni pad u zdravlju drveća krajem srpnja 2018. u usporedbi s prethodnom godinom. Mjerenja na terenu nadalje su pokazala da su manja stabla doživjela veći pad zdravlja, što ukazuje na njihovu povećanu osjetljivost na sušu. Drveće s većim krošnjama i višom visinom pokazalo je relativno manje pogoršanje zdravlja, naglašavajući njihovu otpornost na sušu i toplinski val. Zanimljivo je da su stabla s većim udjelom propusne površine ispod svojih krošnji također doživjela pogoršanja. Ovim otkrićem se pridodaje na važnosti veličine stabla nad svojstvima okolne površine. Pritom su se stabla lipe istaknula kao otpornija na sušu. Ova studija pruža vrijedne uvide u dizajn urbane vegetacije, naglašavajući važnost veličine drveća i poboljšanih strategija rasta stabala u gradovima. Poticanjem rasta većih vrsta stabala, gradovi mogu ojačati otpornost na klimatske promjene i borbu protiv rastuće prijetnje ekstremnih vremenskih nepogoda u budućnosti.

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Abbreviations

CHDI – Climatological Heat Wave Index

GIS – Geographic Information System

NDVI – Normalized Difference Vegetation Index

ΔNDVI – Difference between NDVI in July 2018 compared to July 2017

NIR – Near Infrared

SMHI – Swedish Meteorological and Hydrological Institute

UHI – Urban Heat Island

UHIC – Urban Heat Island Circulation

1. Introduction

In 2018, Central and Northern Europe experienced a prolonged drought and heat wave with severe consequences for both the population and the environment, both in rural and urban areas (Åström and Forsberg 2019; Marchin et al. 2022; Oudin Åström et al. 2020). Southern Sweden witnessed one of the most severe droughts in recent history, which not only impacted the rural and urban vegetation but also exacerbated the urban heat island (UHI) effect, making urban areas less comfortable for human habitation due to increased temperatures.

The lack of vegetation in urban areas across Europe amplified the UHI effect, resulting in higher temperatures and reduced comfort. Negative impacts, which affected forest ecosystems outside of urban areas, included reduced tree growth, earlier leaf discoloration, wilting, and even tree death (Malmquist et al. 2021; Schuldt et al. 2020). Understanding the impact of droughts and extreme weather events on urban vegetation is crucial for developing effective strategies to manage urban vegetation and mitigate climate change's impact on urban ecosystems (Dawes et al. 2018; Winbourne et al. 2020).

This study aims to examine the impact of the 2018 summer drought on the urban tree vegetation of Gothenburg, exploring the specific ways in which trees might have been affected. Additionally, the study investigates various tree-specific traits and location properties of affected and unaffected trees to identify potential links between planting design, habitat, and tree health. The Normalized Difference Vegetation Index (NDVI) was used as a measure for changes in tree health during this period. By comparing changes in tree traits with NDVI changes through regression analyses, statistical significance can potentially be found. The study uses remote sensing to determine the conditions of trees during the end of July 2018 and compares them with the conditions during the same period in 2017. By filling the research gap in this area, this study provides valuable insights into the effects of heat and drought on urban trees in Gothenburg. This will potentially contribute to the development of effective strategies for urban vegetation management and highlight the importance of proactive measures to protect urban ecosystems from the impacts of climate change.

2. Background

2.1. 2018 European heat wave & Sweden

With climate change causing an increase in the occurrence and length of periods of high air temperatures in most areas around the globe, it comes as no surprise that some of these events become classified as extreme weather events. Heat waves fall into this category and are considered periods of extremely high temperatures that deviate from standard high temperatures during regular summer seasons.

To properly classify an event as a heat wave, several definitions have been made by the European Environment Agency, with a focus on daily temperatures that differ from regular hot summer days. One that is based on maximum daily temperatures is the climatological heatwave days index (CHDI). It is defined as "a period of at least three consecutive days when the daily maximum temperature exceeds the 99th percentile of daily temperature values from May to September in a given location over the reference climate period" (Crespi et al. 2020).

Heat waves in Sweden, however, are defined differently. According to Döscher et al. (2019) and Nikulin et al. (2011), a heat wave in Sweden is classified as a period of temperatures higher than 25°C for at least 5 consecutive days. This definition was adopted by the Swedish Meteorological and Hydrological Institute (SMHI) and used to determine the severity of the heat wave in 2018. Additionally, SMHI introduced the term "high summer days" as days with maximum temperatures equal to or above 25°C. Both terms were used to distinguish regular summer days from the heat wave in 2018 and are still in use (SMHI 2023).

The 2018 summer drought and heat wave in Europe was one of the most extreme heat-related events in recent decades. Northern Europe was particularly affected, including Sweden, where it resulted in wildfires throughout the country and caused an excess in heat-related mortality (SMHI 2019; Statens offentliga utredningar 2019). Compared to the extreme summers that occurred in 2003 and 2010, this event differed in three ways. Firstly, the heat wave occurred mostly in central Europe and higher latitude countries in the north, which are generally not used to long-lasting droughts and high temperatures. Secondly, a swift transition from wet spring to dry summer conditions occurred, which led to earlier growing seasons and faster soil moisture depletion. Lastly, such an occurrence of a strong preceding heat wave during spring in May amplified the drought effects that would continue throughout the summer.

The legacy effects of increased sunlight and warming during spring caused a decline in CO_2 uptake within forest ecosystems, particularly in central Europe (Bastos et al. 2020). On the other hand, Scandinavian forest ecosystems showed a brief increase in CO_2 uptake. This positive effect lasted shortly during spring, which later led to a substantial decline in soil moisture as the year progressed, especially during summer and July 2018. These findings indicate that extreme drought and heat during summer have a direct negative impact on ecosystems, and these events are projected to occur more frequently or intensify in the future (Bastos et al. 2020).

As seen in Fig. 1, average monthly temperatures deviated substantially from May to August of 2018, especially during May and July, when virtually all of Sweden experienced temperatures ~5°C higher than usual. Deviations in precipitation compared to average values are shown in Fig. 2, and during July 2018, precipitation rates were much lower than usual, especially in Southern Sweden. Precipitation rates increased during August, which marks the end of the drought and heat wave.

Swedish society and infrastructure are mostly adapted to life in rather cold climate conditions (Lilja 2017). For example, passive housing has become a modern trend in both rural and urban areas, intending to reduce energy consumption and ecological footprints for heating. Such housing models focus on trapping heat and improving insulation (Janson 2008; Niskanen and Rohracher 2020). This further increases the vulnerability of Sweden's urban population to extreme heat events (Malmquist et al. 2021). Southern Swedish cities would therefore be especially vulnerable, considering that temperatures remained above average throughout the summer of 2018 (Fig. 2).

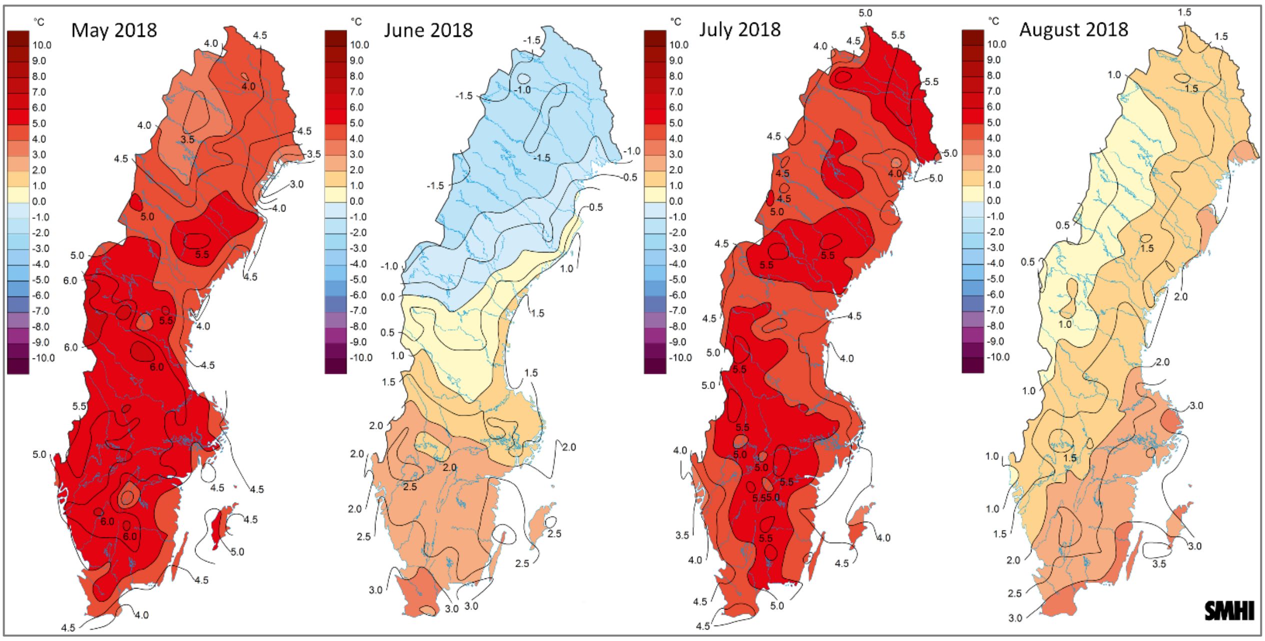


Fig. 1. Deviation of monthly average temperature (in °C) in 2018. Reference normal period: 1961-1990. Left to right: May, June, July, and August. Source: SMHI (2023).

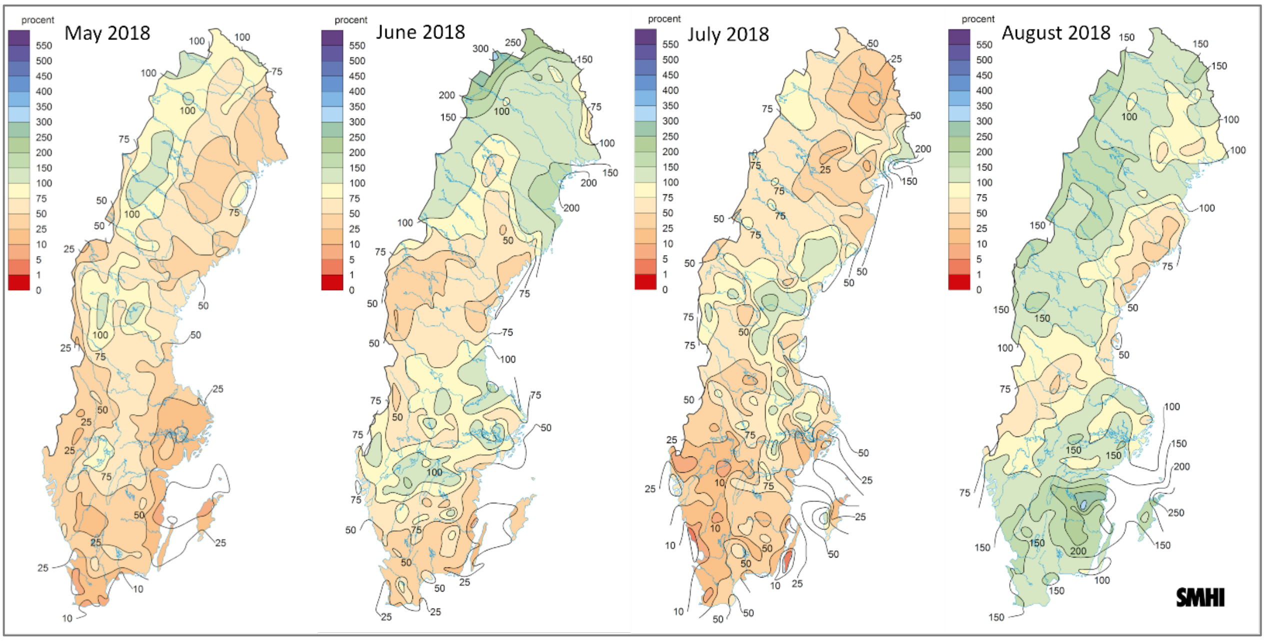


Fig. 2. Monthly precipitation as a percentage of normal values for 2018. Reference normal period: 1961-1990. Left to right: May, June, July, and August. Source: SMHI (2023).

2.2. The role of greenery in urban environments

Every city around the world is unique in some way or form (Pretzsch et al. 2017). Concordantly, each city has its unique problems and challenges to face. This is where vegetation has been shown to play a crucial role in regulating various ecological and environmental processes in cities, especially in cities severely affected by climate change (Esperon-Rodriguez et al. 2022). Trees have a natural cooling potential that can reduce urban street surface temperatures, especially over asphalt, which has a lower albedo than the surrounding area. By providing shade, they help in cooling the surrounding areas and block sunlight from reaching heat-absorbing surfaces (Rahman et al. 2020). On top of that, there are elements offered by vegetation which improve the overall comfort of the urban microclimate, such as air pollution mitigation. By absorbing CO_2 through photosynthesis, plants also act as carbon-sinks (Arcos-LeBert et al. 2021). The presence of vegetation in cities offers more than climate and temperature regulation. It provides benefits to everyday human life and activity in cities, some of which include air quality and noise pollution regulation, improved stormwater runoff, and increased biodiversity. Tree roots can also stabilize the soil and prevent erosion (Nowak and Dwyer 2000).

It is also important to note that vegetation can cause drawbacks in urban areas if planted and designed poorly. If that is the case, trees can cause the opposite effect and decrease air quality, trapping air pollutants near the ground, thereby decreasing human health and comfort (Nowak et al. 2018). Additionally, the urban microclimate differs within the city and is often complex and non-uniform. For example, dense concrete areas with skyscrapers and high-rise buildings contrast greatly from park-like areas. These differences are mostly in temperature, soil composition, water availability, non-permeable land cover and building density (Heris, Middel, and Muller 2020; Shafaghat et al. 2016). Street trees with greater impermeable surface areas and lower water availability are prone to higher stress levels compared to trees in more park-like conditions, resulting in reduced tree growth and health (Mullaney, Lucke, and Trueman 2015; North, D'Amato, and Russell 2018; Roman and Scatena 2011; Sand et al. 2018). Therefore, choosing the best type of vegetation for each area is necessary to optimize the urban microclimate (Dimoudi et al. 2013; Winbourne et al. 2020).

An essential aspect of urban vegetation for maximum thermal comfort is species origin. Sometimes tree species non-native to the local region might be as effective or perform better than native populations in mitigating the UHI effect. These traits mostly refer to greater resistance to heat, drought and pollution (Riley, Herms, and Gardiner 2018). Several studies have been conducted on preferences for native vs. exotic tree species, where the opinion of citizens was taken into consideration. Most of the studies conclude that while native species provide beneficial ecosystem services, exotic species have shown to be more adaptable in the face of climate change and extreme urban environments (Potgieter et al. 2017; Riley et al. 2018; Sjöman et al. 2016; Thom et al. 2022). However, some studies found no such correlation (Esperon-Rodriguez et al. 2019). Thus, it is necessary to know which tree species would excel in specific urban areas. Because of the topic's complexity, one should take these factors into account when conducting research on urban vegetation.

2.3. The UHI effect & Gothenburg

It has been well documented that cities and urban areas tend to have higher air temperatures than surrounding rural areas, no matter the season. When the natural land cover is replaced with dense concentrations of buildings, pavement and other dry and heat-absorbing surfaces, the UHI phenomenon occurs (KIM 1992; Roth 2013; Yang et al. 2016). This effect reduces the overall thermal comfort, trapping heat and increases stormwater runoff due to decreased ground permeability. Evapotranspiration is impacted the most by the UHI. This natural cooling process provided by vegetation (Grimmond and Oke 1999) is heavily affected when it is replaced by urban structures. Less vegetation leads to lower transpiration rates, and impermeable surfaces prevent water from infiltrating into the ground, thereby limiting the water supply for existing vegetation (Taha 1997).

The UHI of Gothenburg has been studied for decades. It extends vertically from 40-70 meters and horizontally from 10-13 kilometers. The UHI effect is greatest during clear skies and low wind speeds. Under these conditions, there is a positive net radiation balance, and a heat island intensity of at least 2.5°C. Regional winds high above the heat island do not influence the airflow below the city, but rather an independent circulation is formed within the UHI. This urban heat island circulation (UHIC) plays a crucial role for air pollution concentrations, influencing the mixture of both polluted and clean air in Gothenburg (Eliasson and Holmer 1990).

Geometry and urban design also play an important role in the UHIC in Gothenburg. A study by Thorsson et al. (2011) found that narrow streets (urban street canyons) and densely built structures show lower temperatures due to shading when compared to paved open areas during the summer. They also experience warmer temperatures during winter due to heat from buildings and indoor human activity being retained within these street canyons. The study also points out that by 2099, heat stress within the city is expected to triple when compared to current conditions.

The UHI can impact the vegetation within cities as well. A study by Pretzsch et al. (2017) evaluated the effect of the UHI on urban trees in 10 metropolitan areas across the world. It was found that older urban trees influenced by the UHI effect generally experience higher growth rates when compared to their rural counterparts. However, in the last few decades, rural tree growth has become faster than urban tree growth due to climate change and additional heat stress in cities. Accelerated urban tree growth may be beneficial in the short term, but it also shortens the lifespan of trees, thereby requiring frequent urban tree replacements and limiting their ecosystem services (Pretzsch et al. 2017). A shorter life span means higher tree mortality, which is already naturally high in cities. High tree mortality rates require repeated replacements, which makes urban vegetation maintenance more costly (Nowak and Dwyer 2000).

Study Aims and research questions

This study aims to examine and compare the locations and amount of urban tree vegetation that was much or little negatively affected by the 2018 summer heat wave and drought in Gothenburg. The degree of impact in 2018 was determined by comparing the Normalized Difference Vegetation Index (NDVI) data with the previous year. The specific questions this study aims to answer are as follows:

- Was there an overall decline in NDVI for the urban vegetation of Gothenburg?

