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Master's Thesis

Efficiency of green roofs as a climate change mitigation measure. Case study in Prague (Czech Republic).

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DIPLOMA THESIS ASSIGNMENT

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Landscape Engineering
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Thesis title

Efficiency of green roofs as a climate change mitigation measure. Case study in Prague (Czech Republic)

Objectives of thesis

The objective of the research is to explore the potential role of green roofs in the chosen study area as a supplement to the green spaces of developed areas as a means to buffer the associated impact due to the increase of surface temperature due to urban heat island effect and of course climate change. The main research questions are:

- Can green roofs be a beneficial addition to green spaces to reduce surface temperature?
- To explore if there is a relationship between green roof type, land surface temperature, and vegetation cover.
- How do green roofs mitigate urban heat island effects?
- To clarify possible measurement methods for estimating land surface temperature.

Methodology

The proposed methodology is applied to green roofs located in Prague and additionally, a green roof site in Lisbon was observed, two cities with different climate conditions, density variations, and geometrical and typological characteristics. The methodology may be considered as a base to estimate the potential of green roofs. Further research with a great number of green roofs is needed in the future in order to better quantify this effect.

The study has collected its information from three sources; a literature review, on-site measured data, and satellite remote sensing measurement data.

The purpose of the research is achieved through different methods of approach over a long-term investigation. All of the collected data will be considered in this research, and on-site measured data will be compared with satellite remote sensing data in order to discuss alternative and more automatic measurements. The first part of the research involves satellite images, in order to understand time-series changes in vegetation cover in the Prague study area. NDVI images were obtained from January to December 2022 period using the ESA satellite Sentinel-2 (Sentinel Hub API). The initial analysis is based on measuring the land surface temperature of green roofs with a hand-held digital thermometer. Field data collection continued in Lisbon from December 2022 to February 2023, where a thermal camera was used in the study area in addition to a hand-held digital thermometer.

The proposed extent of the thesis

65 pages

Keywords

green roofs, urban heat island, climate change, surface temperature, NDVI

Recommended information sources

Chen X, Huang P, Zhou Z and Gao C 2015 A review of green roof performance towards management of roof runoff J. Appl. Ecol.26(8) 2581–90

Liu C, Li Y and Li J 2017 Geographic information system-based assessment of mitigating flash-flood disaster from green roof systems Comput. Environ. Urban Syst 64 321–331

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Teemusk A, Mander Ü. Greenroof potential to reduce temperature fluctuations of a roof membrane: a case study from Estonia. Build Environ 2009;44:643–50

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Diploma Thesis Author's Declaration

I hereby declare that the work presented in this thesis entitled "Efficiency of green roofs as a climate change mitigation measure. Case study in Prague (Czech Republic)" is original and done by me independently, under the supervision of doc. Peter Kumble, Ph.D. I have listed all literature reviews and publications from which I acquired information in the attached list of references at the end of the thesis.

31.03.2023 Saule Beken

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Abstract

The following research is focused on the analysis of Land Surface Temperature changes which is an essential aspect in many domains, including the potential of green roofs as a climate change mitigation measure and a strategy to reduce the urban heat island effect. The present LST was obtained by the use of a handheld thermometer and satellite images.

Installation of green roofs can be advantageous for both the building and the city because it can: save energy; reduce stormwater runoff; reduce thermal fluctuations on the roof surface, which can ultimately increase the lifespan of the membrane; improve urban biodiversity; contribute to the beautification; mitigate urban heat island effect; reduce noise and air pollution.

A comprehensive, interdisciplinary methodology was developed that consists of the following steps: observational, including on-site observations and remote sensing, data analysis, and conclusion. Information obtained from the experimental sites was compared with satellite remote sensing measurement data.

The methodology applied in this research may be considered as a base to estimate the cooling potential of green roofs at the Czech University of Sciences in Prague. Further field data collection continued in Lisbon to explore an additional approach using a thermal camera.

This research will help to understand the effectiveness of green roofs in decreasing surface temperature. During the field measurements, LST was measured at 261 points using a hand-held thermometer. The vegetation cover of the study area in Prague was analyzed along the year by the Normalized Difference Vegetation Index (NDVI).

The result of on-site measurements in Prague shows that the implementation of green roofs confirms greenery and vegetation reduce the land surface temperature and reduce the urban heat island effect at the building scale and the remote sensing data at the city scale. Recommendation for future studies, corrective studies are needed with a great number of green roofs, considering the external environment in order to obtain a more accurate LST. As a solution to better quantify this effect, unmanned air vehicles such as Infrared Drone Camera that takes thermal images with a spatial resolution from the air in the summertime when the LST is higher can be used.

Keywords: green roofs, urban heat island, climate change, surface temperature, NDVI

Abstrakt

Následující výzkum je zaměřen na analýzu změn povrchové teploty půdy, což je zásadní aspekt v mnoha oblastech, včetně potenciálu zelených střech jako opatření ke zmírnění změny klimatu a strategie ke snížení efektu městského tepelného ostrova. Současný LST byl získán pomocí ručního teploměru a satelitních snímků.

Instalace zelených střech může být výhodná jak pro budovu, tak pro město, protože může: šetřit energii; snížit odtok dešťové vody; snížit tepelné výkyvy na povrchu střechy, což může v konečném důsledku zvýšit životnost membrány; zlepšit městskou biologickou rozmanitost; přispět ke zkrášlení; zmírnit efekt městského tepelného ostrova; snížit hluk a znečištění ovzduší.

Byla vyvinuta komplexní interdisciplinární metodologie, která se skládá z následujících kroků: pozorování, včetně pozorování na místě a dálkového průzkumu Země, analýza dat a závěr. Informace získané z experimentálních míst byly porovnány s daty měření družicového dálkového průzkumu Země.

Metodika použitá v tomto výzkumu může být považována za základ pro odhad chladicího potenciálu zelených střech na České univerzitě v Praze. Další sběr dat v terénu pokračoval v Lisabonu s cílem prozkoumat další přístup využívající termokameru.

Tento výzkum pomůže pochopit účinnost zelených střech při snižování povrchové teploty. Během terénních měření byla LST měřena ve 261 bodech pomocí ručního teploměru. Vegetační kryt studovaného území v Praze byl v průběhu roku analyzován pomocí indexu normalizované diference vegetace (NDVI).

Výsledek měření na místě v Praze ukazuje, že realizace zelených střech potvrzuje, že zeleň a vegetace snižují povrchovou teplotu pozemku a snižují efekt městského tepelného ostrova v měřítku budovy a data dálkového průzkumu Země v měřítku města. Doporučení pro budoucí studie, opravné studie jsou potřebné pro velký počet zelených střech s ohledem na vnější prostředí, aby bylo možné získat přesnější LST. Jako řešení pro lepší kvantifikaci tohoto efektu lze použít bezpilotní vzdušné prostředky, jako je infračervená dronová kamera, která pořizuje termosnímky s prostorovým rozlišením ze vzduchu v létě, kdy je LST vyšší.