- Was there a difference in certain traits (e.g., species composition, height, crown surface) between grouped and single trees?

-Which tree species have shown the most and least resilience to the heat wave?

-How did the surrounding area in terms of urban design, structure and planting influence the studied tree groups?

3. Materials and methods

3.1 Study plan – remote sensing and NDVI

The first part of the study consisted of using remote sensing methods to quantify the overall change in vegetation health & greenness in the area of central Gothenburg during 2018, with a reference period in 2017. The indicator used in this study to observe changes in greenness was the Normalized Difference Vegetation Index (NDVI). NDVI is a measure that represents vegetation greenness (i.e., leaf area combined with leaf chlorophyll content) as a function of spectrally contrasting red light and near-infrared (NIR) light reflectance. It is often used in vegetation phenology to study the sensitivity of vegetation to climate variability and change (Tucker 1979; Tucker and Choudhury 1987). The equation for calculating NDVI is listed below:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Where

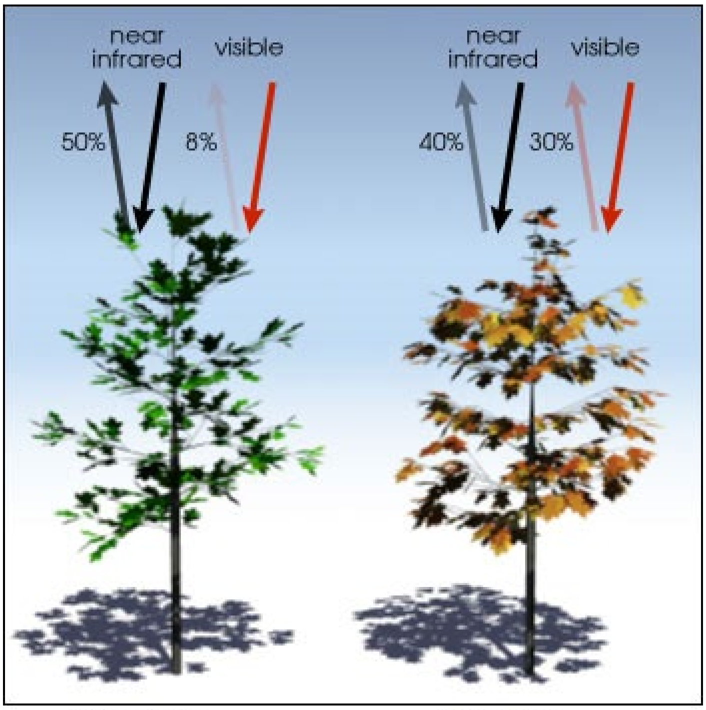
NDVI is the normalized difference vegetation index

NIR stands for near-infrared radiation (λ~0.8 µm)

“Red” stands for the red spectrum of visible light (λ~0.6 µm)

The connection between NDVI and vegetation in the form of surface reflectance is illustrated in Fig. 3. Surface reflectance data refers to measurements or information about the amount of light reflected by Earth's surface across different wavelengths of the electromagnetic spectrum. It provides insights into how different materials and surfaces interact with and reflect light. This data is typically obtained through satellite remote sensing or other sensor-based technologies (Filippa et al. 2018).

Low values indicate either non-vegetative areas (i.e., water or bare soil) or vegetation with poor health that does not absorb the red spectrum of visible light (tree to the right). Higher NDVI values indicate healthy vegetation areas (tree to the left) which absorb much more red light and reflect much of the NIR light.



$$\frac{(0.50 - 0.08)}{(0.50 + 0.08)} = 0.72 \qquad \frac{(0.4 - 0.30)}{(0.4 + 0.30)} = 0.14$$

Fig. 3. Example of NDVI calculation from visible red and near-infrared light reflected by vegetation. Source: NASA (2000), page 1.

3.2. PlanetScope and NDVI

NDVI was calculated from PlanetScope satellite data (Planet 2023). PlanetScope has a constellation of more than 130 satellites which allow the acquisition of daily imagery. Launched in 2014, the data collected by PlanetScope is often used by researchers to gain insights into Earth's changing landscapes, monitor natural resources, track deforestation, study urban development, and support decision-making processes in numerous industries (Roy et al. 2021). The satellite's spatial resolution was 3 m * 3 m per pixel.

For greater accuracy in calculating NDVI from satellite imagery, certain criteria had to be met. Images with clear days and without any clouds scattered accross the city was one of them. Cloudy or foggy weather isn't suitable for this data analysis, as clouds interfere with NIR and infrared emissions, providing less accurate NDVI calculations (Alvarez-Mendoza, Teodoro, and Ramirez-Cando 2019). Even though most of 2018 was a dry period, which meets previously mentioned requirements, satellite data showed a great number of days with minor clouds scattered over the Gothenburg area.

To overcome this obstacle and to find suitable satellite imagery with clear skies, data on precipitation was analyzed from the Swedish Meteorological and Hydrological Institute (SMHI). After confirming that precipitation levels increased in early/mid-August with the arrival of rain (Fig. 4), thus ending the dry period, the end of July 2018 was chosen for finding satellite images and NDVI level comparison. This period was also the driest during the entire heat wave, which would most likely show the accumulated effect of the entire drought period, compared to a hot day in May, where the effects have not accumulated yet.

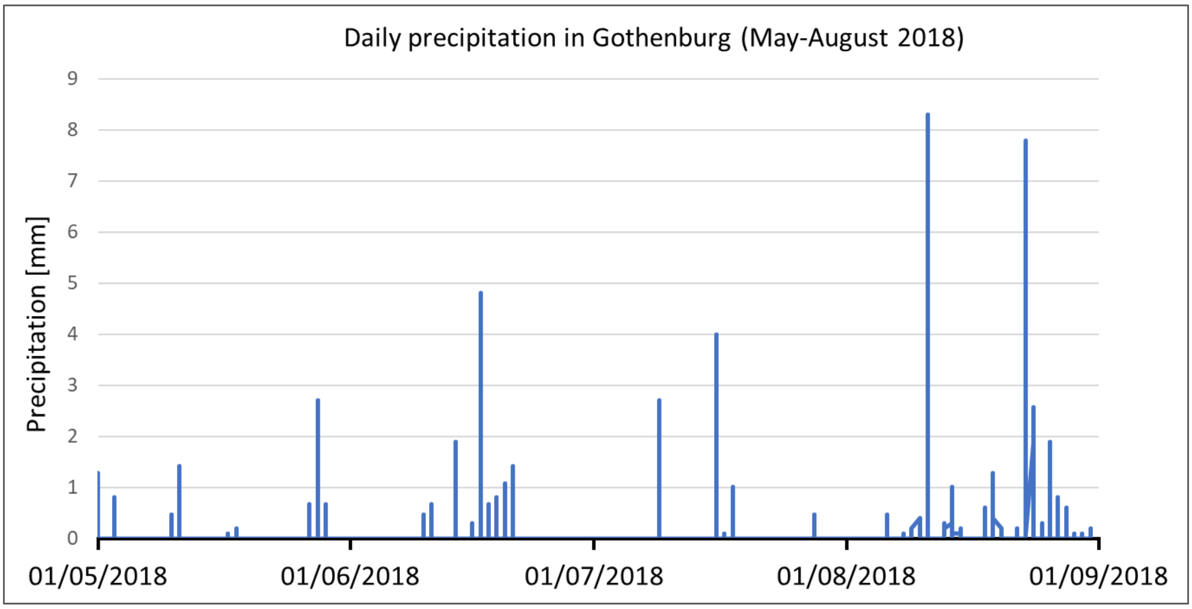


Fig. 4. Daily precipitation (in mm) in Gothenburg, from May to September of 2018. Source: SMHI (2023).

Satellite data was obtained, where one satellite image represented each month selected for analyses. A total of 18 satellite images were obtained for representing June, July, and August of 2017 to 2022. Precise data on satellite images can be found in Appendix C. Due to a short amount of time, this study focused on only data from 2017 as the reference year and 2018 as the drought year. The reference satellite image that was used was from July 20th, 2017, while the data used for comparison and analysis was from July 27th, 2018.

To find out if the summer of 2017 was similar to 2018, additional data on precipitation and temperatures from SMHI was collected for the reference year of 2017. This was done to make sure that the reference period was suitable for comparison, and not an anomaly year similar to 2018. A comparison between summer temperature deviations from the 30-year norm for both 2017 and 2018 can be seen in Fig. 5, and precipitation deviations are shown in Fig. 6. Both precipitation and temperatures in 2017 did not deviate from the 30-year reference point of 1961-1990. As such, the reference year was confirmed to be suitable for comparison with 2018, as it also reflects the average 30-year standard data.

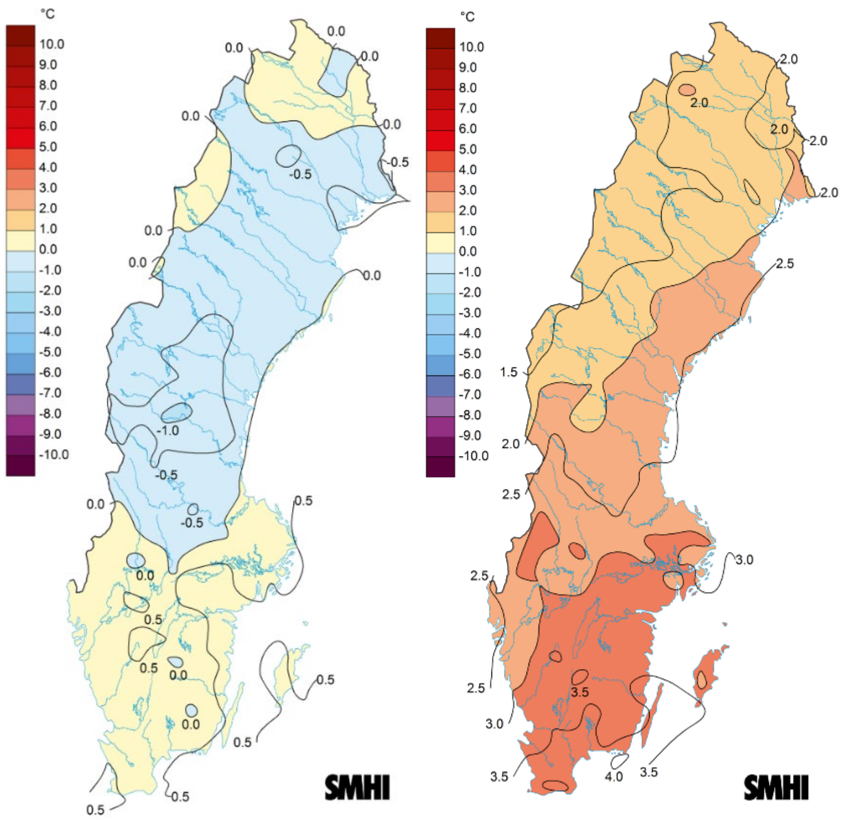


Fig. 5. Deviation of the average temperature during the summer of 2017 (left) and 2018 (right). Reference normal period: 1961-1990. Source: SMHI (2023).

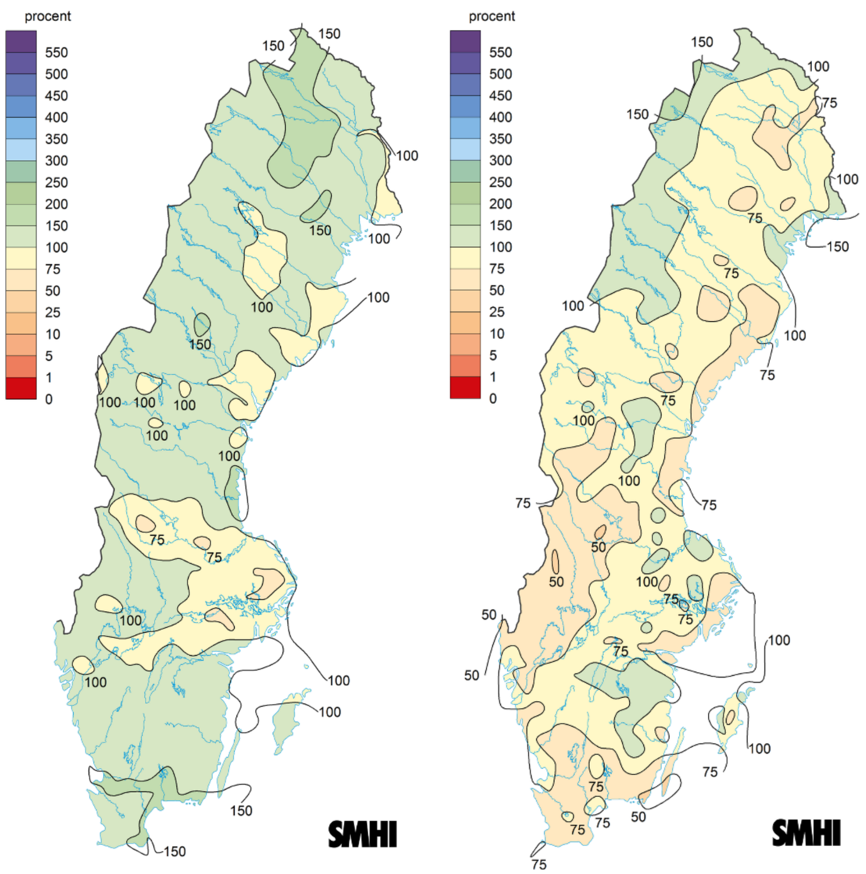


Fig. 6. Precipitation as a percentage of normal for the summer of 2017 (left) and 2018 (right). Reference period: 1961-1990. Source: SMHI (2023).

3.3. Study area - Gothenburg

Gothenburg is the second largest city in Sweden, with over 580 000 inhabitants. Located on the west coast of Sweden, it is influenced by a temperate oceanic climate, accompanied with mild annual temperatures. The abundance of forests surrounding the city, as well as parks and reserves within Gothenburg allow for comfortable climate conditions (Fig. 7). As the city is expected to increase in population to about 700 000 by 2015, green areas surrounding the city might be at risk from rapid urbanization (Göteborgs stad 2021).

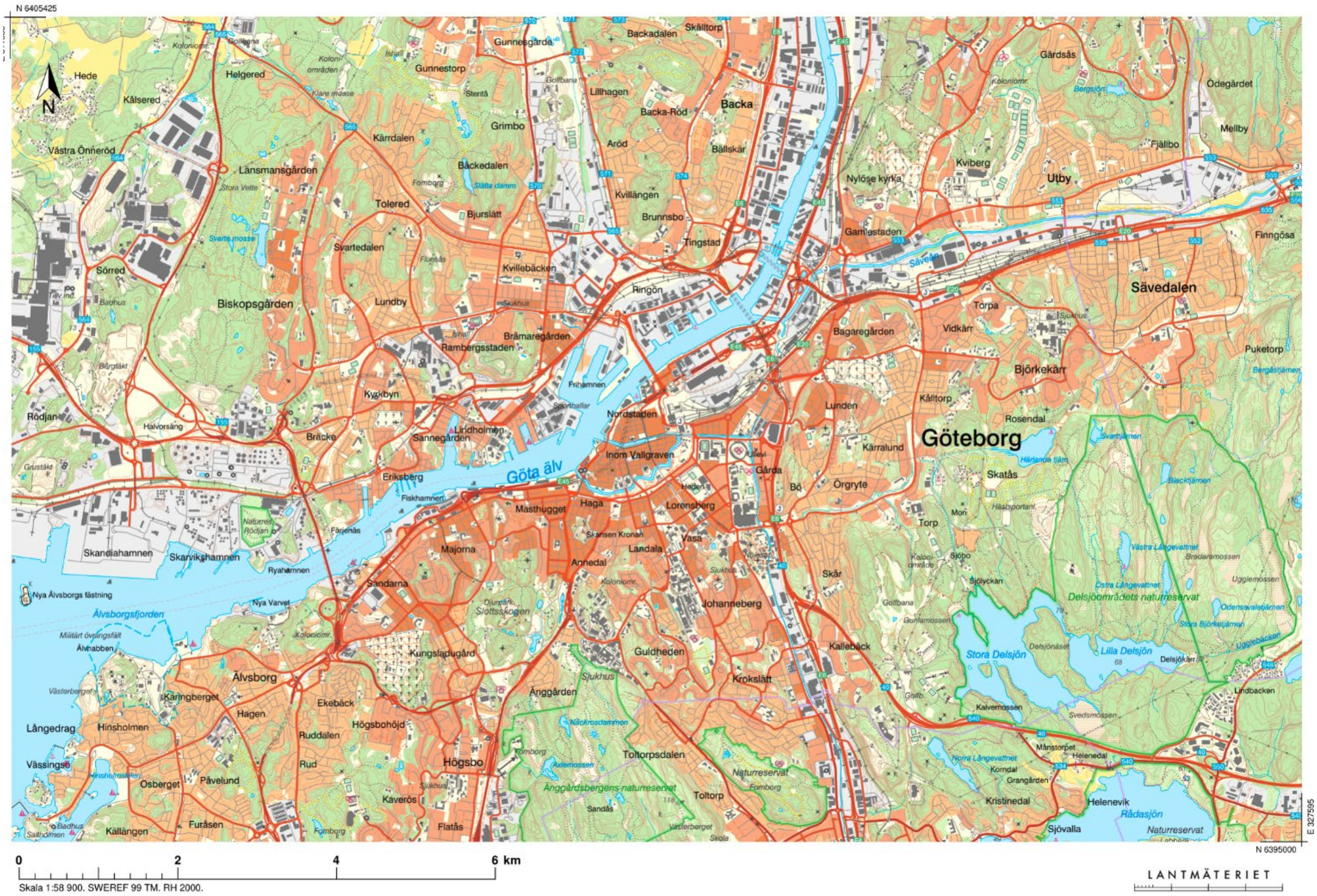


Fig. 7. Base map of urban Gothenburg. Green, orange, and blue areas represent vegetation, urban structures, and water bodies, respectively. Source: Municipality of Gothenburg (lantmateriet.se).