Klíčová slova: zelené střechy, městský tepelný ostrov, změna klimatu, povrchová teplota, NDVI

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1. Introduction

Today, urban areas are facing a variety of challenges that threaten the environment, such as intense urbanization and population growth, as well as migration to urban areas, which increased the demand for water, energy, and food, leading to resource depletion, limited green space for recreation, contamination of surface water, displacement of wildlife, and not the least of which is climate change. For instance, air quality, local air temperature, and water management are critical issues that must be addressed in order to plan smarter and more resilient cities. Moreover, urban areas are vulnerable to thermal stresses such as heatwaves and tropical nights because of the urban heat island (UHI) phenomenon. The replacement of urban green spaces by artificial land cover materials with high solar radiation absorption has caused an increase in land surface temperature (LST) (Givoni, 1998; Voogt and Oke, 2003; Weng, 2009; Bowler et al., 2010). As a consequence, urban areas experience temperatures that are greater than suburban areas (Voogt and Oke, 2003; Adams and Smith, 2014). In this regard, understanding LSTs is critical for studying climate change and the urban heat island (UHI) phenomenon. Ecosystem service values must be integrated into urban decision-making to improve urban resilience, health, and quality of life while reducing cities' ecological footprint, and negative effects of dense cities, and ensuring energy saving.

Due to interest growing towards climate change mitigation and the urban heat island effect, in cities around the world, the implementation of green roofs is growing as policymakers become more interested in enhancing the urban environment (Köhler, Schmidt, Grimme, Laar, Paiva & Tavares, 2002; Wong, Chen, Ong & Sia, 2003; Susca, 2019). In this context, green roofs are beneficial in reducing the negative effects of impermeable surfaces and radiated heat. It provides ecological, economic, and social benefits (Yang et al., 2008, Berndtsson et al., 2009) through nature-based solutions and it is a key to the development and planning of sustainable and smart cities.

Green roofs provide several benefits to urban environments, including: 1) ecological benefits, such as effectively reducing the heat island effect, improving urban comfort and air quality, lowering building energy consumption, and noise pollution, CO_2 emissions, stormwater management, enhancing biodiversity, etc.; 2) economic benefits, such as lowering energy costs through improved thermal insulation, protecting building roofs from thermal, UV radiation fluctuations and works as a shield from acid rain which increase the lifespan of the roof; 3) social benefits, such as providing additional outdoor recreational areas, green spaces for physical and leisure activities, adding aesthetic value to the city (Berardi, 2016; Scharf and Zluwa, 2017; Shafique et al., 2018; Todorov et al., 2018; Baraldi et al., 2019; Santos et al., 2019; Zhang et al., 2020).

Typically, green roofs are planted with drought-tolerant species (grasses, moss, succulents, and some herbaceous plants) and require little irrigation (Dunnett & Kingsbury, 2004; Oberndorfer et al., 2007; Burszta-Adamiak, Fudali, Piotrowski, & Kolasiska, 2019). However, this is very much specific to the local climate and rainfall of a given location. Green roofs are frequently divided into intensive, extensive, and semi-intensive green roofs, which are distinguished by different depths of growing media and plant sizes.

Although extensive green roofs are the most common type of green roof and can be built on almost any roof, they have the disadvantages of having a smaller retention capacity and drying out more quickly than intensive roofs (Stovin, Vesuviano, Kasmin et al., 2012). Low greenery such as grasses, perennials, succulents, and others are used for extensive green roofs. With a larger substrate thickness above 20 cm all types of plants, shrubs, and trees, including low greenery are used in intensive green roof systems. The vegetation layer on rooftops provides insulation, keeping buildings cool by reducing heat flow passing through the roof into the building and reducing the amount of rainwater discharged into the sewers.

Green roofs, among other things, also help to mitigate urban "heat islands effects", which are associated with much warmer metropolitan regions than adjacent rural areas (Santamouris, 2001). This is accomplished by reducing heat-retaining impermeable surface areas (roofs) and increasing evapotranspiration.

Green roofs are either required, recommended, and/or subsidized in several major cities, including Basel (Switzerland), Toronto (Canada), Stuttgart and Munich (Germany), Copenhagen (Denmark), Vienna (Austria), Paris (France), Singapore, Portland (US), and Tokyo (Japan) (Berardi et al., 2014). While the number of vegetation-covered roofs in the Czech Republic and Portugal continues to increase, the total number of installations is still low compared to other European countries.

The aim of this study was to analyze LST changes across different types of green roofs over a long-term study to help understand the potential benefits of green roofs as a climate change mitigation measure. LSTs were obtained using an actual hand-held thermometer at four study locations in Prague and Lisbon, two European urban areas with extremely distinct climatic characteristics. Both cities are capitals and largest cities, Prague occupies an area of around 496 km^2, with about 1.3 million people living there, while Lisbon's area covers around 100 km^2 with a population of approximately 0.54 million people.

2. Aims of the Thesis

The aim of the research is to investigate the use of green roofs as a strategy to reduce the urban heat island effect (UHI) based on case study locations and understand the role of green roofs as an alternative addition to the city's green spaces to buffer the negative effect of an increase in maximum temperature due to climate change.

The objective of the research has been the analysis of surface temperature changes of several green roofs located at the Czech University of Life Sciences Campus in Prague and the University of Lisboa in Lisbon.

The hypothesis of this research is that a green roof can be a more beneficial addition than a standard conventional roof to reduce surface temperature.

Studies based on field measurements of temperature changes of different green roof surfaces were carried out from December 2021 to March 2023. All obtained information will be considered in this research, and on-site measured data will be compared and validated with satellite remote sensing measurement data.

3. Literature review

This chapter presents the current knowledge of green roofs, providing the context for this study. First, a historical exploration of the origin of green roofs is presented, and how and in which way different weather conditions and urbanization have influenced it. After that, a comprehensive understanding of the types of green roofs, their components, advantages, and disadvantages, and the cost is explained.

Information was collected from various scientific articles and scholarly online databases such as Science Direct, ResearchGate, and others found in the CULS Libraries, as well as other online academic search sources.

3.1 Discussion on green roofs

Green roofs, also known as living roofs, are buildings' roofs that are entirely or partially covered in plants and growth medium. In addition to vegetation and soil layers, green roofs also have other components such as a drainage layer, a roof barrier, and an irrigation system, shown in Figure 2.

Other terms are often used to describe green roofs, like as VCPH (Horizontal Vegetated Complex Partitions), "eco-roofs," "vegetated roofs," "living roofs," and "bio rooftops" (Rahman et al.,2012; Mathey et al.,2011; Hien et al.,2007).

Green roofs can be installed on both new and old buildings, as well as modest garages and bigger government, industrial, and commercial buildings, and can offer a variety of functions to buildings, such as creating green recreational space, rainwater absorption, insulation, saving energy, noise reduction, a more aesthetically pleasing view, wildlife habitat creation (primarily for insects). Of note, green roofs need not be flat or horizontal as some are on an incline, they can be installed on steeply pitched roofs as well.

3.2 Historical exploration of the origins of green roofs

From a historical perspective, green roofs and roof gardens date back nearly a thousand years and spanning multiple cultures, beginning in Neolithic times (Kristjansdottir et al., 2001, Loveday, 2006). Historically, the uses of vegetated roofs were quite diverse. The ancient green roof's evolution has been interpreted in terms of human efforts to create effective and practical shelters. Its origins can be traced back to antiquity when it began as pragmatic earth daubing on a crude wooden frame to seal gaps and increase the ability of simple shelters to resist the elements.

According to Peck (1999), the earliest example of green roof constructions were sod roofs above caves, where soil and plants were used for farming, housing, and ceremonial purposes. Those houses offered weather protection, strong thermal insulation in the winter, and a cool place in the summer.

Although it has been mentioned previously in this thesis, there are two basic types of green roofs: intensive and extensive. Due to the thicker profile of intensive green roofs, which enables small trees and a variety of other plants to grow in the soil, they are frequently known as "roof gardens." The ziggurats, which were in Mesopotamia between 4000 and 600 BC are considered to be the first known roof gardens. These were enormous stone-stepped pyramid towers constructed in stages, and trees and bushes were planted on flat terraces at the landings of these stepped towers to facilitate climbing and provide shade from Babylon's heat (Werthmann, 2007). Etemenanki, the most well-known of the ziggurats, was constructed in Babylon in the square of the enormous Esagil Temple.

The Hanging Gardens of Babylon, also called the Gardens of Semiramis, were built by King Nebuchadnezzar II to comfort his wife, Amytis, who had a passion for mountain surroundings and was longing for the greenery of her homeland of Media (Osmundson, 1999). The Hanging Gardens is shown in Table 1, one of the Seven Wonders of the Ancient World was built in approximately 500 B.C. and is unquestionably one the most well-known ancient green roofs. The Hanging Gardens were waterproofed by a layering of reeds and thick tar and were constructed above arching stone beams providing cool shades and helping to cool the inside of the buildings. According to Osmundson (1999), the existence of references to gardens in ancient Greek, Roman, and Assyrian texts provides enough evidence that the idea of a green roof has always been implemented in the collective mind.

Examples of early roof gardens are Augustus and Hadrian's mausoleums presented in Table 1, b. It is widely known that the Romans planted trees atop numerous public buildings. Pliny, an ancient historian, said that trees had been brought in specifically for these rooftop gardens. According to Peck (1999), sloping terraced gardens and roof gardens were common in Genoa throughout the Renaissance period.

Table 1. Ancient roof gardens example

Figure	**Description**
	a) The Hanging Gardens of Babylon (New World Encyclopaedia). Source: http://www.heathershimmin.com/a-brief-history-of-roof-gardens

	b) Ruins of the Mausoleum of Augustus, 28 B.C.E. in Rome, Italy. This aerial view shows the central cylinder housing Augustus's burial chamber as it appeared in 2019. Source: https://greenrooftechnology.com/the-oldest-existing-green-roof-in-the-world/
	a) Torre Guinigi Tower in Lucca, Italy. This 44-meter-high tower is planted with oak trees and it is one of the last from the Middle Ages. Source: https://greenrooftechnology.com/the-oldest-existing-green-roof-in-the-world/

Roof gardens once more developed during the Middle Ages and during the Renaissance period, particularly in Italy, and were the property of wealthy people and Benedictine monks. Rooftop gardens were built on top of the Pienza's Palazzo Piccolomini, Medici palaces. Another example is Torre Guinigi Tower in Lucca which is the oldest known and still existing roof garden in the world, where seven oak trees were originally planted on the rooftop approximately in the 14th - 15th centuries as presented in Table 1, c. Oak trees were specifically chosen by the Guinigi family as a symbol of renewal and rebirth.

Extensive green roofs have a thinner profile making them less costly to construct and also lighter in overall mass weight. Examples of extensive green roofs used as a survival tool in extreme climates include Viking longhouses during the Norse era. Vikings covered the walls and roofs of their houses with turf that had birch wood substrates and water-retentive membranes to have shelter from the elements (Table 2). According to Minke (2001) in tropical regions, for instance in Tanzania sod roofs were utilized for the opposite purpose of insulating the interior from outside heat.

Nordic countries Denmark, Norway, Sweden, Finland, Iceland, Greenland, Vinland, and the Faeroe Islands are just examples of countries with a long history of using sod roofs. In fact, archaeologists are still discovering ruins of these homes more than 300 years later, demonstrating the extraordinary durability of the structure. Their design and use were solely functional (Dunnett and Kingsbury 2004; Getter and Rowe 2006). Similar turf houses have been developed by North America's indigenous Inuits (Morrison and Germain, 1995; Snow and Forman, 2009). There are several Vikings era sod roofs and French sod roofs examples found in Canada as presented in Table 2, Newfoundland and Nova Scotia. Due to timber scarcity, early American settlers of the Great Plains also used this technique in the late 1800s (Hammer, 1968).

Table 2. Examples of green roofs / green covers

Figure	Description
	a) The figure depicts a living roof in Mallhaugen Open Air Museum in Norway. Turf pitched roofs and walls were essential elements used during the Viking era to keep the building warm during the winter. This technique was used between 800 AD and the late 9th century.
	b) Norse settlement which is an archaeological site in L'Anse aux Meadows in Newfoundland, Canada. The area is now owned by Parks Canada as a "living history" museum.

Source: https://www.thoughtco.com/lanse-aux-meadows-vikings-north-america-167165

In 1856, Robert Chambers traveled to Iceland and the Faeroe Islands, and after his trip, he wrote about the timber scarcity of Faeroe. He described the climate as a “wild, uncouth, and arctic region” where man is “roughened” and building materials were in short supply (Chambers, 1856). Chambers says that the houses in the Faeroes look like "bright patches of green" that are "anomalous," and that these green patches are the "sod-covered roofs of houses" (Chambers, 1856). The suburbs of Iceland were inhabited by fishermen and their houses, described as “sod-covered hovels” were “prevalent” (Chambers, 1856).

Nomadic people in the steppe of Central Asia in treeless temperate grassland (steppe) built houses from the abundant turf present (Ching, 2012). Their successful adaptability to the harsh environment while using limited resources shows the universality of human creativity across cultures. The expression of environmental determinism is analogous to human efforts to design homes that meet local needs and work around restrictions (Gottmann, 1957; Rotne and Albjerg, 2010; Srensen and Miller, 2010). Turf-covered roofs have also been used for centuries in parts of the Middle East.

Extensive green roofs have a much less well-documented history than intensive green roofs. Therefore, the historical development of roof gardens is directly tied to climate conditions and can be linked to cities, particularly wealthy citizens, as a means of displaying their social standing, while extensive roofs are more commonly seen in rural areas or town settings. In warmer regions, such as the Mediterranean, there are many roof gardens, but in colder regions like Nordic countries, they are not very prevalent. Extensive green roofs were common there and were more of a realistic approach to using nature in the battle against the weather.