3.4. Tree data selection

NDVI data were collected together with finer-scale areal photography (orthophoto) of Gothenburg taken in 2019 to find exact tree locations. The orthophoto of the city was obtained from the Gothenburg Municipality, with a resolution of 16*16 cm for each pixel. Tree data was obtained from the Gothenburg Municipality as well, which contained over 70,000 individual tree data points, as seen in Appendix B (Fig. B.1). Due to data points being unevenly spread out across town, a study area was chosen which can be sampled evenly, so that results can be applicable for the entire area of Gothenburg. A grid with equally sized cells (Fig. 8) containing 25 smaller quadrants was designed as the sampling area.

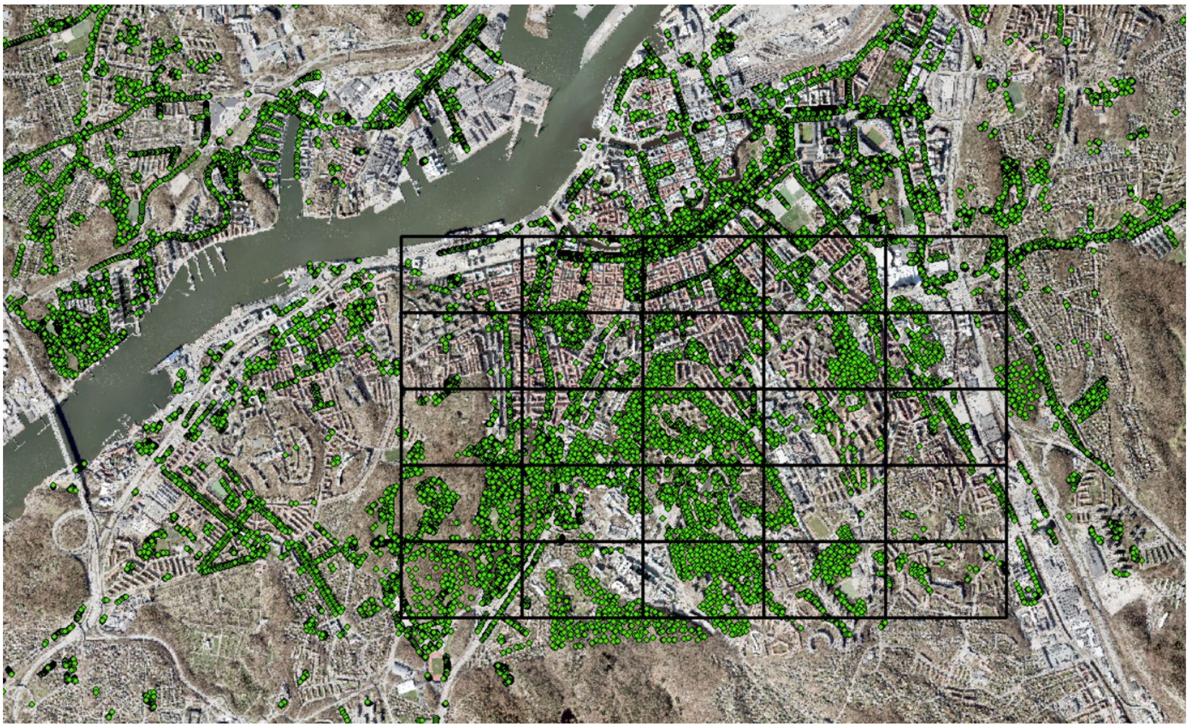


Fig. 8. Orthophoto of Gothenburg with the sampling area. The black grid symbolizes 25 quadrants of equal size. Green dots represent tree position. Source: Municipality of Gothenburg (lantmateriet.se).

Within each quadrant, four types of tree groups were randomly sampled for comparing July 2018 vs. 2017 NDVI:
- solitary trees in controlled, park-like conditions with no NDVI change;
- grouped trees in controlled, park-like conditions with no NDVI change;
- solitary trees in street-like conditions that showed a marked NDVI decline;
- grouped trees in street-like conditions that showed a marked NDVI decline.

Two trees per group and quadrant were selected, equaling to 200 potentially sampled trees. The only prerequisite for choosing trees from the Municipality's tree database was to know their species and planting date before sampling.

3.5. GIS data analysis

NDVI was analyzed by using Geographic Information System (GIS) software, namely ArcMap and Quantum Geographic Information System (QGIS). Figures 9 and 10 represent NDVI values over Gothenburg on July 20th, 2017, and July 27th, 2018, respectively. Values were obtained in ArcMap using the formula for NDVI calculation in chapter 3.1. Data obtained from the two Figures was subtracted from one another (NDVI values for July 2017 subtracted from NDVI values for July 2018) to find the overall change in NDVI.

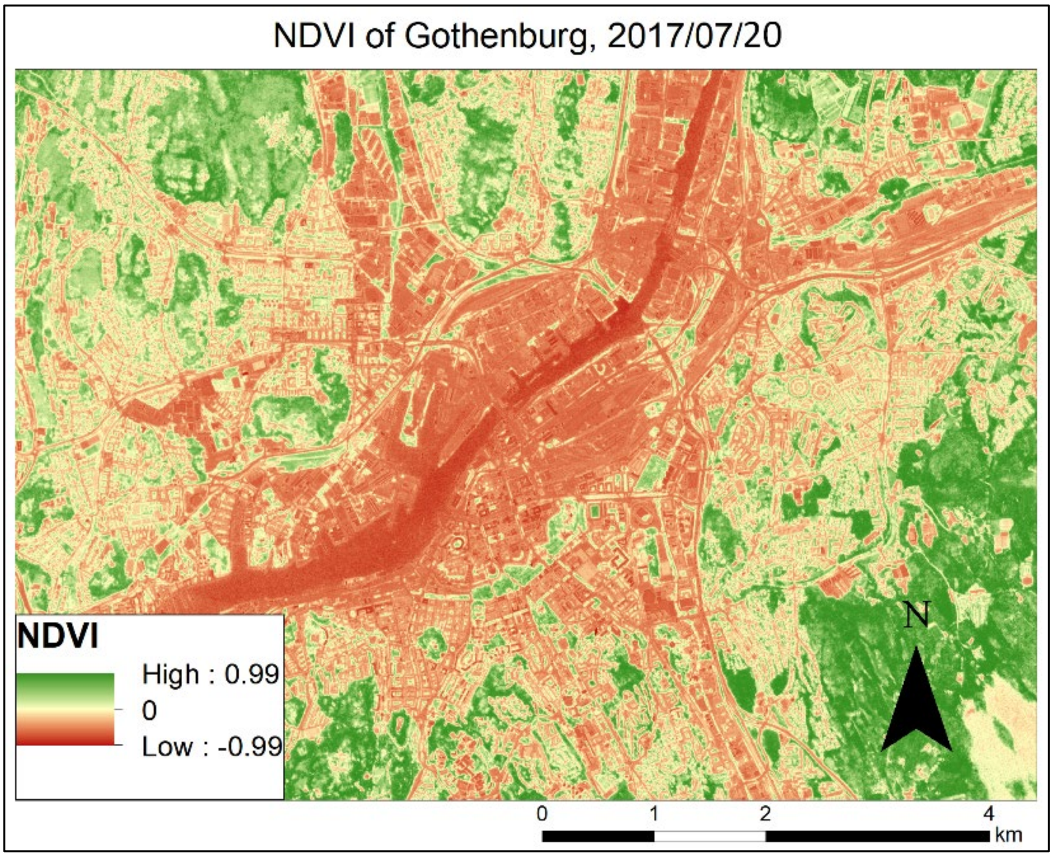


Fig. 9. NDVI of Gothenburg, 20. July 2017 (Arcmap). Negative, neutral, and positive changes are marked with red, bright yellow, and green colors, respectively.

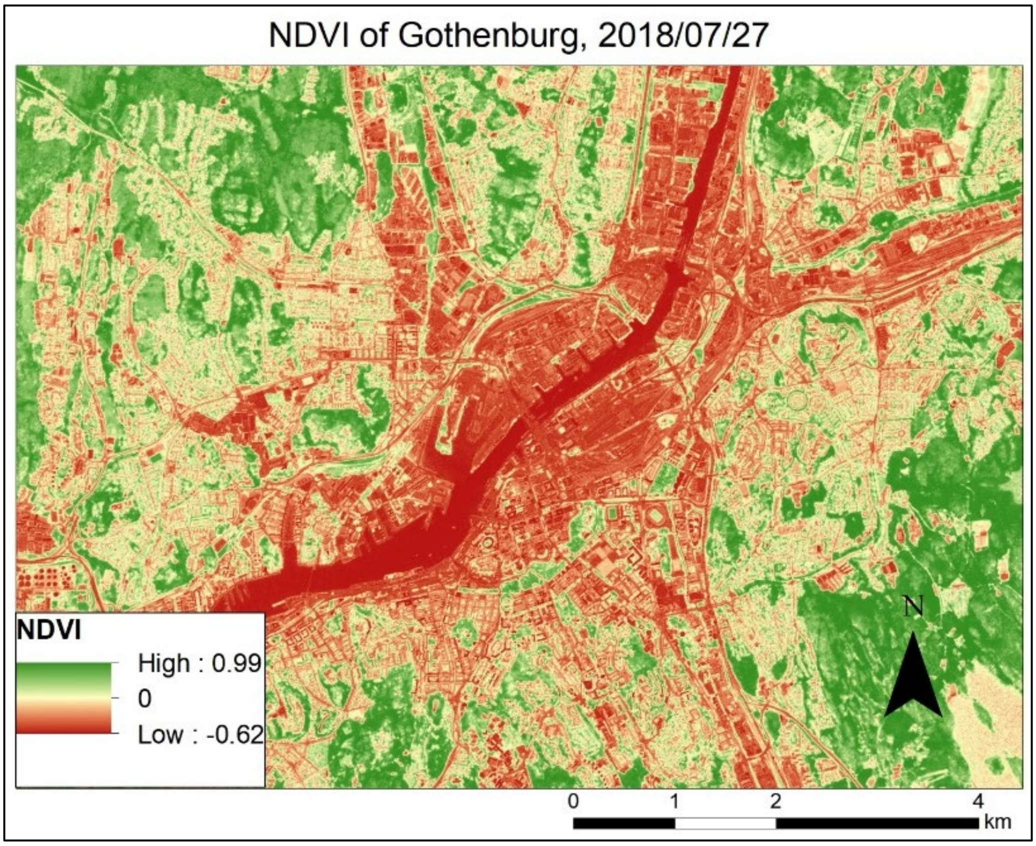


Fig. 10. NDVI of Gothenburg, 20. July 2017 (Arcmap). Negative, neutral, and positive changes are marked with red, bright yellow, and green colors, respectively.

Tree locations and points chosen for field sampling are presented in Fig. 11. Quadrants were labeled according to their designated letter and number. The areas of Gothenburg within these quadrants included Järntorget and Masthugget districts in the northwest (A1, B1), parts of the Slottskogen park and Botaniska Tradgården in the southwest (C1-E1, D2-E2) the downtown of Haga, Landala and Johanneberg area in the central quadrants, parts of Heden and Liseberg in the east (A4-A5, B5, C5), and Guldheden in the south (E3-E5).

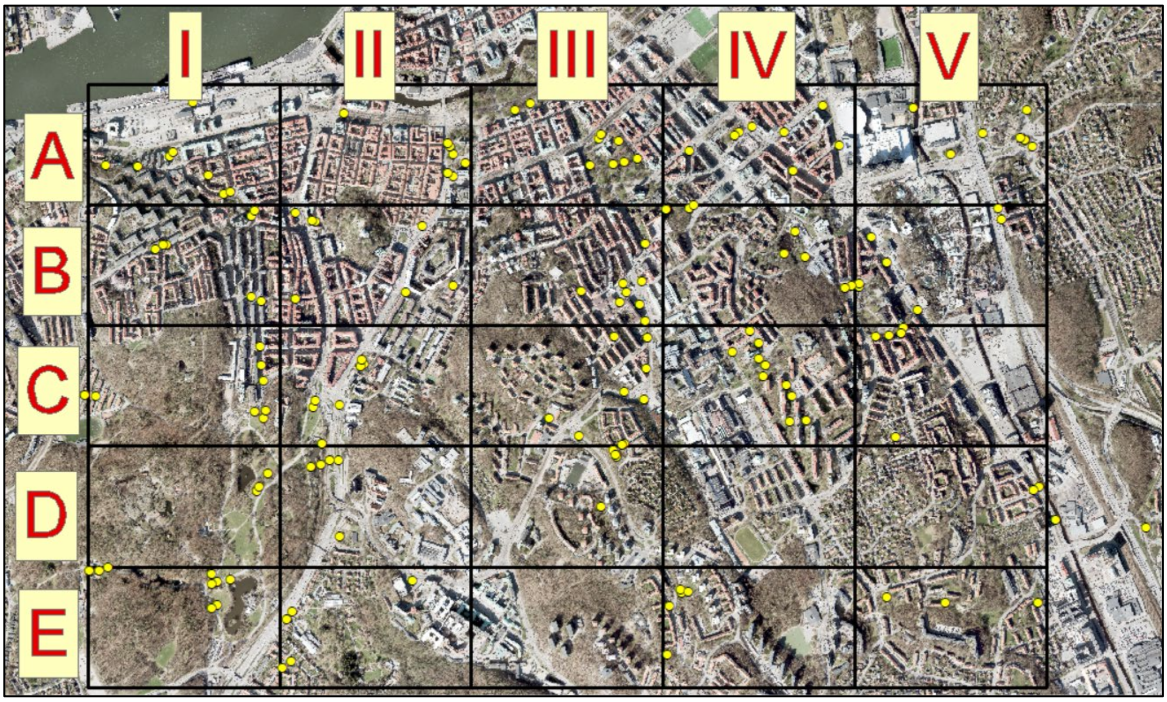


Fig. 11. Orthophoto of the study area. Yellow points represent chosen tree location with datasets for field sampling. Quadrants were organized and labelled accordingly.

Examples of orthophoto images compared with NDVI values when looking at potential tree sampling sites are shown in Figures 12 and 13. Fig. 12 represents an area where there was a significant decline in NDVI values for that year. Trees that are found within the decline area are seen on the orthophoto to be within paved urban areas. Fig. 13 shows an opposite example, where park-like trees had little to no decline in NDVI values.

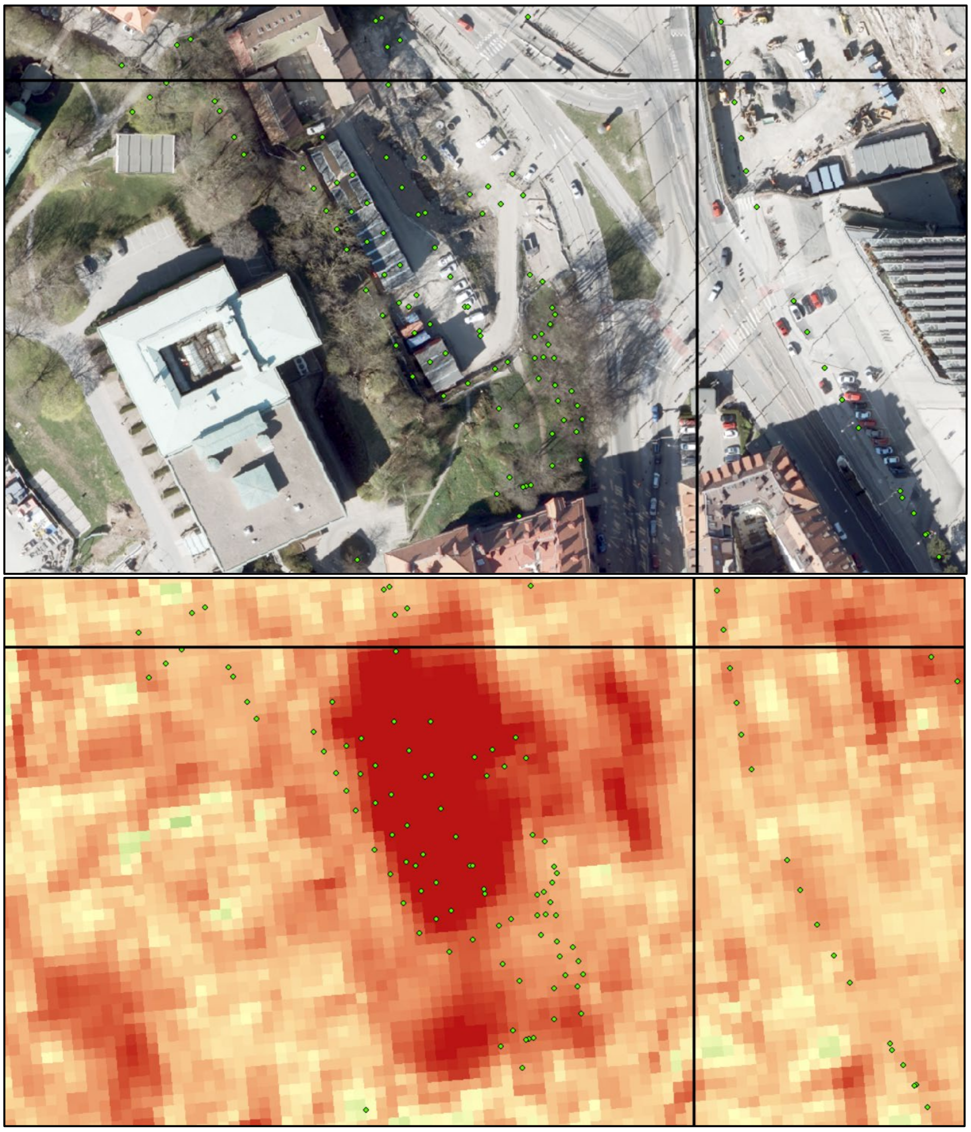


Fig. 12. Orthophoto & Planet image example of a severe NDVI decline marked in red (July 2018 vs. 2017). Green points represent tree locations. Negative, neutral, and positive changes are marked with red, bright yellow, and green colors, respectively.

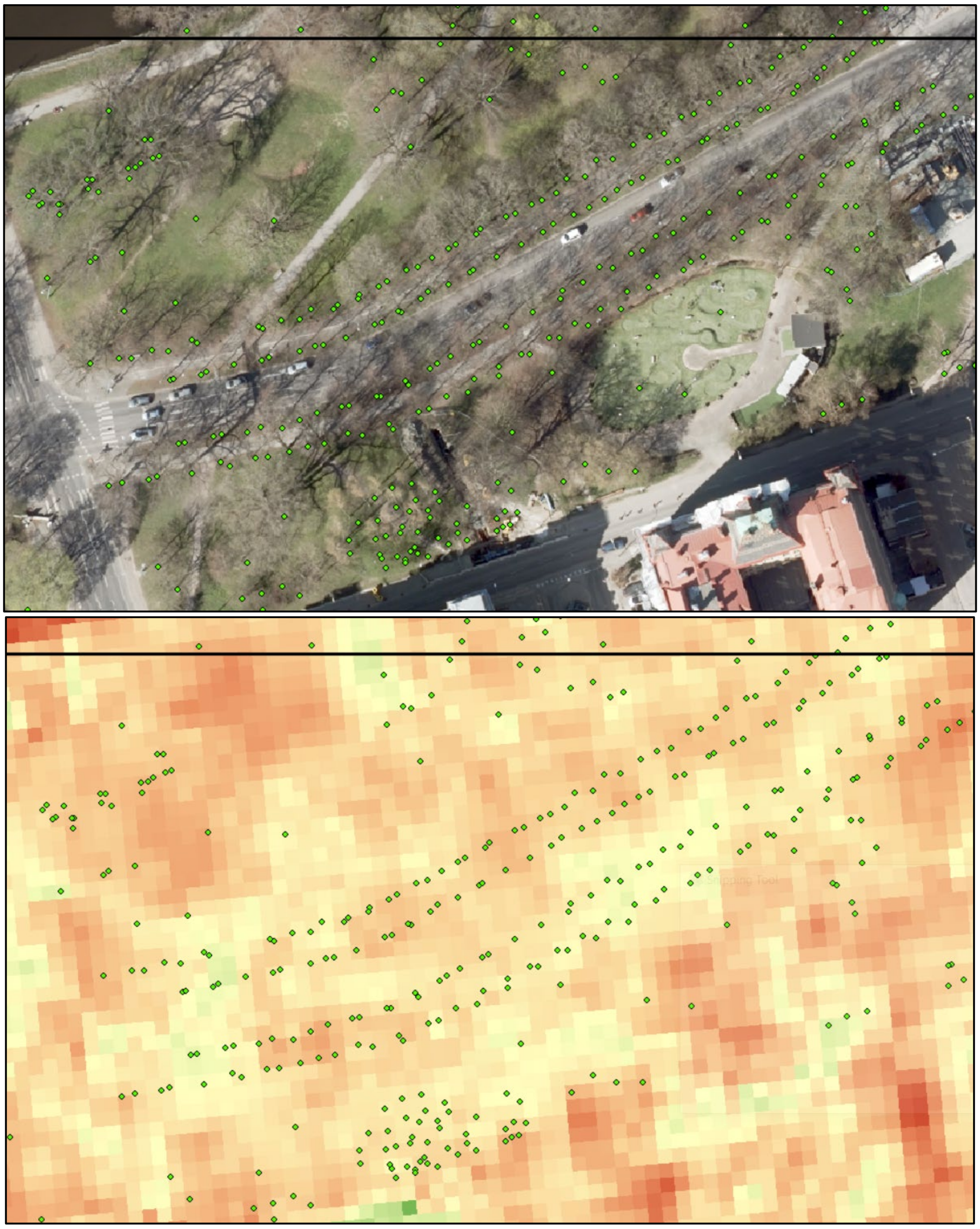


Fig. 13. Orthophoto & Planet image example of no or little NDVI decline (July 2018 vs. 2017). Green points represent tree locations. Negative, neutral, and positive changes are marked with red, bright yellow, and green colors, respectively.

3.5. Field sampling & setup

After identifying areas where NDVI exhibited either no change or a marked decrease, the second part of the study was to visit each of the chosen tree sites, to collect physical data on possible factors predisposing trees to drought and heat stress. Such initial factors worth sampling were tree size, planting date, tree height, stem width, crown surface area, permeable surface and its percentage under the tree crown, and distance from roads and buildings, respectively. The field data was then compared with the remote sensing data (NDVI change) in a GIS to find key factors correlating with drought stress predisposition.

The equipment used for measurement sampling included: a clinometer (using for a 20 m distance reading), a 20 m long rope, a small measuring tape (1.5 m), a 30 m long measuring flexible steel tape, a mirror device for measuring the crown edge, a book for recognizing tree species during winter (Den Stora Knoppboken), a map of Gothenburg with the study area, a compass mobile application, and the ARuler® mobile application. All hardware equipment is shown in Fig. 14, and the map in Fig. 15.

Fig. 14. Equipment used for field sampling. Top left to right: Flexible steel measuring tape, clinometer, 20m rope. Bottom left to right: small measuring tape, Mirror device for measuring the edge of tree crowns, and “Den Stora Knoppboken” book for tree species identification during winter.

Fig. 15. Map of central Gothenburg with the study area and tree sampling location (four types of symbols).

A measurement protocol was made (see Appendix, Protocol), with an intention to be used also in future studies on this topic. Sampling began on March 8th and ended on March 24th, 2023. Afterwards, sampling data was analyzed and compared to NDVI data. Practical fieldwork is illustrated in Fig. 16.

Fig. 16. Field work & sampling on one of the sites. Top left: tree species identification; top right: Unwinding the 20 m rope for tree height measurements; bottom left: crown edge surface measurement; bottom right; tree height measurement via clinometer from a fixed distance of 20 m. Photo: Marko Plavetić.

After the sampling was complete, statistical analysis was conducted. Linear regression for NDVI values was obtained using Excel software (version 2019) with combined experimental sampling data from and remote sensing data. Statistical tests that were performed included the Chi-squared (X^2) test for variables related to categories, and linear regression for quantitative data analysis. P-values lower than 0.05 indicate statistical significance.

4. Results

A total of 142 trees were sampled within the study area, as seen in Fig. 11, with a detailed list in Table C.1 within Appendix C. This number did not meet the desired goal of 200 samples, resulting in an undersampling of data. Of the 142 samples, 73 were single tree areas, and 69 were group tree sample areas.

After subtracting NDVI values for July 2017 from NDVI values for July 2018, the difference image depicting the overall change in NDVI over Gothenburg for July 2018 was obtained (Fig. 17). Red colors indicate areas with significant NDVI declines, while green colors depict an increase in NDVI. Bright yellow colors indicate little to no change in NDVI. For colorblind readers, identical figures can be found in Appendix D, with blue colors replacing green areas.

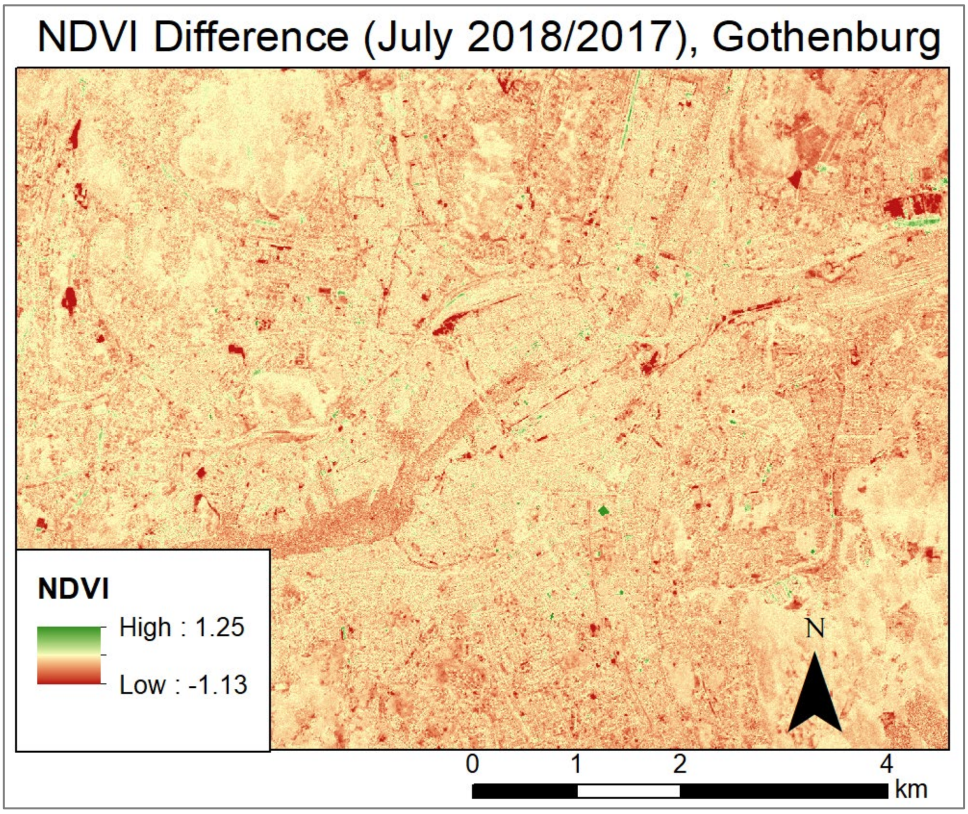


Fig. 17. Difference in NDVI levels for July 2018 and 2017 in Gothenburg. Negative, neutral, and positive changes are marked with red, bright yellow, and green colors, respectively.

Fig. 18 shows the NDVI change in 2018 for the sampling area. NDVI values for each sampling location were analyzed and compared with data from the field, resulting in Figures 19, 20, 21, 22 and 23.

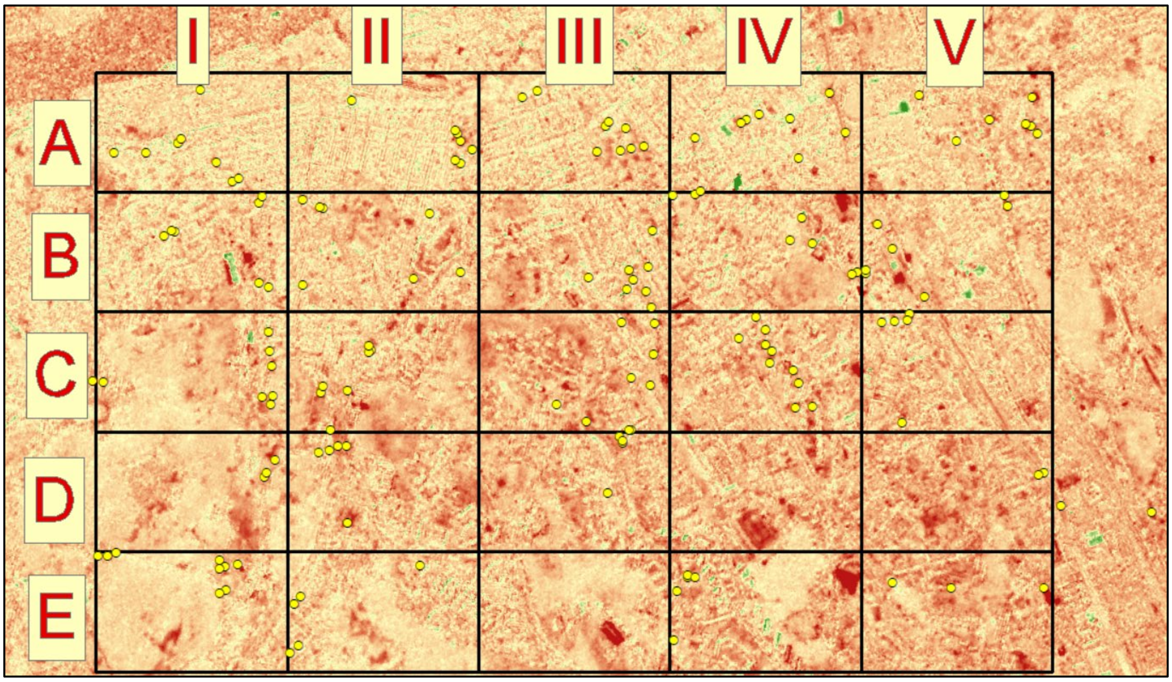


Fig. 18. NDVI difference between July 2018 and 2017 for the study area. Negative, neutral, and positive changes are marked with red, yellow, and green colours, respectively. Yellow points represent chosen tree locations with datasets for field sampling.

4.2. Statistical analysis

The following results in Table 1 and Figures 19-23 are the outcome of comparing remote sensing data with sampling data.

Table 1. Two types of statistical results: Regression analyses between NDVI change (y axis) and tree height, crown surface, permeable surface, and fractions of permeable surface; X^2 tests of differences in species compositions between different tree groups. P-values are considered significant at <0.05.

	X^2	R^2	*Df*	*p-value*
NDVI Change (July 2018 vs 2017) vs. tree height (regression)		0.12		<0.01
NDVI Change (July 2018 vs 2017) vs. crown surface (regression)		0.06		<0.01
NDVI Change (July 2018 vs 2017) vs. permeable surface (regression)		0.03		0.04
Tree height vs. permeable surface percentage (regression)		0.03		<0.01
NDVI change (July 2018 vs 2017) vs. permeable surface percentage (regression)		0.09		<0.01
NDVI change (July 2018 vs 2017) vs. crown surface >18 m^2 (regression)		0.01		0.21
Difference in species composition between NDVI by all neighbourhood groups (X^2 test)	169.0		141	0.05
Difference in species composition between neighbourhood groups; single vs grouped trees (X^2 test)	68.2		47	0.02
Difference in species composition between NDVI groups; control vs decline trees (X^2 test)	54.2		47	0.22
Difference in species composition between NDVI groups; grouped trees only (X^2 test)	7.2		8	0.51
Difference in species composition between NDVI groups; single trees only (X^2 test)	3.8		8	0.87

Table C.1 in Appendix C shows the total number of species found in the study area in their respective category. The first X^2 test related to NDVI (Table 1) was between all 4 categories (group control, group decline, single control, and single decline). The resulting p-value (0.054) showed potential statistical significance. Some species occurred more frequently in one category than another. Linden trees (*Tilia Europaea*) were more present in grouped control sites that showed little to no NDVI change, rather than in single decline sites were found in the grouped control category. Magnolias (*Magnolia spp.*) were found exclusively in single decline sites and nowhere else. The common oak (*Quercus robur*) was present mostly in grouped decline sites (four samples), and only once in every other neighbourhood group.

Further X^2 tests were conducted for species composition comparison between grouped and single trees, regardless of NDVI value. This is where the X^2 test shows the highest significance (p=0.02). Further X^2 tests showed no significance in species composition differences, whether it was control vs. decline, group control vs. group test, or single control vs. single test comparisons.

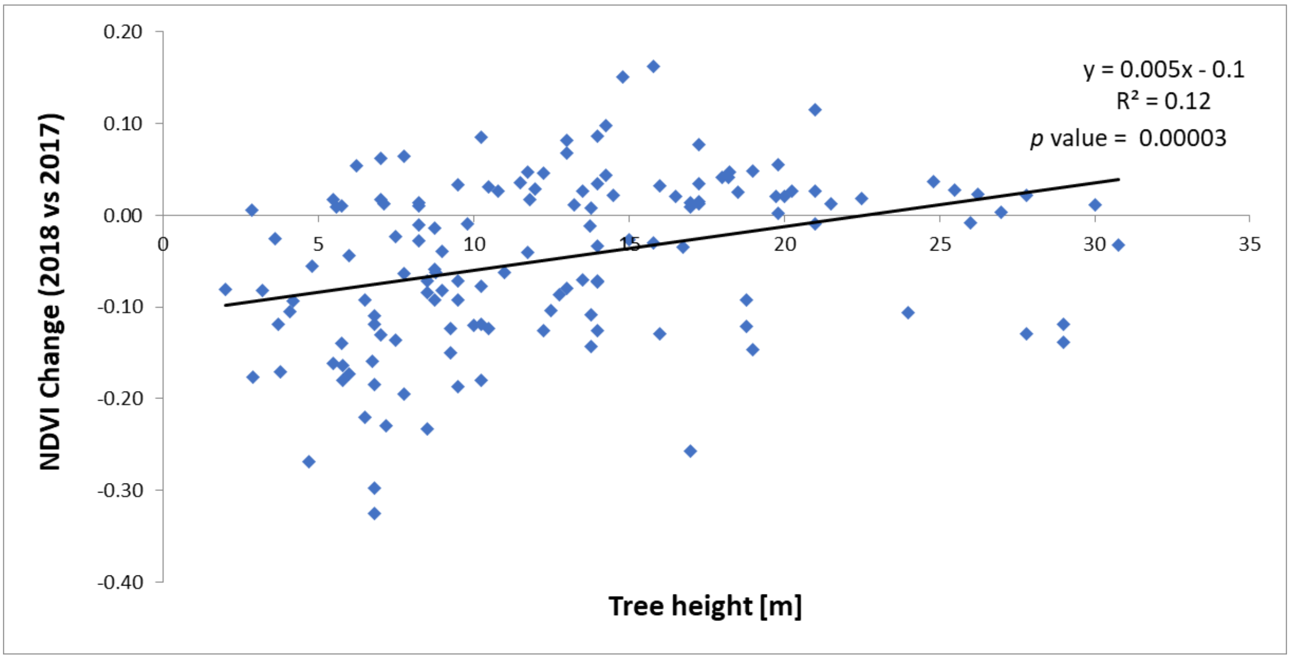


Fig. 19. Linear regression analysis of the difference in NDVI between the end of July in 2018 vs. 2017 plotted against tree height.