3.2.1 The modern green roofs

Later, green roof usage extended throughout northern Europe, primarily in Germany, for rural and agricultural applications. Urbanization and industrialization in Germany exploded in the 1880s. Low-cost housing was roofed with tar, which is very flammable, and a roofer named H. Koch wanted to reduce the risk of fire by adding a sand and gravel base. After a while, errant seeds started to naturally germinate in the substrate forming green meadows across the industrialized skyline (Francis and Lorimer, 2011).

One of the first examples of a planted concrete roof in Europe was presented at the EXPO in Pa in when attendees had the opportunity to learn about extensive green roofs in general and view a concrete "nature roof" showcase (Dunnett and Kingsbury, 2008). Roof greening declined dramatically during the Great Depression and World War II. The desire to build green roofs for environmental reasons and bring nature back into. The lives of citizens arose only in the 20th century. It was embraces by creators of modern architecture such as Le Corbusier, Frank Lloyd Wright, and Alvar Alto. For instance, in 1927 Le Corbusier presented his “The Five Points of a New Architecture“ where roof gardens came second. The five points became a guideline for many architects and continue to influence the most diverse contemporary architectural projects to this day.

Green roofs at the La Tourette Monastery which were designed by Le Corbusier (built 1953-1961), and the Rockefeller Center rooftop green gardens in New York which are considered the first modern green roofs in the US (1930) are great examples of modern green roofs (Figure 1).

Modern green roof technology flourished in the 1960s when Germany pioneered a new robust technology providing sophisticated irrigation and roof intrusion protection. With the invention, Germany promoted and advanced the innovative green roof technology on an unprecedented scale. In the 1970s, there was a great number of conducted studies of layers of green roofs, such as root membranes and waterproofing membranes, drainage and filter layers, and growing medium. The majority of the earliest green roofs investigations in Europe during that time were conducted in Germany, Switzerland, and Nordic countries, and were not written in English (Dvorak, 2010; Koehler, 2007; Mentens et al., 2006). Throughout the 1980s, the German market for green roofs experienced remarkable expansion, with a typical annual growth rate between 15% and 20%. According to Ermakova and Muikova (2009), Germany had erected 1 million m^2 of green roofs by 1989, and 10 million m^2 by 1996.

This growth was made possible by state legislation, local grants, and policies that have been followed by other European nations as well. Several medium and large sized cities have included rooftop and vertical gardening in their by-laws and planning regulations. In many European countries, including Germany, France, Austria, Norway, and Switzerland, green roofs have emerged as a common element of the urban landscape and construction sector.

Figure 1. a) La Tourette Monaster; b) The Rockefeller Center
Source: https://www.innovatopgreen.com/en/green-roofs/the-evolution-of-green-roofs/

Today, the use of green roofs has spread around the world, especially in developed countries and regions in Europe, North America, and Asia. Earlier studies on green roofs were carried out in European countries such as Switzerland and Germany and have since resulted in the establishment of recognized guidelines and standards such as FLL (FLL, 2008; Dvorak and Volder, 2010).

3.3 Types of green roofs

Despite the different types of green roofs in Figure 2, the main components remain the same such as weight, biotic components, substrate, succession, drought tolerance, and roof as an environment is of great importance in their design (Mentens,2006). As a hybrid of the two, a third type called semi-intensive has emerged (Ampim, 2010).

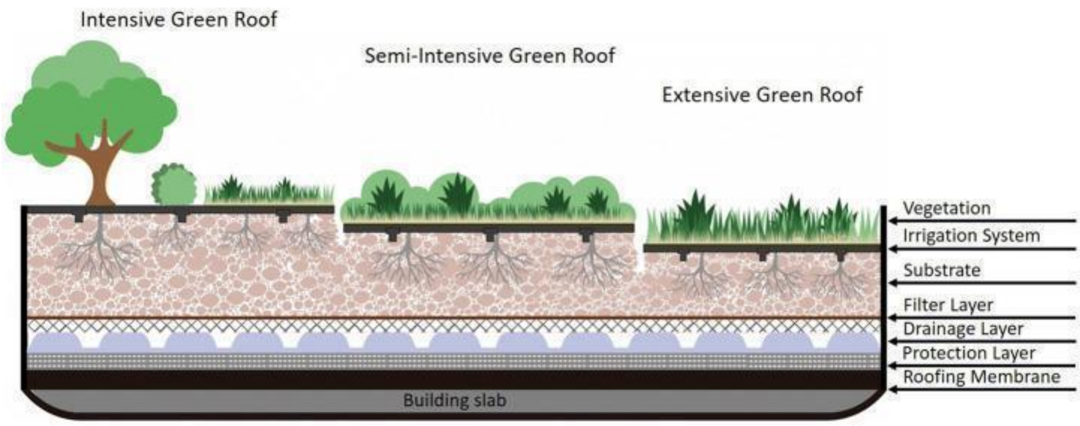


Figure 2. Typical green roof cross-sectional layers and classification (not to scale)
Source: https://europepmc.org/article/med/34888555

The intended uses and individual profiles of all three reveal the major differences between them. Table 3 shows the classification and comparison of green roof types.

Table 3. Green roof types

Type	Intensive	Semi-intensive	Extensive
Load-bearing component	Concrete (max. pitch 5%)	Concrete	Concrete, wood
Plant choice	Lawns/perennials, shrubs, trees	Perennials, grass, herbs, small shrubs, lawns	Sedums, herbs, mosses, perennials
Thickness of growing medium	300 and over mm	120-300 mm	40-150 mm
Weight of complete system (kg/m2)	500 to 2000	200 to 500	75 to 180
Irrigation	Yes	Yes	No
Maintenance	Very high	High	Low
Cost	High	Periodic	Low
Accessibility	Yes	Limited	No

Source: adapted from Tailor (2010)

Intensive green roofs

As previously mentioned intensive green roofs are called "roof gardens" and function as typical gardens or recreational areas and have a soil layer larger than 150 mm (Table 3). Thick soil layer, various vegetation cover, and increased weight-bearing and stress load characterize intensive green roofs and they also need higher structure support measurements and maintenance. Intensive roofs are typically constructed when the slope is less than 10 degrees (Krupka, 1992; Kolb and Schwarz, 1999). Systems with an intensive roof might be as thick as the engineering of the building's roof structure can support. Vegetables, grasses, perennial herbs, shrubs, and trees are among the more varied vegetation kinds.

The main benefit of an intensive roofing system is the improvement of biodiversity by fostering a more natural environment. Intensive green roofs perform significantly better than extensive green roofs in terms of reducing runoff and altering the quality of runoff water. For instance, intensive green roofs reduce runoff by 85% when compared to typical conventional roofs, while extended green roofs only cut runoff by 60%. In addition, the amounts of lead, zinc, cadmium, and copper contamination in the runoff from intensive green roofs are significantly less than the amounts from extensive green roofs.

Semi-intensive green roofs

Semi-intensive green roofs are a hybrid of both extensive and intensive green roofs (Table 3), requiring periodical irrigation, and modest upkeep. This system has the ability to support a more diverse ecology and hold more runoff than extensive green roofs. Due to the lesser covering of growth medium layer compared to intensive green roofs, this type of roof has the potential to be used as an amenity. Ground coverings, grasses, tiny herbaceous plants, and small bushes can be planted on this roof.