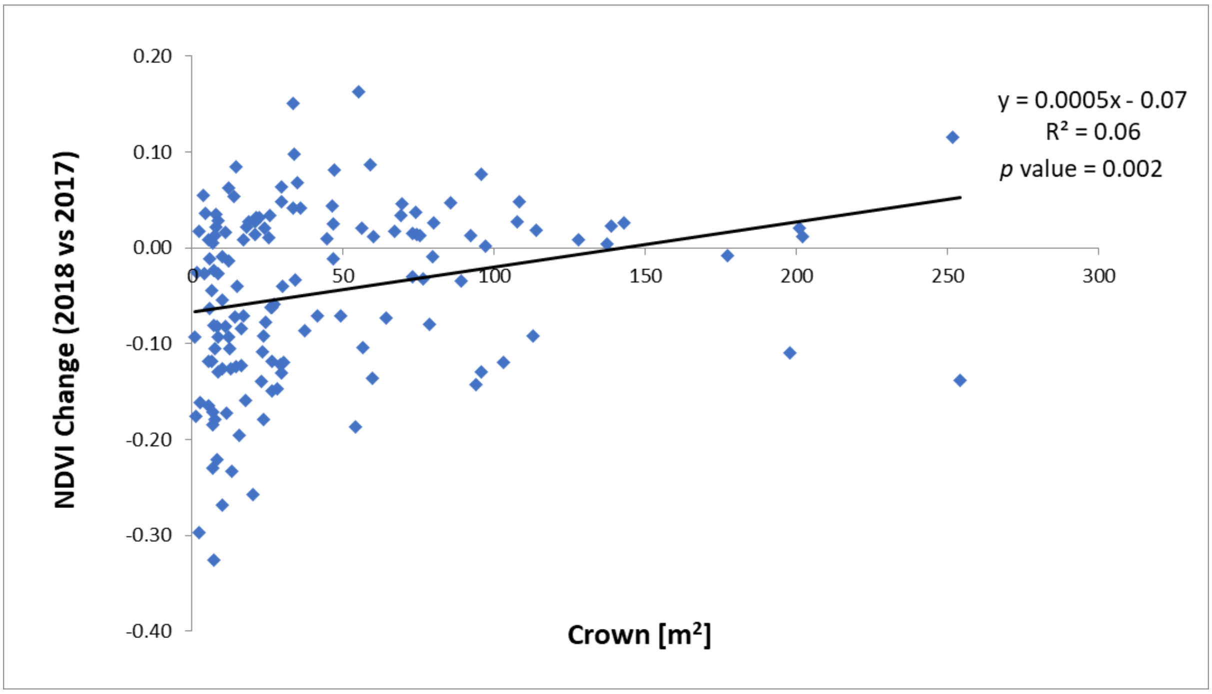


Fig. 20. Linear regression analysis of the difference in NDVI between the end of July in 2018 vs. 2017 plotted against crown surface.

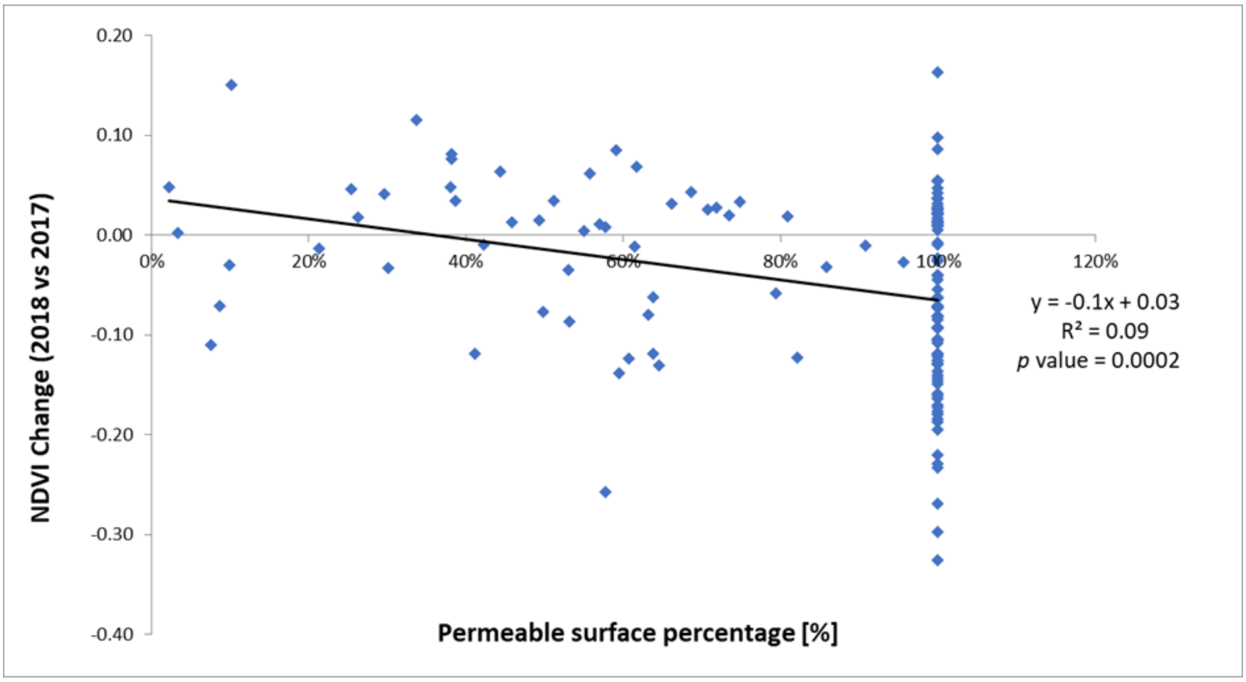


Fig. 21. Linear regression analysis of the difference in NDVI between the end of July in 2018 vs. 2017 plotted against the fraction of permeable surface under the crown.

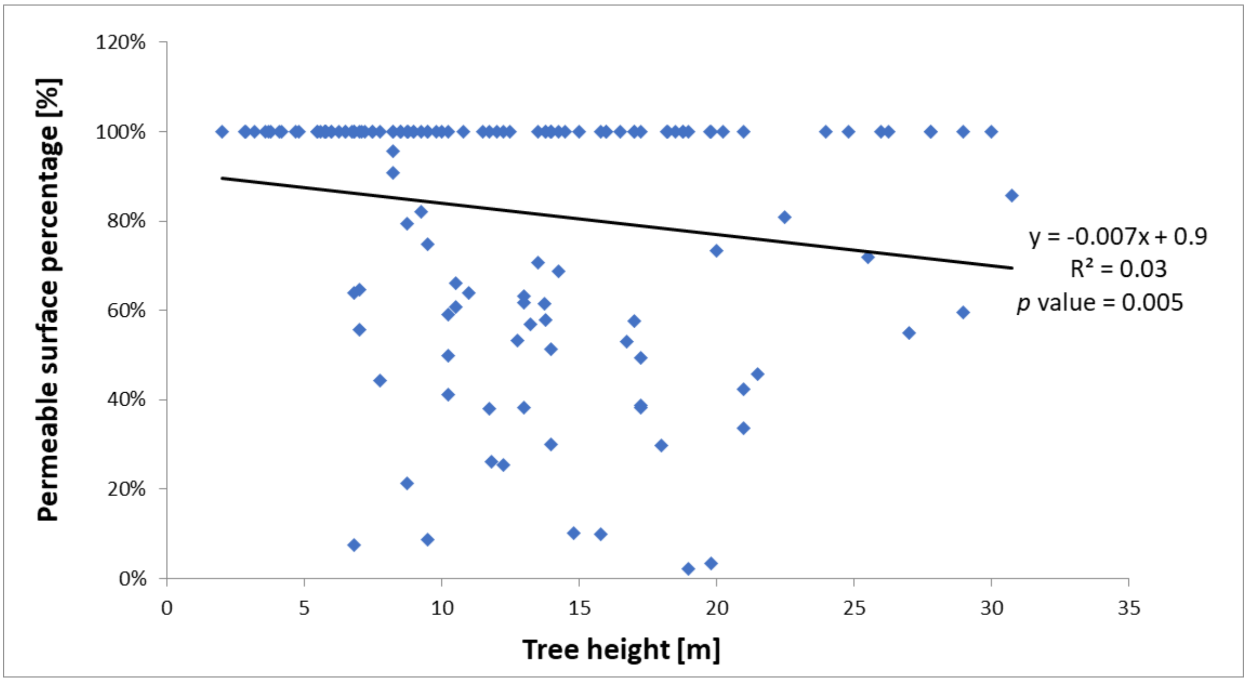


Fig. 22. Linear regression analysis of the difference in permeable surface fraction under the crown plotted against tree hight.

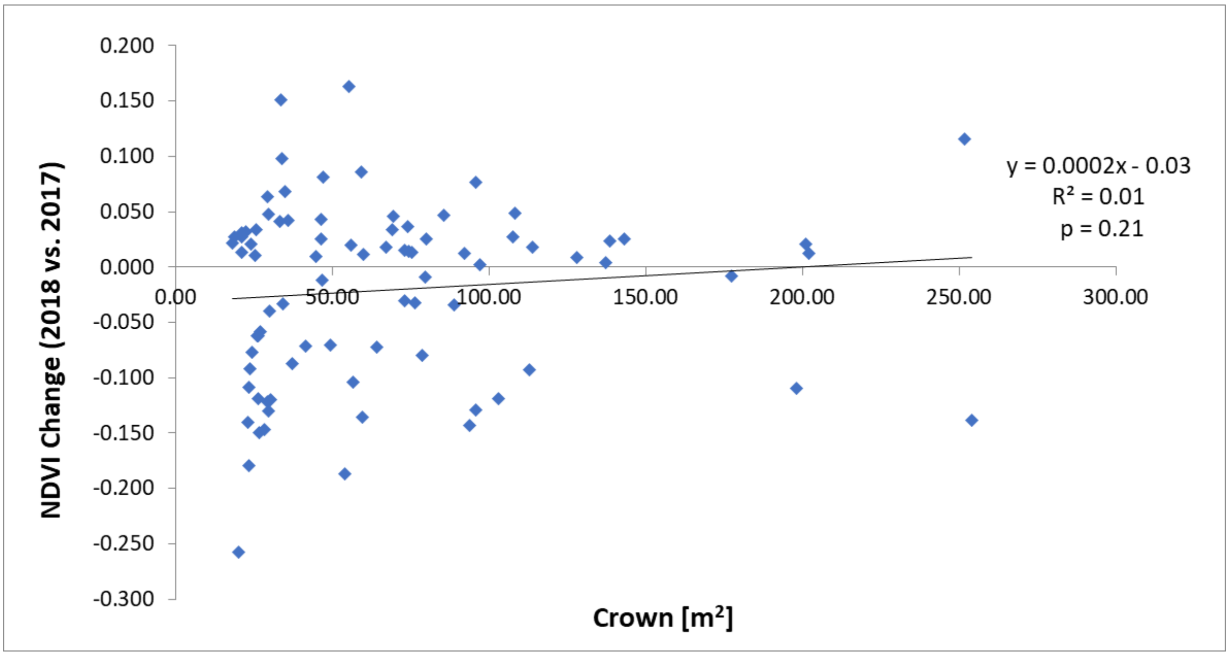


Fig. 23. Linear regression analysis of the difference in NDVI between the end of July in 2018 vs. 2017 plotted against trees with crown surface area greater than 18 m^2.

5. Discussion

5.1. Overall NDVI Change

The initial part of acquiring NDVI results rested on the reliability of satellite image quality. As seen in Fig. 4.1, satellite images differ in area coverage. Since PlanetScope is a network of over 130 satellites, each with different orbital patterns and coverage, there was a difference in area covered. Nevertheless, the study area of Gothenburg was covered by both images, which allowed NDVI comparison. Dense urban areas and buildings in central Gothenburg are clearly shown in red colors. This can be seen in Fig. 9 and Fig. 10. What is visibly noticeable is the sharper contrast and greater decline in NDVI for July 2018 (Fig. 17).

The answer to the research of the overall impact of the heat wave and drought on the vegetation and urban area of Gothenburg can be deduced from the total decline in NDVI (Fig. 17), constructed as a difference between NDVI in 2017 (Fig. 9) and NDVI in 2018 (Fig. 10). Steep NDVI declines were found in some urban areas (Fig.15), as well as generally little to no declines in park-like areas (Fig. 16). This result was expected, especially in downtown Gothenburg, where the influence of the UHI is likely strongest.

The question remains if this event was an anomaly for Sweden and Gothenburg that occurs irregularly, regardless of extreme drought effects. A study by Wilcke et al. (2020) which used climate model simulations based on data from the 2018 heat wave found that such anomalies occurred in pre-industrial climate models, but the occurrence probability was lower. Due to human-induced climate change, this is expected to change, and such anomalies are suspected to happen more frequently. This goes hand in hand with data from SMHI in Appendix A (Fig.A.1.-A.4.), showing an increase in the average annual number of high summer days, especially in southern Sweden since 1961. The area around Gothenburg from 1991-2020 shows an increase in annual high summer day occurrence by eight. Additionally, the number of them occurring one after another (high summer days in a row) increased by three (SMHI 2023). This means that hot summer days are likely to occur together and more frequently.

With that in mind, heat waves and droughts like the one in 2018 are expected to occur more frequently and last longer, thus becoming less of an anomaly. With anthropogenic climate change being the main reason, if not mitigated by the end of this century (IPCC 2014), such events would further exacerbate the situation in Sweden, regionally and locally.

5.2. Study area sampling

Despite a dataset of over 70,000 tree data points provided by the Municipality, many of them contained little to no information about the trees themselves. Many of the data points had no information, and from those that did, some of them had either no data on tree species or planting date, which made them unsuitable for sampling. Thus, two out of 25 quadrants within the study area had no sampling locations for all four groups (E3 and D4).

Additionally, because the orthophoto of the city was taken in 2019, there was a chance that a few trees would have been cut down or removed in the time before this study took place in 2023. This was indeed the case, and 10 trees that were mapped in Fig. 9 for sampling were not included in the total amount of samples, due to them being cut down or displaced. The final number of trees would otherwise have been 152. This lack of data is something that could be considered in future studies.

The reason why tree species was a prerequisite necessary for sampling was to answer whether some species appeared in a specific category more than in others, e.g., in control vs. NDVI decline areas. Greater occurrence of linden trees (*Tilia Europaea*) in grouped control sites than in single decline sites was expected to happen, due to lindens being more tolerant to drought and heat stress. Lindens are large trees that can reach up to 25 m in height, with large crown areas, and are often planted in urban areas in Sweden, including Gothenburg. Most linden trees can handle poor soil conditions (Bengtsson 2000; Lööw 2018). Indeed, there were many locations throughout central Gothenburg where lindens with low permeable surface fractions showed no NDVI decline. However, continuous NDVI monitoring should be conducted to confirm that there were no permanent negative effects.

The same couldn't be said for Magnolias (*Magnolia spp.*) and pedunculate oaks (*Quercus robur*), which were mostly found in categories with NDVI decline, with magnolias being only found in single decline sampling sites. *Magnolia* are generally small trees, usually up to 5 m tall, and do not tolerate extended periods of drought (Vastag et al. 2020; Watkins et al. 2020). Thus, despite their benefits in aesthetics, they might not be suitable for urban areas like Gothenburg if drought conditions like in 2018 were to occur more frequently.

Unlike magnolias, pedunculate oaks are native to Sweden and commonly found in urban areas (Lööw 2018), which explains why they were mostly sampled in grouped decline areas throughout the city. Despite oaks showing an increase in tree ring growth after the 2018 heat wave in Europe (Neuwirth et al. 2021), a decline in growth rate for oaks happens 2 to 3 years after exposure to drought (Perkins et al. 2018). Monitoring oak growth rates and NDVI after 2018 in Gothenburg would provide better conclusions on any permanent effects of the drought that happened that year.

For all other species, the results remain mostly inconclusive, with some species found in both grouped and single tree sites and both in control areas and NDVI decline areas. While some species were indeed found in only one category there were too few of these samples to make any meaningful conclusions based on species occurrence or survivability. Some of them were sampled only once, e.g., *Dravidia involucrata* and *Aesculus carnea*, found only in single control sites. No conclusion could therefore be drawn on those species' drought tolerance. Further X^2 tests showed no significance in species composition differences, whether it was control vs. decline, group control vs. group test, or single control vs. single test comparisons.

5.3. NDVI Regression analyses with specific traits

The study's primary focus was to find statistical significance between urban tree health in the form of NDVI values and specific tree attributes obtained through field work sampling. The most important findings are presented in Figures 19-22.

A significant relationship was present when comparing NDVI decline with tree height (Fig. 19) and crown surface area (Fig. 20). Because crown areas and tree size co-vary, this indicates that large trees show lesser NDVI declines than smaller trees in urban areas after drought exposure. A study by Trugman et al. (2018) found a similar result where larger trees are more tolerant to droughts and heat waves and show behavior of proactive recovery, which might explain why linden trees showed greater drought resistance in Gothenburg.

While the results from this study indicate that trees with greater height end up being healthier, a study in California found an opposite correlation between tree height and drought mortality. Larger trees died twice as fast as shorter ones when exposed to extreme droughts. Factors that contributed to height-related mortality intensity included temperature, water availability and competition (Stovall, Shugart, and Yang 2019). For this study area in Gothenburg, it appears that results align with the previously mentioned study by Trugman et al. (2018).

The most important findings are found in Figures 21 and 22. One of the traits that was investigated was the fraction of permeable surface under the crown for all sampled trees and how it correlates with NDVI. A regression analysis for NDVI with the fraction of permeable surface under the crown (Fig. 21) was expected to show how trees with less permeable fraction fare worse than trees with greater permeable surface percentage. On the contrary, more trees with 100% permeable surface had negative NDVI values than positive, showing an inconsistency. Since tree height covaries with the permeable surface percentage in regards to NDVI values, a regression analysis was made to see which of these two traits is more statistically relevant for NDVI (Fig. 22). Indeed, the graph indicates a much higher occurrence of trees with 100% permeable surface fractions under 10m tree height. This means that smaller trees, which are more likely to have higher permeable surface percentage below the crown due to their size alone, show greater NDVI declines. Thus, it can be said that tree size is a more relevant factor for tree health, and not permeable surface fraction.

The question remains how can trees with low permeable surface show little to no decline in health during drought conditions. Several studies found that trees growing in less permeable soil can develop deeper root systems, thereby adapting to water shortages. These deep root systems can tap into groundwater reserves or reach deeper layers of soil where moisture is retained for longer periods. (McDowell et al. 2008; Nardini 2021; Sevanto 2018). This can partially explain the reasoning behind trees with poor soil conditions being more adapted to droughts. However, there are other factors that should be considered. Another study by Mina Johansson (2023) found that urban trees are able to adapt to drought conditios, but this depends on multiple factors like tree species, age, climate zone location, planting design and maintenance. Since this study in Gothenburg did not focus on sampling particular tree species, this could be useful to consider when conducting future studies.

It should be noted, however, that during remote sensing analysis via satellite images, small trees (and subsequently their crown surfaces) were smaller than the pixel areas in which they were found. Since one pixel equals to 9 m^2 (3 * 3 m resolution) this could have lead to non-permeable surfaces being included in the pixel (such as gravel, concrete or asphalt). Subsequently, this would lead to NDVI values for the tree within this pixel being lower than they should be. However, this could also lead to more surrounding grass being included within the pixel, which is highly succeptible to drought, losing greenness in the process. An additional analysis (Fig. 23) excluded sampled trees with crown areas under 18 m^2 to find if the results also hold. After calculating the p-value (0.21), this indicates that a possibility of greater NDVI decline in small tree pixels cannot be ruled out, and could partly be due to declines in surrounding areas around the trees.

In older parts of central Gothenburg, one unforseen pattern that influenced data sampling were trees with no branches, trimmed purely for aesthetic purposes. Those were found to be mostly elms (*Ulmus glabra*). Such trimmed trees were found mainly in downtown Gothenburg, around Linneplatsen, Järntorget, Haga and Vasaplatsen. This was not accounted for when looking at satellite images, which led to data inconsistencies. The average permeable surface percentage for both street and park-like trees was 82%. For future studies, this factor should be taken into account that some street trees which show NDVI decline have been artificially trimmed and groomed, decreasing the crown surface and increasing permeable soil percentage underneath. Such modifications can alter final results and give inconclusive answers.

Conclusions

The effects of climate change are becoming more and more evident, and the recent heat wave, combined with a long drought that swept across Sweden in 2018 serves as a warning of the dangers that may lie ahead. These events have had a significant impact on both the population and the environment, particularly in urban areas where the UHI effect can exacerbate the impacts of extreme heat. There are several measures that can be taken to address the effects of heat waves and droughts. One approach is to implement UHI mitigation strategies, such as planting trees and creating green spaces that can provide shade and reduce temperatures. However, it is important to note that these measures alone might not be enough. Vegetation is also sensitive to heat stress and has its limits, which is why it is imperative to plant vegetation resilient to heat stress, whilst also providing resilient planting design and conditions.

The study used satellite images to investigate the heat stress and the impact of the heat wave and drought on vegetation in Gothenburg, Sweden, in 2018. By using NDVI as an indicator for tree health, a significant decline in NDVI values was found for the entire area of Gothenburg during the driest period at the end of July 2018, as compared to the same period in 2017.

A total of 142 sampled trees were sorted into four tree categories, depending on their NDVI values (control vs. decline) and neighborhood conditions (grouped vs. single trees). Within these categories, there was no statistical significance regarding species composition between all categories, as some species were sampled only once in one group or were present in all four categories. Magnolia (*Magnolia spp*). and oak (*Quercus robur*) species, however, were found mostly in decline areas, while linden trees (*Tilia Europaea*) were prevalent in grouped control areas, showing little to no NDVI decline, while being less present in single tree decline areas.

This finding of linden trees being more present in control areas concurs with tree traits that were found to have a positive correlation with NDVI changes, such as tree height and crown surface area. Large tree species, such as linden trees, show greater drought resistance throughout the city. The permeable surface fraction under the crown area was shown to negatively correlate with NDVI changes. After finding that tree height co-varies with the permeable surface fraction, with smaller trees showing 100% permeable surface percentages, I conclude that tree size is the more significant indicator and predictor for trees vulnerable to drought.

Overall, the study highlights the importance of mitigating human-induced climate change to avoid exacerbating the impact of extreme weather events on vegetation and the environment, particularly in urban areas located in climates that are not used to such extremes. The findings of this study could be useful for policymakers and urban planners to implement measures to minimize the effects of UHI and enhance or improve urban greenery in areas with high vegetation decline. Choosing species that can reach larger tree size in the urban environment, whilst improving the planting design for trees that have already been planted to grow even more could potentially help mitigate heat stress and improve urban thermal comfort. Additionally, such measures can prolong the life of trees, which would reduce replacement costs and replanting maintenance. Further research could investigate the correlation between NDVI values and tree species in other areas and explore the potential of using NDVI as a tool for monitoring vegetation health and identifying vulnerable areas in urban environments.

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Literature

Alvarez-Mendoza, Cesar I., Ana Teodoro, and Lenin Ramirez-Cando. 2019. 'Improving NDVI by Removing Cirrus Clouds with Optical Remote Sensing Data from Landsat-8 – A Case Study in Quito, Ecuador'. *Remote Sensing Applications: Society and Environment* 13:257–74. doi: 10.1016/j.rsase.2018.11.008.

Arcos-LeBert, Gabriela, Tamara Aravena-Hidalgo, Javier A. Figueroa, Fabián M. Jaksic, and Sergio A. Castro. 2021. 'Native Trees Provide More Benefits than Exotic Trees When Ecosystem Services Are Weighted in Santiago, Chile'. *Trees* 35(5):1663–72. doi: 10.1007/s00468-021-02144-5.

Åström, Christofer, Bjelkmar P, and Bertil Forsberg. 2019. 'Attributing Summer Mortality to Heat during 2018 Heatwave in Sweden'. *Environmental Epidemiology* 3:16–17. doi: 10.1097/01.EE9.0000605788.56297.b5.

Bastos, A., P. Ciais, P. Friedlingstein, S. Sitch, J. Pongratz, L. Fan, J. P. Wigneron, U. Weber, M. Reichstein, Z. Fu, P. Anthoni, A. Arneth, V. Haverd, A. K. Jain, E. Joetzjer, J. Knauer, S. Lienert, T. Loughran, P. C. McGuire, H. Tian, N. Viovy, and S. Zaehle. 2020. 'Direct and Seasonal Legacy Effects of the 2018 Heat Wave and Drought on European Ecosystem Productivity'. *Science Advances* 6(24):eaba2724. doi: 10.1126/sciadv.aba2724.

Bengtsson, Rune. 2000. *Stadsträd A-Z.* Stockholm: Svensk byggtjänst.

Crespi, Alice, Stefano Terzi, Silvia Cocuccioni, Marc Zebisch, Julie Berckmans, and Hans-Martin Füssel. 2020. 'Climate-Related Hazard Indices for Europe'. doi: 10.25424/CMCC/CLIMATE_RELATED_HAZARD_INDICES_EUROPE_2020.

Dawes, Leaundre C., Alison E. Adams, Francisco J. Escobedo, and José R. Soto. 2018. 'Socioeconomic and Ecological Perceptions and Barriers to Urban Tree Distribution and Reforestation Programs'. *Urban Ecosystems* 21(4):657–71. doi: 10.1007/s11252-018-0760-z.

Dimoudi, A., A. Kantzioura, S. Zoras, C. Pallas, and P. Kosmopoulos. 2013. 'Investigation of Urban Microclimate Parameters in an Urban Center'. *Energy and Buildings* 64:1–9. doi: 10.1016/j.enbuild.2013.04.014.

Döscher, Ralf, Peter Berg, Denica Bozhinova, Lars Bärring, Anna Eronn, Erik Kjellström, Katharina Klehmet, Jonas Olsson, Carin Nilsson, Helena Martins, David Segersson, Gustav Strandberg, Danijel Belusic, and Christiana Photiadou. 2019. 'Climate Extremes for Sweden - State of Knowledge and Implications for Adaptation and Mitigation'. doi: doi.org/10.17200/Climate_Extremes_Sweden.

Eliasson, I., and B. Holmer. 1990. 'Urban Heat Island Circulation in Göteborg, Sweden'. *Theoretical and Applied Climatology* 42(3):187–96. doi: 10.1007/BF00866874.

Esperon-Rodriguez, Manuel, Sally A. Power, Mark G. Tjoelker, Linda J. Beaumont, Hugh Burley, Dayenari Caballero-Rodriguez, and Paul D. Rymer. 2019. 'Assessing the Vulnerability of Australia's Urban Forests to Climate Extremes'. *PLANTS, PEOPLE, PLANET* 1(4):387–97. doi: 10.1002/ppp3.10064.

Esperon-Rodriguez, Manuel, Mark G. Tjoelker, Jonathan Lenoir, John B. Baumgartner, Linda J. Beaumont, David A. Nipperess, Sally A. Power, Benoît Richard, Paul D. Rymer, and

Rachael V. Gallagher. 2022. ‘Climate Change Increases Global Risk to Urban Forests’. *Nature Climate Change* 12(10):950–55. doi: 10.1038/s41558-022-01465-8.

Filippa, Gianluca, Edoardo Cremonese, Mirco Migliavacca, Marta Galvagno, Oliver Sonnentag, Elyn Humphreys, Koen Hufkens, Youngryel Ryu, Joseph Verfaillie, Umberto Morra di Cella, and Andrew D. Richardson. 2018. ‘NDVI Derived from Near-Infrared-Enabled Digital Cameras: Applicability across Different Plant Functional Types’. *Agricultural and Forest Meteorology* 249:275–85. doi: 10.1016/j.agrformet.2017.11.003.

Göteborgs stad. 2021. ‘Översiktsplan för Göteborg – förslag till granskningshandling mars 2021’. *Samrådshandling 2018. Kalmar: Göteborgs stad*.

Grimmond, Christine, and T. Oke. 1999. ‘Evapotranspiration Rates in Urban Areas’. *IAHS-AISH Publication* 259.

Heris, Mehdi P., Ariane Middel, and Brian Muller. 2020. ‘Impacts of Form and Design Policies on Urban Microclimate: Assessment of Zoning and Design Guideline Choices in Urban Redevelopment Projects’. *Landscape and Urban Planning* 202:103870. doi: 10.1016/j.landurbplan.2020.103870.

IPCC. 2014. ‘Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)].’ Retrieved 27 April 2023 (https://www.ipcc.ch/report/ar5/syr/).

Janson, Ulla. 2008. ‘Passive Houses in Sweden - Experiences from Design and Construction’. Licentiate Thesis, Energy and Building Design, Lund University.

Johansson, Mina. 2023. ‘Effekterna av torka på urbana träd’.

KIM, H. H. 1992. ‘Urban Heat Island’. *International Journal of Remote Sensing* 13(12):2319–36. doi: 10.1080/01431169208904271.

Lilja, Sven. 2017. ‘Climate, History, and Social Change in Sweden and the Baltic Sea Area From About 1700’. *Oxford Research Encyclopedia of Climate Science*. Retrieved 28 April 2023 (https://oxfordre.com/climatescience/display/10.1093/acrefore/9780190228620.001.0001/acrefore-9780190228620-e-633).

Lööw, Claes. 2018. *Den stora knoppboken: Sveriges lövfällande lignoser i vintertid*. Lomma: Claes Lööw.

Malmquist, Anna, Tora Lundgren, Mattias Hjerpe, Erik Glaas, Emily Turner, and Sofie Storbjörk. 2021. ‘Vulnerability and Adaptation to Heat Waves in Preschools: Experiences, Impacts and Responses by Unit Heads, Educators and Parents’. *Climate Risk Management* 31:100271. doi: 10.1016/j.crm.2020.100271.

Marchin, Renée M., Diana Backes, Alessandro Ossola, Michelle R. Leishman, Mark G. Tjoelker, and David S. Ellsworth. 2022. ‘Extreme Heat Increases Stomatal Conductance and Drought-induced Mortality Risk in Vulnerable Plant Species’. *Global Change Biology* 28(3):1133–46. doi: 10.1111/gcb.15976.

McDowell, Nate, William T. Pockman, Craig D. Allen, David D. Breshears, Neil Cobb, Thomas Kolb, Jennifer Plaut, John Sperry, Adam West, David G. Williams, and Enrico A. Yepez. 2008. ‘Mechanisms of Plant Survival and Mortality during Drought: Why Do Some

Plants Survive While Others Succumb to Drought?’ *New Phytologist* 178(4):719–39. doi: 10.1111/j.1469-8137.2008.02436.x.

Mullaney, Jennifer, Terry Lucke, and Stephen J. Trueman. 2015. ‘A Review of Benefits and Challenges in Growing Street Trees in Paved Urban Environments’. *Landscape and Urban Planning* 134:157–66. doi: 10.1016/j.landurbplan.2014.10.013.

Nardini, Andrea. 2021. ‘Can Trees Harden up to Survive Global Change-Type Droughts?’ *Tree Physiology* 41(11):2004–7. doi: 10.1093/treephys/tpab128.

NASA. 2000. ‘Measuring Vegetation (NDVI & EVI)’. Retrieved 6 May 2023 (https://earthobservatory.nasa.gov/features/MeasuringVegetation/measuring_vegetation_2.php).

Neuwirth, Burkhard, Inken Rabbel, Jörg Bendix, Heye R. Bogena, and Boris Thies. 2021. ‘The European Heat Wave 2018: The Dendroecological Response of Oak and Spruce in Western Germany’. *Forests* 12(3):283. doi: 10.3390/f12030283.

Nikulin, Grigory, Erik Kjellström, Ulf Hansson, Gustav Strandberg, and Anders Ullerstig. 2011. ‘Evaluation and Future Projections of Temperature, Precipitation and Wind Extremes over Europe in an Ensemble of Regional Climate Simulations’. *Tellus A: Dynamic Meteorology and Oceanography* 63(1):41. doi: 10.1111/j.1600-0870.2010.00466.x.

Niskanen, Johan, and Harald Rohracher. 2020. ‘Passive Houses as Affiliative Objects: Investment Calculations, Energy Modelling, and Collaboration Strategies of Swedish Housing Companies’. *Energy Research & Social Science* 70:101643. doi: 10.1016/j.erss.2020.101643.

North, Eric A., Anthony W. D’Amato, and Matthew B. Russell. 2018. ‘Performance Metrics for Street and Park Trees in Urban Forests’. *Journal of Forestry* 116(6):547–54. doi: 10.1093/jofore/fvy049.

Nowak, David J., and John F. Dwyer. 2000. ‘Understanding the Benefits and Costs of Urban Forest Ecosystems’. Pp. 11–25 in *Handbook of Urban and Community Forestry in the Northeast*, edited by J. E. Kuser. Boston, MA: Springer US.

Nowak, David J., Satoshi Hirabayashi, Marlene Doyle, Mark McGovern, and Jon Pasher. 2018. ‘Air Pollution Removal by Urban Forests in Canada and Its Effect on Air Quality and Human Health’. *Urban Forestry & Urban Greening* 29:40–48. doi: 10.1016/j.ufug.2017.10.019.

Oudin Åström, Daniel, Christofer Åström, Bertil Forsberg, Ana M. Vicedo-Cabrera, Antonio Gasparrini, Anna Oudin, and Kristina Sundquist. 2020. ‘Heat Wave–Related Mortality in Sweden: A Case-Crossover Study Investigating Effect Modification by Neighbourhood Deprivation’. *Scandinavian Journal of Public Health* 48(4):428–35. doi: 10.1177/1403494818801615.

Perkins, Diana, Enno Uhl, Peter Biber, Ben Du Toit, Vinicio Carraro, Thomas Rötzer, and Hans Pretzsch. 2018. ‘Impact of Climate Trends and Drought Events on the Growth of Oaks (Quercus Robur L. and Quercus Petraea (Matt.) Liebl.) within and beyond Their Natural Range’. *Forests* 9(3):108. doi: 10.3390/f9030108.

Planet. 2023. ‘Planet | Homepage’. *Planet | Homepage*. Retrieved 31 May 2023 (https://www.planet.com/?utm_source=google&utm_medium=paid-search&utm_campaign=discovery&utm_content=main-brd-responsive-search&gad=1).