Extensive green roof

Extensive green roofs have thin soil depth and fewer layers, allowing for easier maintenance and making them more accessible (F.L.L., 2008). The major benefit of extensive roofing systems is that they are less costly and the main specifications are shown in Table 4. The substrate layer in extensive green roofs is no more than 150 mm deep. This type does not require a construction process that is technically difficult and can be installed on sloped roofs. In some cases, extensive green roofs can be installed on roofs that are as steep as 45 degrees. The tough species of sedum are the dominant vegetation type. This genus is typically low-growing in height and drought-tolerant, with low nutritive requirements and biomass. It also has minimal seasonal die-back and does not require maintenance and does not pose a fire hazard, as there is little dry material present.

The widespread adoption of extensive green roof technology in the 1980s accelerated the practice. Considering a sustainable urban ecology, extensive roofs are more significant since, due to their lightweight, they can be installed on more rooftops (Benvenuti, 2010). Because of the dynamic and customizable technology, buildings can select which green roof is best for them, allowing a larger population to take part in the sustainable practice of growing green roofs.

Figure 3. Green roofs of the High-tech Educational Pavilion of the Faculty of Forestry and Wood Sciences CULS in Prague
Source: https://www.ftz.czu.cz/en/r-10623-news-home/czu-is-once-again-the-most-environmentally-friendly-universi.html

Green roofs of the newly constructed High-tech Educational Pavilion of the Faculty of Forestry and Wood Sciences on the CULS campus in Prague-Suchdol are an excellent and contemporary example of both extensive and intensive green roofs in Prague, Czech Republic (Figure 3).

3.4 Components of green roof systems

The design must take into account many factors, including the type of green roof, weight, biotic components, substrate, succession, drought tolerance, and the surroundings of the roof. Vegetation with shallow and horizontal root growth is recommended, as well as with a slow growth rate.

Generally, green roofs consist of five main parts from the bottom to the top: root membranes and waterproofing membrane, a drainage layer, a filter layer overlaid by a geotextile material, growth media retainer (soil), and landscape materials on the top, i.e., plants as listed in Figure 4.

The type of each green roof component depends on the geographic location and each country with different climatic conditions and building characteristics must conduct local studies to determine the components for a successful green roof.

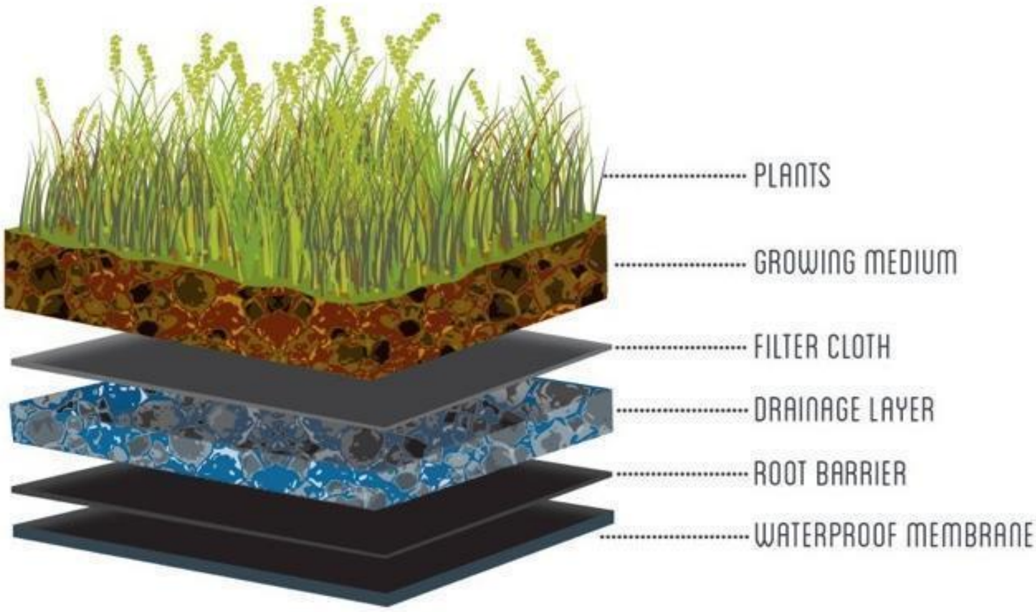
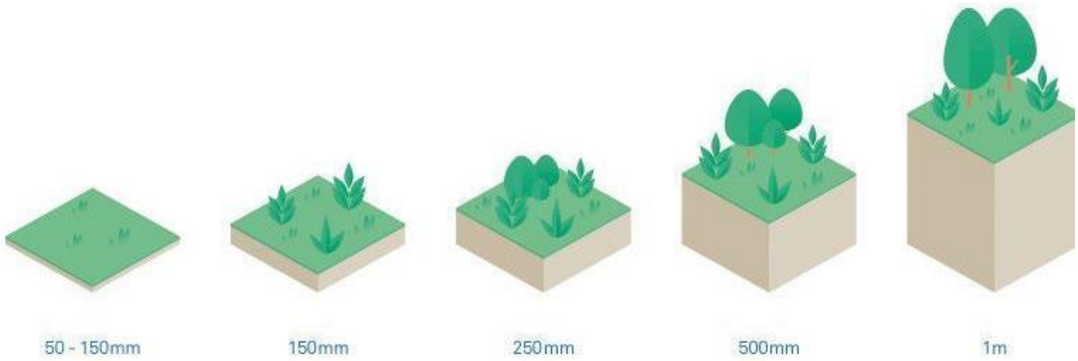


Figure 4. A green roof section shows the major components of a typical green roof
Source: https://www.architectureanddesign.com.au/features/features-articles/a-guide-for-specifying-green-roofs-in-australia

3.4.1 Vegetation layer

The top layer of a green roof comprises plants, which give the system life. Plants improve runoff quality, air quality, thermal performance, and soil quality. Plantings must be irrigated frequently during the first two months of the establishment.



Low growing succulents	Annual to biennial Plants, herbaceous perennials	Small shrubs, turf	Scrubs up to 2m	Small trees

Figure 5. Groups of vegetation that can be planted on a roof
Source: https://agritech.tnau.ac.in/horticulture/horti_Landscaping_roofgarden.html

Dunnett and Kingsbury, 2004 state that it is still difficult to choose the appropriate plant species for green roofs since they must be able to withstand extreme temperature changes, thin soils, and strong winds. Priority should be given to species that easily adapt to extreme conditions, species that are resistant to diseases with low nutrient requirements, do not cause allergies or toxicity, are not resistant to urban pollution, and have non-aggressive root development (so they cannot damage waterproofing or other building elements) and are non-invasive.

Some examples of vegetation planted on the green roofs of the CZU campus are shown in Table 4 below.

Table 4.Different types of vegetation on the green roofs of study area

Source: Author, 2022

Herbaceous perennials and members of the Sedum family, which includes 600 varieties of succulents, many native plants from coastal and arid interior regions are suited for extensive green roofs since they require low maintenance (Figure 5). Based on a number of different studies, researchers have estimated that vegetation (sedum) on green roofs can catch an amount of 0.2 kilograms of airborne particles per 1 m^2 of green roof every year. These airborne particles include smog, heavy metals, and volatile organic compounds (Peck, S. W., M. Kuhn, et al., 2003).