Potgieter, Luke, M. Gaertner, Christoph Kueffer, Brendon Larson, Stuart Livingstone, Patrick O’Farrell, and David Richardson. 2017. ‘Alien Plants as Mediators of Ecosystem Services and Disservices in Urban Systems: A Global Review’. *Biological Invasions* 3571–88.

Pretzsch, Hans, Peter Biber, Enno Uhl, Jens Dahlhausen, Gerhard Schütze, Diana Perkins, Thomas Rötzer, Juan Caldentey, Takayoshi Koike, Tran van Con, Aurélia Chavanne, Ben du Toit, Keith Foster, and Barry Lefer. 2017. ‘Climate Change Accelerates Growth of Urban Trees in Metropolises Worldwide’. *Scientific Reports* 7(1):15403. doi: 10.1038/s41598-017-14831-w.

Rahman, Mohammad A., Laura M. F. Stratopoulos, Astrid Moser-Reischl, Teresa Zölch, Karl-Heinz Häberle, Thomas Rötzer, Hans Pretzsch, and Stephan Pauleit. 2020. ‘Traits of Trees for Cooling Urban Heat Islands: A Meta-Analysis’. *Building and Environment* 170:106606. doi: 10.1016/j.buildenv.2019.106606.

Riley, Christopher B., Daniel A. Herms, and Mary M. Gardiner. 2018. ‘Exotic Trees Contribute to Urban Forest Diversity and Ecosystem Services in Inner-City Cleveland, OH’. *Urban Forestry & Urban Greening* 29:367–76. doi: 10.1016/j.ufug.2017.01.004.

Roman, Lara A., and Frederick N. Scatena. 2011. ‘Street Tree Survival Rates: Meta-Analysis of Previous Studies and Application to a Field Survey in Philadelphia, PA, USA’. *Urban Forestry & Urban Greening* 10(4):269–74. doi: 10.1016/j.ufug.2011.05.008.

Roth, M. 2013. ‘- Urban Heat Islands’. in *Handbook of Environmental Fluid Dynamics, Volume Two*. CRC Press.

Roy, David P., Haiyan Huang, Rasmus Houborg, and Vitor S. Martins. 2021. ‘A Global Analysis of the Temporal Availability of PlanetScope High Spatial Resolution Multi-Spectral Imagery’. *Remote Sensing of Environment* 264:112586. doi: 10.1016/j.rse.2021.112586.

Sand, Emilia, Janina Konarska, Alessandro W. Howe, Yvonne Andersson-Sköld, Filip Moldan, Håkan Pleijel, and Johan Uddling. 2018. ‘Effects of Ground Surface Permeability on the Growth of Urban Linden Trees’. *Urban Ecosystems* 21(4):691–96. doi: 10.1007/s11252-018-0750-1.

Schuldt, Bernhard, Allan Buras, Matthias Arend, Yann Vitasse, Carl Beierkuhnlein, Alexander Damm, Mana Gharun, Thorsten E. E. Grams, Markus Hauck, Peter Hajek, Henrik Hartmann, Erika Hiltbrunner, Günter Hoch, Meisha Holloway-Phillips, Christian Körner, Elena Larysch, Torben Lübbe, Daniel B. Nelson, Anja Rammig, Andreas Rigling, Laura Rose, Nadine K. Ruehr, Katja Schumann, Frank Weiser, Christiane Werner, Thomas Wohlgemuth, Christian S. Zang, and Ansgar Kahmen. 2020. ‘A First Assessment of the Impact of the Extreme 2018 Summer Drought on Central European Forests’. *Basic and Applied Ecology* 45:86–103. doi: 10.1016/j.baae.2020.04.003.

Sevanto, Sanna. 2018. ‘Drought Impacts on Phloem Transport’. *Current Opinion in Plant Biology* 43:76–81. doi: 10.1016/j.pbi.2018.01.002.

Shafaghat, Arezou, Golnoosh Manteghi, Ali Keyvanfar, Hasanuddin Bin Lamit, Kei Saito, and Dilshan Remaz Ossen. 2016. ‘Street Geometry Factors Influence Urban Microclimate in

Tropical Coastal Cities: A Review'. *Environmental and Climate Technologies* 17(1):61–75. doi: 10.1515/rtuect-2016-0006.

Sjöman, Henrik, Justin Morgenroth, Johanna Deak Sjöman, Arne Sæbø, and Ingo Kowarik. 2016. 'Diversification of the Urban Forest—Can We Afford to Exclude Exotic Tree Species?' *Urban Forestry & Urban Greening* 18:237–41. doi: 10.1016/j.ufug.2016.06.011.

SMHI. 2019. 'Climate Extremes for Sweden | SMHI'. *SMHI - Sveriges Meteorologiska Och Hydrologiska Institut*. Retrieved 26 April 2023 (https://www.smhi.se/forskning/forskningsenheter/klimatforskning/forskningsprojekt/klimatextremer-for-sverige-1.151681).

SMHI. 2023. 'Värmebölja (In English: Heat Wave)'. *SMHI - Sveriges meteorologiska och hydrologiska institut*. Retrieved 26 April 2023 (https://www.smhi.se/kunskapsbanken/klimat/varmebolja-1.22372).

Statens offentliga utredningar, ed. 2019. *Skogsbränderna sommaren 2018: betänkande*. Stockholm: Norstedts Juridik.

Stovall, A. E. L., H. Shugart, and X. Yang. 2019. 'Tree Height Explains Mortality Risk during an Intense Drought'. *Nature Communications* 10(1). doi: 10.1038/s41467-019-12380-6.

Taha, Haider. 1997. 'Urban Climates and Heat Islands: Albedo, Evapotranspiration, and Anthropogenic Heat'. *Energy and Buildings* 25(2):99–103. doi: 10.1016/S0378-7788(96)00999-1.

Thom, Jasmine K., Stephen J. Livesley, Tim D. Fletcher, Claire Farrell, Stefan K. Arndt, Janina Konarska, and Christopher Szota. 2022. 'Selecting Tree Species with High Transpiration and Drought Avoidance to Optimise Runoff Reduction in Passive Irrigation Systems'. *Science of The Total Environment* 812:151466. doi: 10.1016/j.scitotenv.2021.151466.

Thorsson, Sofia, Fredrik Lindberg, Jesper Björklund, Björn Holmer, and David Rayner. 2011. 'Potential Changes in Outdoor Thermal Comfort Conditions in Gothenburg, Sweden Due to Climate Change: The Influence of Urban Geometry'. *International Journal of Climatology* 31(2):324–35. doi: 10.1002/joc.2231.

Trugman, A. T., M. Detto, M. K. Bartlett, D. Medvigy, W. R. L. Anderegg, C. Schwalm, B. Schaffer, and S. W. Pacala. 2018. 'Tree Carbon Allocation Explains Forest Drought-Kill and Recovery Patterns'. *Ecology Letters* 21(10):1552–60. doi: 10.1111/ele.13136.

Tucker, Compton J. 1979. 'Red and Photographic Infrared Linear Combinations for Monitoring Vegetation'. *Remote Sensing of Environment* 8(2):127–50. doi: 10.1016/0034-4257(79)90013-0.

Tucker, Compton J., and Bhaskar J. Choudhury. 1987. 'Satellite Remote Sensing of Drought Conditions'. *Remote Sensing of Environment* 23(2):243–51. doi: 10.1016/0034-4257(87)90040-X.

Vastag, E., S. Orlović, A. Konôpková, D. Kurjak, C. Cocozza, E. Pšidová, K. Lapin, L. Kesić, and S. Stojnić. 2020. 'Magnolia Grandiflora L. Shows Better Responses to Drought than Magnolia × Soulangeana in Urban Environment'. *IForest - Biogeosciences and Forestry* 13(6):575. doi: 10.3832/ifor3596-013.

Watkins, J. Harry R., Ross W. F. Cameron, Henrik Sjöman, and James D. Hitchmough. 2020. 'Using Big Data to Improve Ecotype Matching for Magnolias in Urban Forestry'. *Urban Forestry & Urban Greening* 48:126580. doi: 10.1016/j.ufug.2019.126580.

Wilcke, Renate Anna Irma, Erik Kjellström, Changgui Lin, Daniela Matei, Anders Moberg, and Evangelos Tyrlis. 2020. 'The Extremely Warm Summer of 2018 in Sweden – Set in a Historical Context'. *Earth System Dynamics* 11(4):1107–21. doi: 10.5194/esd-11-1107-2020.

Winbourne, Joy B., Taylor S. Jones, Sarah M. Garvey, Jamie L. Harrison, Liang Wang, Dan Li, Pamela H. Templer, and L. R. Hutyra. 2020. 'Tree Transpiration and Urban Temperatures: Current Understanding, Implications, and Future Research Directions'. *BioScience* 70(7):576–88. doi: 10.1093/biosci/biaa055.

Yang, Li, Feng Qian, De-Xuan Song, and Ke-Jia Zheng. 2016. 'Research on Urban Heat-Island Effect'. *Procedia Engineering* 169:11–18. doi: 10.1016/j.proeng.2016.10.002.

Appendix

Appendix A

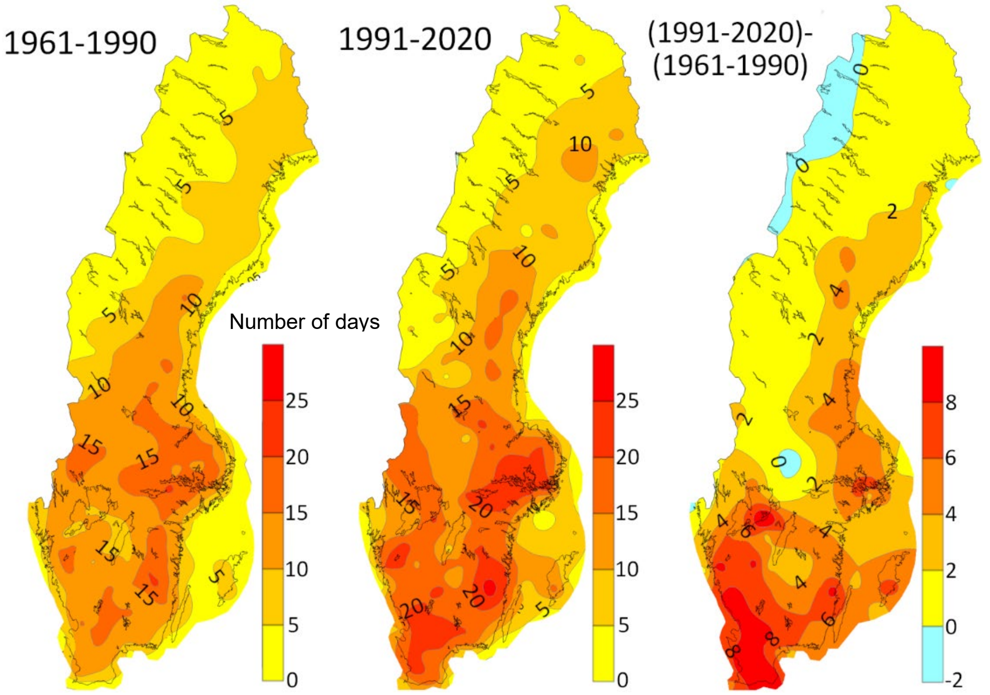


Fig. A.1. Mean values of the maximum number of high summer days in a year during the period of 1961-1990 and 1991-2020, and the difference between the latter and former periods. High summer days are defined as days with maximum temperatures equal to or above 25°C. Source: SMHI (2023).

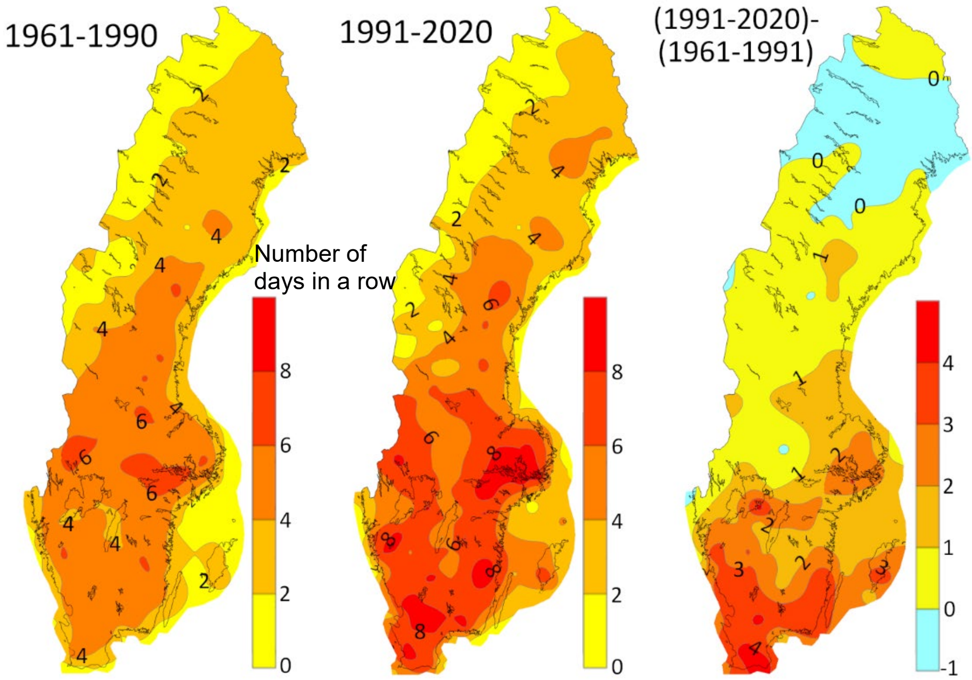


Fig. A.2. Mean values of the maximum number of high summer days in a row during the period of 1961-1990 and 1991-2020, and the difference between the two periods, respectively. High summer days are defined as days with maximum temperatures equal to or above 25°C. Source: SMHI (2023).

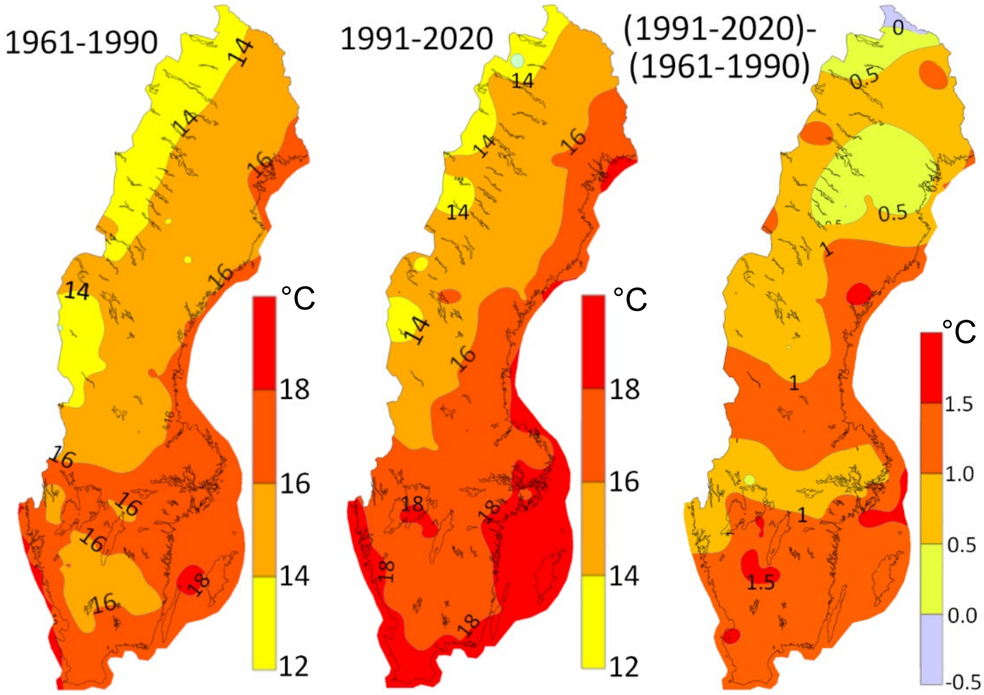


Fig. A.3. Mean values of the highest annual minimum temperature (in °C) during the period of 1961-1990 and 1991-2020, and the difference between the two periods, respectively. The highest annual minimum temperatures are defined as the lowest nighttime temperature during heat waves. Source: SMHI (2023).

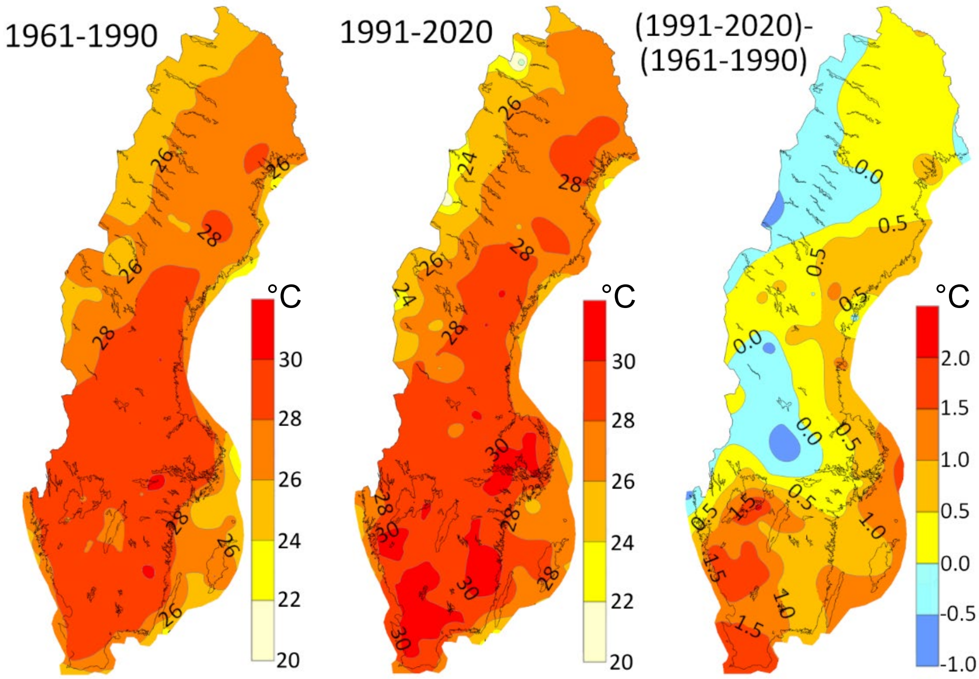


Fig. A.4. Mean values of the annual maximum temperature (in °C) during the period of 1961-1990 and 1991-2020, and the difference between the two periods, respectively. Source: SMHI (2023).