The maintenance requirements for intensive green roof plants are comparable to those for ground-level gardens, however, native species are recommended. Small shrubs and turf can be grown on intensive green roofs with substrate layer depths of over 250 mm (Figure 5). Waterproofing membranes can be damaged by the roots of certain grasses, such as Couch Grass *(Cynodon dactylon)* and Kikuyu *(Pennisetum clandestinum)* and these grasses should be avoided. Shrubs up to 2m tall can grow in soil that is deeper than 500mm, but plants with dense, upright habits should only be used where wind exposure is minimal. A few examples of acceptable shrubs include the Pink Velvet-bush *(Lasiopetalum behrii),* the Grey Honey-Myrtle *(Melaleuca incana),* and several species and cultivars of Westringia. In areas with strong winds, trees with sparse crowns, flexible trunks, and high heat tolerance are recommended. Deeper than 1m substrate can support small trees up to 5m tall (Figure 5).

According to Kurn, D M; Bretz, S E; Huang, B; Akbari, H. vegetation lowers air and surface temperature by directly shading surfaces, reducing solar heat input through plant evapotranspiration, and converting incident solar radiation into latent heat. In addition, as a result of the lower temperature, the long-wave radiation emitted by the ground and leaves become less than that of nearby artificial hard surfaces, which reduces radiation exposure to people.

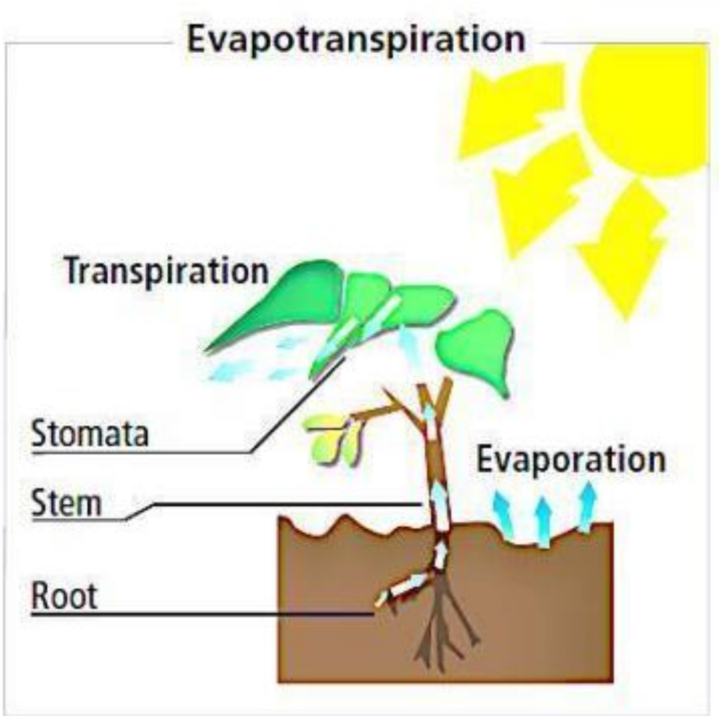


Figure 6. Evapotranspiration
Source: https://www.pinterest.com/pin/279575089342127514/

Plant height, leaf area index (LAI), fractional coverage, albedo, and stomal resistance are the most important plant characteristics that have an influence on heat transfer on green roofs. "Transpiration" is the term for the movement of water that appears when plants absorb water through their root system and releases it through leaves, shown in Fig.6 above. The process activates in the morning because sunlight controls the opening of the stoma, through which water evaporates, transforming from a liquid to a gas. It cools the air by using evaporating water by utilizing the heat from the air. "Evapotranspiration" is the term used to describe these processes and it is a combination of evaporation and transpiration. Summer peak air temperatures can be decreased by evapotranspiration alone or in conjunction with shade. In addition, shade reduces land surface temperature under plants and tree canopies, as a result, the heat transformation into buildings (Scott, K., J.R. Simpson, and E.G. McPherson. 1999).

3.4.2 Soil layer

The growth substrate or soil layer (Figure 7) has a direct impact on plant growth and the performance of green roofs. As a result, selecting an appropriate substrate is critical for the success of any green roof. There is no universal growing medium suitable for all climates and plant species. It is common practice to combine components with different properties in predetermined ratios to form a growth medium composed mainly of mineral components, with an organic content suitable for each type of green roof. Typically substrates are free of fine particles (clay or limo), or have very low percentages of these elements, allowing them to maintain a good structure over time and providing assurance that the system will continue to drain excess water.

According to Berndtsson (2010), one of the characteristics that affect the runoff's ability to be reduced is the soil's thickness, which generally depends on the green roof system and design (Table 3, Figure 5). In order to support plant growth, the substrate must be lightweight, porous, and low density, with sufficient fertility and drainage capacity, allow water absorption and infiltration, water and air retentive, a good rooting medium, resistant to heat, frost, shrinkage, and rot, chemically and physically stable (Baldessar 2012 and Woods Ballard, 2007). The main characteristics of substrates are shown below in Table 5.

Table 5. Characteristics of commercial green roof substrate

Type of green roof	Extensive (Sedum)	Extensive (Rocky type plant)	Semi-extensive	Intensive
Granules of <0.063 mm Ø	≤7%	≤15%	≤15%	≤20%
Salt content	≤2.5%	≤2.5%	≤2.5%	≤1.5%
Porosity	63%	63%	64%	64%
pH value	7.9	7.8	7.8	7.8
Dry weight	980 kg/m3	980 kg/m3	940 kg/m3	930 kg/m3
Saturated weight	1240 kg/m3	1330 kg/m3	1360 kg/m3	1400 kg/m3
Maximum water capacity	25%	36%	42%	46%
Air content at max water capacity	38%	27%	22%	18%
Water permeability	≥0.1 cm/s	≥0.097 cm/s	≥0.064 cm/s	≥0.034 cm/s

Source: https://www.sciencedirect.com/science/article/pii/S0169204611002441

This layer is the heaviest and it is necessary to take into account the weight that the structure can support when saturated with water (expected maximum load). The growing medium must also contain a minimum amount of nutrients to avoid weed formation and eutrophic runoff. This requires the use of nutrient-deficient inorganic recycled materials as the main components of the substrate. Therefore, there is growing interest in using local low-density inorganic recycled materials as sustainable sources for green roofs and a strategy to reduce the weight of the layer (Oberndorfer et al., 2007). In addition, it is recommended to minimize the volume of organic matter in green roof substrate due to lack of stability, as organic matter degrades over time, causing the substrate to shrink (A. Nagase, N. Dunnett, 2011). For instance, the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) is german guidelines for green roofs recommend only 4-8% and 6-12% organic matter by volume for extensive green roofs (FLL, 2002).