Appendix B

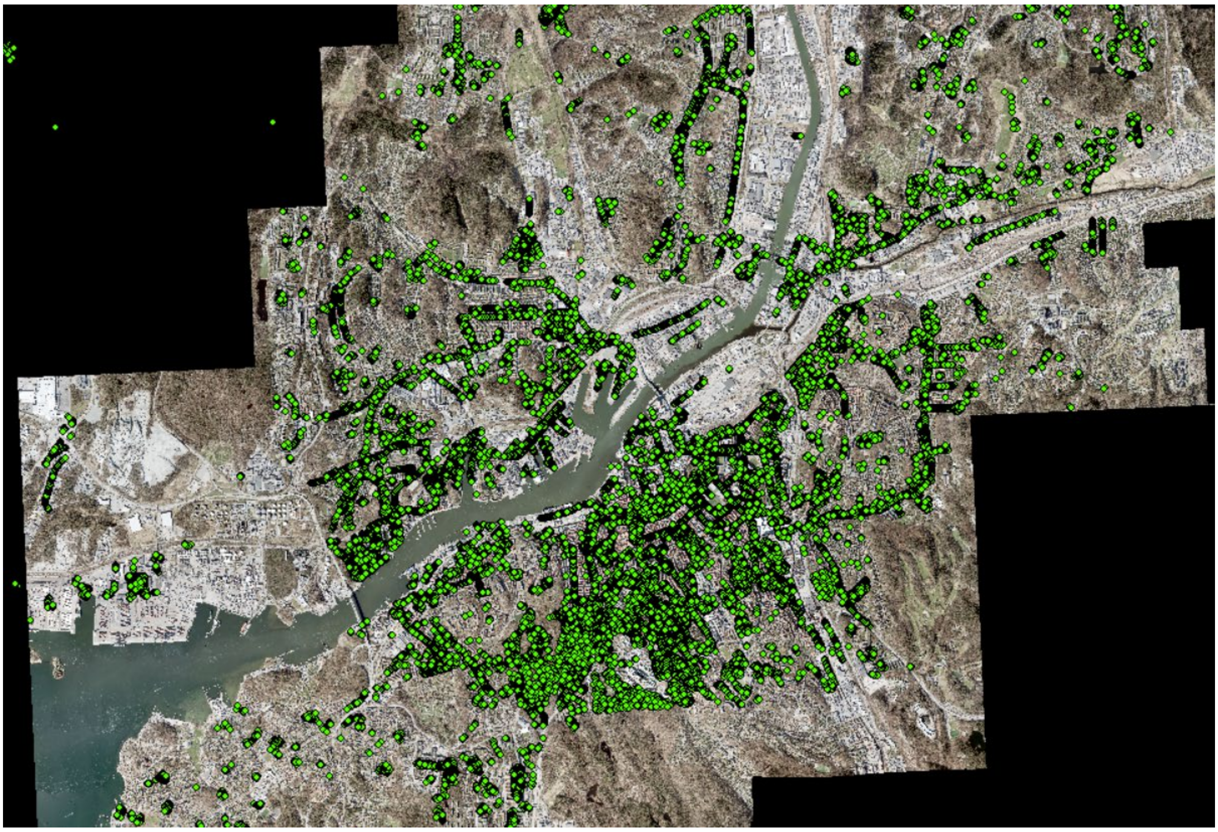


Fig. B.1. Orthophoto satellite image of Gothenburg. Green dots represent tree positions. Source: Municipality of Gothenburg (lantmateriet.se).

Appendix C

Table C.1. Total number of tree species sampled in each of the investigated groups.

Tree species	Group control	Group decline	Single control	Single decline	Total
Acer platanoides	0	1	2	3	6
Acer rubrum	0	0	0	1	1
Acer saccharinum	0	0	2	1	3
Aesculus carnea	0	0	1	0	1
Aesculus hippocastanum	2	2	2	3	9
Alnus glutinosa	1	0	0	0	1
Betula pendula	4	2	2	4	12
Carpinus betulus	1	2	0	1	4
Corylus colurna	0	1	0	0	1
Crataegus crataegus	0	0	2	2	4
Davidia involucrata	0	0	1	0	1
Fagus sylvatica	0	0	1	3	4
Fraxinus ornus	0	0	0	1	1
Halesia monoticola	1	0	0	0	1
Juglans cinerea	0	0	0	2	2
Juglans nigra	0	0	0	2	2
Laburnum laburnum	0	2	0	0	2
Magnolia spp.	0	0	0	3	3
Malus baccata columnaris	0	0	0	1	1
Malus domestica	1	1	0	0	2
Malus Madonna	1	0	0	0	1
Malus malus	0	2	1	2	5
Metasequoia glyptostroboides	0	0	1	0	1
Picea sp.	0	0	0	1	1
Pinus nigra	1	3	0	1	5
Populus nigra	1	0	0	0	1
Populus Populus	0	0	1	0	1
Prunus avium	0	0	0	1	1
Prunus ceracifera	1	0	0	0	1
Prunus schmitii	0	1	0	0	1
Prunus serulata	0	2	0	0	2
Prunus spp.	1	0	0	0	1
Pseudotsuga menziesii	0	1	0	0	1
Pyrus communis	0	1	0	0	1
Quercus robur	1	4	1	1	7
Querus rubra	0	0	1	0	1
Robinia pseudoacacia	1	1	3	1	6
Salix alba	1	0	0	1	2
Salix salix	0	0	1	0	1
Sorbus intermedia	1	0	0	0	1
Sorbus ulleungensis Dodong	1	1	0	0	2
Syringa vulgaris	0	0	0	1	1
Tilia Cordata	0	0	0	2	2
Tilia Europaea	8	3	4	0	15
Tilia platiphylos	0	0	1	0	1
Tilia tilia	3	3	0	3	9
Ulmus glabra	1	4	1	1	7
Zelkova serrata	0	0	0	3	3
Total	32	37	28	45	142

Appendix D

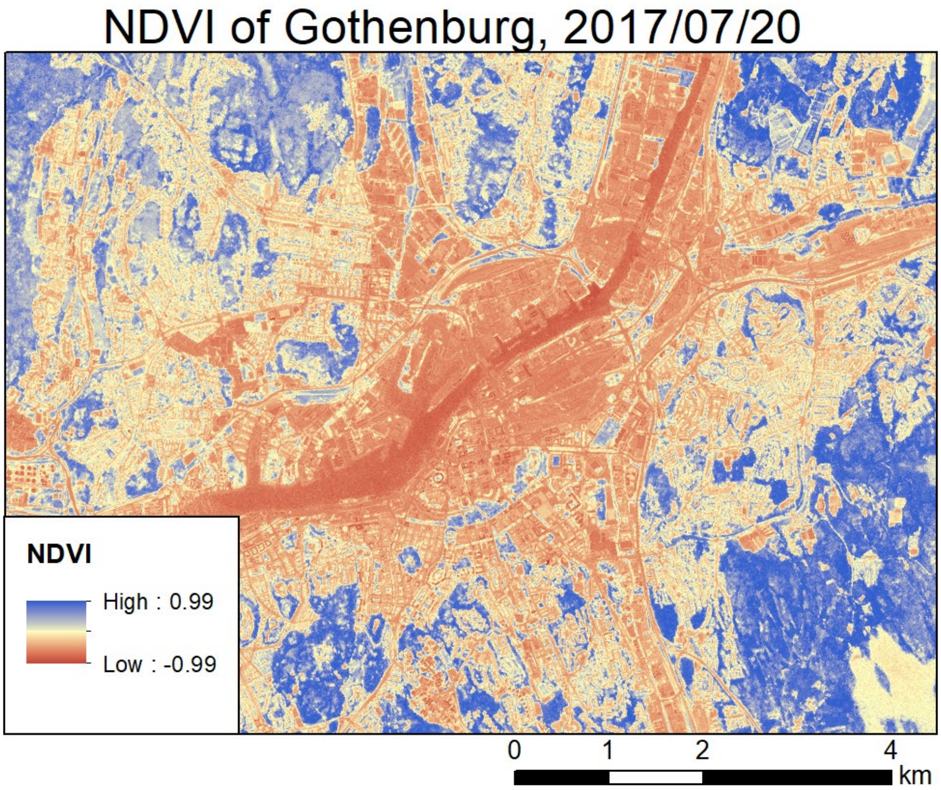


Fig. D.2. NDVI of Gothenburg, 20. July 2017, adjusted for colorblind readers. Negative, neutral, and positive changes are marked with red, bright yellow, and blue colors, respectively.

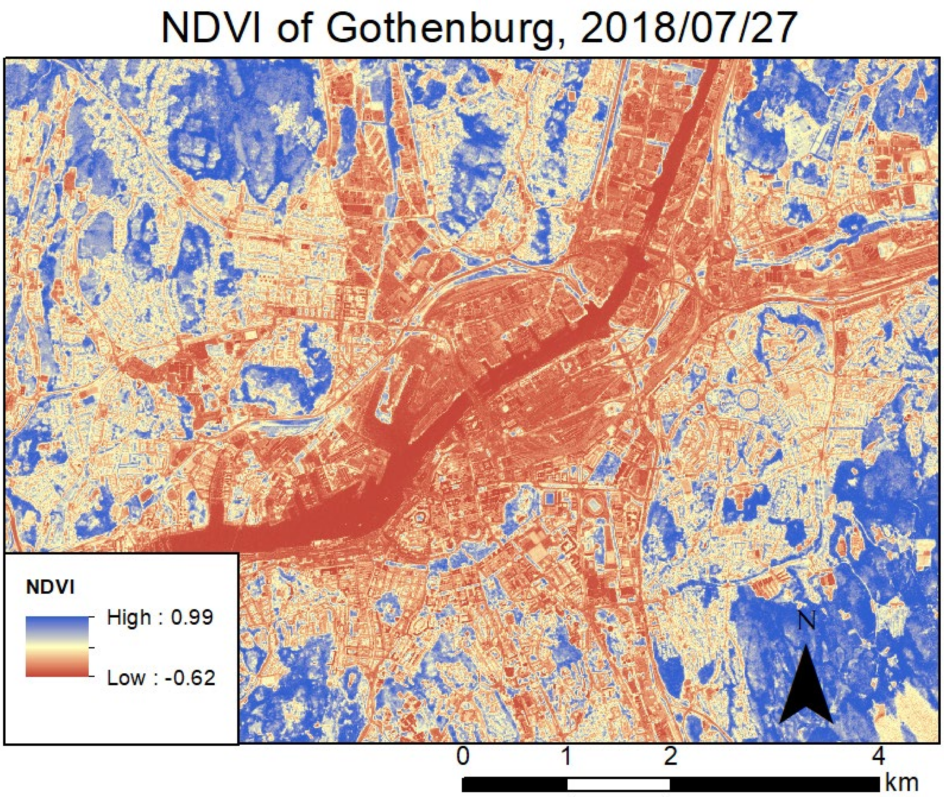


Fig. D.1. NDVI of Gothenburg, 27. July 2018, adjusted for colorblind readers. Negative, neutral, and positive changes are marked with red, bright yellow, and blue colors, respectively.

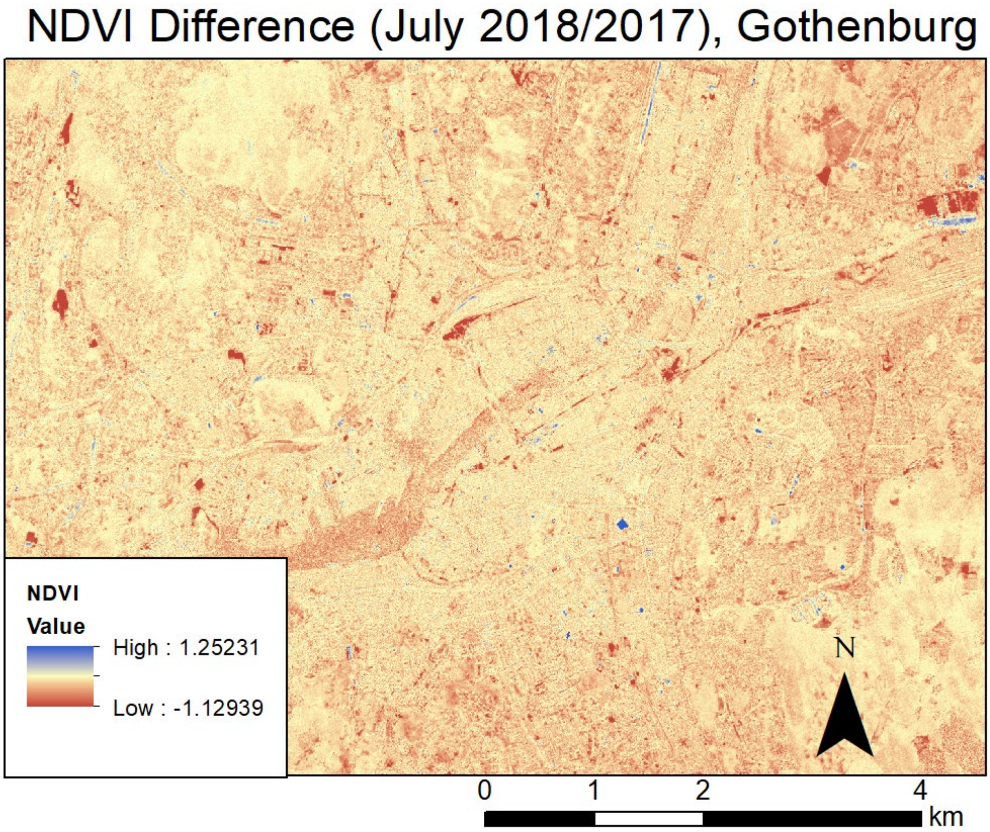


Fig. D.3. Difference in NDVI levels for July 2018 and 2017 in Gothenburg, adjusted for colorblind readers. Negative, neutral, and positive changes are marked with red, bright yellow, and blue colors, respectively.

Protocol

Protocol for Measuring Urban Vegetation Data

Objective: The objective of this experiment is to measure various data related to urban vegetation.

Materials:

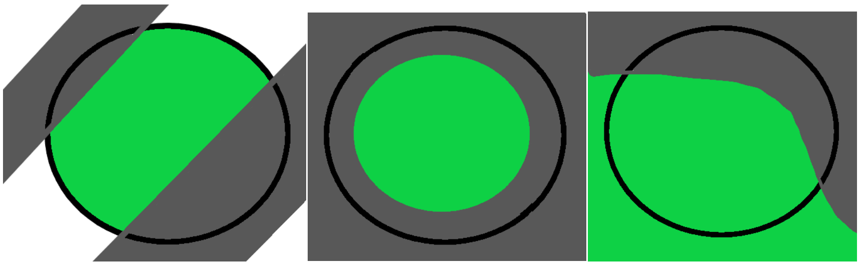
- Measuring flexible steel tape
- Compass
- Clinometer
- Camera (optional)
- Fixed length rope for height measuring
- Tree stem diameter measuring tool

Procedure:

1. Find a sample tree.
2. Confirm/corroborate species identity with the data from the species list in the Excel sheet.
3. Measure the height of the sample tree with a clinometer from a fixed distance of 20 meters (in m).
4. Measure the stem diameter in two perpendicular directions (in cm).
5. Measure the crown diameter of the tree in two perpendicular directions using the measuring tape (in m).
6. If a building is nearby (>30° angle from the horizontal) and within a 90° horizontal field of view facing south from the tree (i.e., ±45° from south), measure the nearest distance to

(in m) and the direction (in °) of the nearest part within the 90° field of view (note: two measurements here!).

7. Measure the hight of the building (targeting the building top at its nearest distance within the 90° field of view) with the clinometer as if it was at a distance of 20 m (height correction for real distance will be made afterwards).
8. Measure the distance from the stem of the tree to the nearest road using the measuring steel tape (in m).
9. If there is a non-permeable (NP) surface below the tree crown, measure the permeable area below the tree crown. Classify the area (lane, circular or irregular). Examples are listed below. Black circle = crown diameter; green area = permeable surface; grey area: non/permeable surface.



10. If the permeable part is a lane, measure (in m) the distance from the stem to the non-permeable surface under the crown. If there are non-permeable areas on both sides of the stem, measure the distances from the stem towards both sides. If the surface surrounding the stem is a circle, measure the radius from the stem's center to the non-permeable surface. Add tree stem dimensions when calculating permeable area afterwards.
11. If there is a larger tree to the south (90 ° field of view, at an angle of >30° from the horizontal), repeat steps 6 and 7, but for the tree.
12. If there is a hard path adjacent to the tree sample area, measure the nearest distance from the tree to the hard path using the measuring tape (in m).
13. (Optional) Take photographs of the trees and their surrounding areas for future reference.

Data Analysis:

1. Calculate the crown surface area for all trees in a sample area from the cross-section measurements.
2. Calculate the permeable surface below the crown for all trees in the sample area, and the fraction of the permeable area below the tree crown.