Figure 7. Green roof system: 1) Vegetation; 2) Soil layer; 3) Filter layer; 4) Drainage layer
Source: https://www.agreenroof.com/green-roofs/green-roof-panel-system/

In fact, several benefits of green roofs are directly related to the properties of the growth substrate, including improved water quality, thermal benefits, reduced peak flow, and sound insulation (K. Vijayaraghavan, 2016). Water-holding capacity (WHC) of substrate components is critical for plant survival in drought conditions and delaying peak flow during storm events. Although increasing the substrate's volume, depth, and organic content enhances WHC, it also alters the substrate's other characteristics. In order to enhance the quality of runoff, sorption capacity may be a useful attribute for growing medium, but sorption capacity is usually limited because of the significant presence of inorganic components in the substrate. However, optimizing these characteristics through ongoing research is critical for green roof long-term success (K. Vijayaraghavan, 2016).

3.4.3 Filter layer

The main purpose of a filter layer is to separate the growing substrate from the drainage layer (Figure 7), preventing the loss of media particles like soil fines and plant debris (Berndtsson, 2010) from entering and clogging the drainage layer below because of small particles from the upper layer, allowing water passage (Baldessar, 2012 and Woods Ballard, 2007). In most cases, geotextile fabrics are used in green roofs. For plants with soft and short roots, the filter fabric also serves as a root-barrier membrane.

3.4.4 Drainage layer

The layer will have different characteristics depending on the type of green roof. The type of drainage board will vary in height, drainage capacity, water-retention capacity, and compression resistance depending on the slope of the roof, the type of vegetation chosen, and the use of the roof (ornamental, for pedestrians, light vehicles, etc.).

Drainage layers are critical to the success of any green roof and they provide an optimal balance between air and water in the green roof system (Fig.4). Drainage layer helps to remove extra water from the substrate and also protects the waterproof membrane and improves thermal properties of the green roof. In recent years, green roofs have mostly used two main types of drainage layers:

- Drainage modular panels made of high-strength plastic materials (polyethylene or polystyrene) with compartments for storing water and allowing excess water to be drained.
- Drainage granular materials. Lightweight expanded clay aggregates (LECA), broken brick, coarse gravel, expanded shale, and stone chips are examples of these materials, which have some WHC and huge pore spaces to store water.

The drainage layer resembles egg cartons in appearance, with cups that can overlap with each other (Figure 7).

3.4.5 Water-proof layer and root barrier

A water-proof layer is critical to the success of any green roof (Woods Ballard, 2007). Even though a water-proofing layer may not be a part of a green roof, it is essential during the installation of any green roof to prevent leaks. From the end user's point of view, it is not surprising that one drop of water seeping through the roof is often regarded as a failure of the green roof. Roof humidity is always high due to wet soil and drainage layers. In addition, in order to find a leak in the existing green roof, it is necessary to remove all layers. Therefore, the application of a water-proof layer is always recommended.

For extensive green roofs, a root barrier is recommended but not necessary, while it is required for intensive green roofs. According to Baldessar and Silva (2012), this layer is used to prevent plant roots from penetrating green roofs upper layers from damaging the roof structure. Consist of an impermeable High-Density Polyethylene (HDPE) membrane, and depending on the application, root barrier may have a thickness of 20 mm, 30 mm, or 400 mm.

Figure 7. Photo of root barrier layer and water-proof layer
Source: https://www.newtonwaterproofing.co.uk/products-systems/products/external-waterproofing-and-drainage-membranes/puncture-resistant-root-barrier-membrane/

3.5 Benefits of green roofs

As described earlier, the benefits of installing green roofs are numerous, as they provide ecological, economic, and social benefits, support sustainable development, and protect the environment and biodiversity of urban areas through nature-based solutions (Yang et al., 2008, Berndtsson et al., 2009). Green roofs are a key to sustainable urban design and development. Table 6 presents the benefits of green roof implementation and these benefits will be analyzed further in order to gain a better understanding of the green roofs.

Table 6. Benefits of green roofs implementation in urban areas

Benefits	Findings
Environmental	- Natural filtration: green roofs act as natural air filtration by absorbing dust and cleaning air; - Stormwater management: green roofs work as porous surfaces that regulate stormwater runoff. - The process of photosynthesis in plants consumes CO_2 emissions and releases oxygen, keeping the air clean and lowering CO_2 dioxide emissions. - Up to 4% of heavy metal city dust could be trapped by green roofs. - Acoustics: green roofs have the potential to manage and minimize sound reflections. The noise level could be reduced by 8-10 dB;
Economic	- Energy: green roofs provide the benefit of reduced energy use by shading, insulation, evapotranspiration, and greater thermal mass; - Green roofs reduce shrinkage and growth of building material due to temperature, in addition, they protect against UV rays and acid rain. - Thermal comfort: plants have a strong system influence to reduce the UHI, which is a major issue in cities and metropolitan regions

	due to its ability to absorb shortwave radiation and cool the atmosphere. - Green roofs are considered as UHI mitigation tools by reducing the ambient temperature from 0.3°C to 3°C,; - Green roofs increase the service life of a building's roof by protecting it from temperature fluctuations, UV radiation fluctuations, and daily loads.
Social	- Green roofs provide rest and relaxation place as well as aesthetic appeal; - In addition, green roofs improve human health and well-being by exposing people to nature; - Plants relieve stress and reduced obesity by being close to green spaces; - Plants positively affect the people working or living nearby. According to the study, buildings with green spaces had higher staff productivity than those with less vibrant environments; - Compared to plants in gardens, plants in urban areas and sheds draw more attention; - Rooftops can offer essential circumstances for seasoned rare or endangered species.

Source: https://iopscience.iop.org/article/10.1088/1757-899X/713/1/012048/pdf

3.5.1 Mitigation of urban heat island effect

According to Santamouris (2001), the urban heat island (UHI) is the most well-documented climate change phenomena which has been recognized for nearly a century and is related to greater temperatures in cities compared to neighboring suburban and rural areas, shown in Figure 8. Modification of the land surface is the primary cause of the UHI effects. Climate change combined with the UHI effect increases the global temperature. The significant release of anthropogenic heat, the excess solar radiation storage by city structures, the absence of green spaces, and cool sinks, and the lack of air circulation in urban canyons are all factors that contribute to higher urban temperatures (Oke, T.R. et al., 1991).

The air temperature difference is usually greater at night than during the day, and it is most noticeable when the winds are light. Summer and winter are the seasons when UHIs are most noticeable. According to Oke (1997), a city with a population of one million or more people may have an annual mean air temperature that is 1 to 3°C warmer than the surrounding region, and on a clear and calm night, this temperature discrepancy can reach 12°C (Oke, T.R. 1987). Although the impact frequently decreases as the town’s size is reduced, heat islands can exist even in tiny towns and villages (Oke T.R. 1982).

High-rise buildings can obstruct the flow of wind that would otherwise provide ventilation, cool the streets below, and accelerate evaporation. This is known as the "urban canyon effect". High-rise buildings can also prevent the release of thermal energy from underground into the atmosphere. As a result, it captures more heat energy and people can feel it. According to a study, heat islands can be affected by proximity to various types of land cover. More specifically, the study found that proximity to barren land makes urban lands hotter, and proximity to vegetation makes them cooler (Mansourmoghaddam, Mohammad; Alavipanah, Seyed Kazem, 2022).

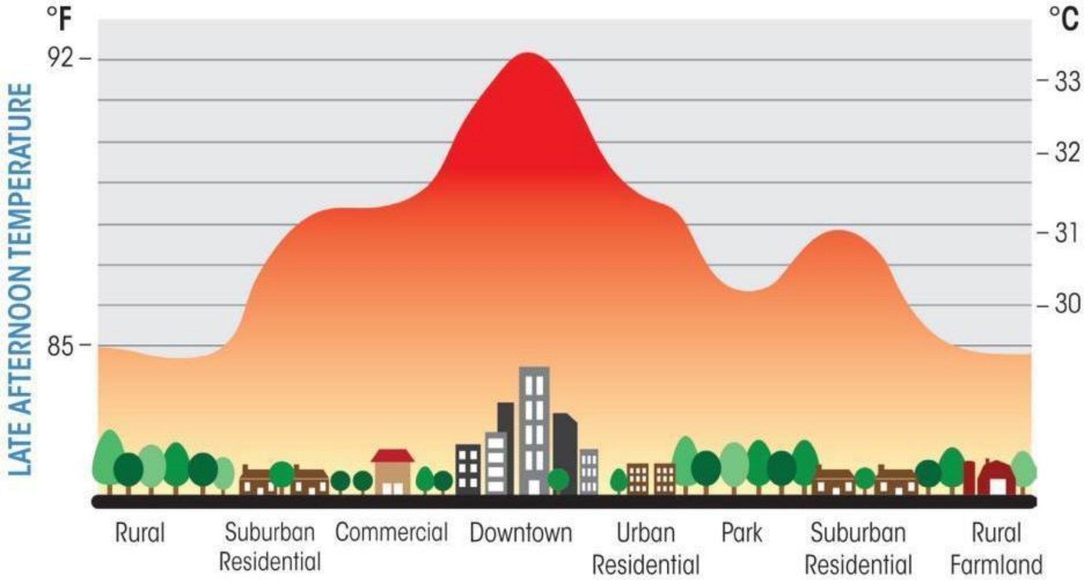


Figure 8. Urban heat island profile
Source: https://eco-intelligent.com/2017/04/13/the-urban-heat-island-effect/

Two types of UHI, surface and atmospheric UHIs differ in the ways they are formed, the techniques used to identify and measure them, their impacts, and to some degree, the methods available to mitigate them. SUHIs are assessed using land surface temperature (LST), while AYHI is determined by air temperature. Each type of heat island is summarized in Table 7 below.

Table 7. Main characteristics of surface and atmospheric urban heat islands

Feature	SUHI	AUHI
Temporal development	Continually present throughout the day and night Most intense during the day in the summer period	During the day it could be little or nonexistent More intense at night or before dawn, and especially in the winter
Peak intensity (most intense UHI conditions)	More temporal and spatial variation: Day: from 10 to 15°C Night: from 5 to 10°C	Less variation: Day: from -1 to 3°C Night: from 7 to 12°C
Typical identification method	Indirect measurement:	Direct measurement:

	- Remote sensing	- Fixed weather station - Mobile traverses
Typical depiction	Thermal image	Isotherm map Temperature graph

Source: https://www.epa.gov/heatislands/learn-about-heat-islands

Urbanization has exacerbated the effects of climate change, and green roofs can be used to mitigate the urban heat island effect. Rooftop revegetation is one of the most promising solutions to this problem that can improve the urban climate through shading and evapotranspiration, as discussed earlier in chapter 3.4.1.

Green roofs can reduce UHI in the following steps:
- Cooling buildings through natural plant processes including shading, evapotranspiration, and photosynthesis distinguish them as a living system (Mayor of London, 2008);
- Increase the quantity of solar energy reflected rather than absorbed;
- Warm up more slowly in the sun than on traditional roofs.

3.5.2 Energy savings

The installation of green roofs can reduce energy consumption by enhancing their thermal performance which benefits both buildings and cities (Takakura, Kitade, Goto, 2000; Theodosiu. 2003, Fang, 2008). Increases in shading, insulation, and thermal mass of the roof system contribute to enhanced thermal efficiency. In both cold and hot climate conditions green roofs are efficient.

The amount of savings varies depending on factors such as green roof type, depth and composition of growing media, climate, plant selection, irrigation type, and insulation specifications (K.L. Getter, D.B. Rowe, J.A. Andresen, I.S. Wichman, et al., 2011). Furthermore, according to Martens et al., the total amount of energy savings of buildings with green roofs is greater for single-story structures than for other types of buildings.

According to a study conducted in Greece, green roofs lower the amount of energy used for cooling by between 2% and 48% (A. Niachou, K. Papakonstantinou, M. Santamouris, A. Tsangrassoulis, G. Mihalakakou, et al., 2001). As a result, the energy consumption of buildings with green roofs is less than buildings without green roofs and might be further reduced by employing night ventilation during the summer. The energy savings are bigger during the winter than during the summer. In addition, buildings with moderately insulated roofs save more energy than those with well-insulated roofs. Green roofs are capable of reflecting 27% of solar radiation, absorbing 60% of solar radiation through photosynthesis, and transmitting up to 13% of the remainder to the growing media (N.H. Wong, D.K.W. Cheong, H. Yan, J. Soh, C.L. Ong, A. Sia, rt al., 2003).

3.5.3 Air quality and noise reduction

According to Currie and Bass (2005), trees are the most influential plants for reducing air pollution. As a result of the type of vegetation, intensive green roofs are the most efficient. A green roof's substrate and flora filter airborne pollutants and toxins from the atmosphere. Currie and Bass (2005) and Deutsch (2005) demonstrated the ability of green roofs to reduce pollution using an urban forest effect model. Furthermore Currie and Bass (2005) estimated that 109 ha of green roofs will eliminate 7,87 metric tons of air pollution per year. Additionally, green roofs reduce air pollution indirectly by lessening the UHI effect and building energy consumption.

According to Nowak (2000), wind currents can also trap particulate matter on the surfaces of vegetation. For instance, gaseous pollutants are absorbed by vegetation via leaf stoma, which subsequently reacts with water within the plant to generate acids and other compounds. While some particles stick to the surface and are resuspended in the air by flows or washed into the soil by rain, others are absorbed by the plant. Urban pollutants like particulate matter (PM), nitrogen oxides (NO_x), ground-level ozone, sulfur dioxide (SO_2), and carbon monoxide (CO) can be reduced by these procedures.

Plants and trees remove and store carbon from the atmosphere and reduce greenhouse gas emissions from power plants by reducing energy demand.

3.5.4 Stormwater management

Green roofs are considered as a Sustainable Urban Drainage System (SUDS) and can help to delay stormwater runoff and reduce its volume, which relieves pressure on the city's storm runoff water systems (Figure 9). Additionally, green roofs may hold more water during smaller storms than they do during larger storms. Some green roofs are set up to collect rainwater as an extra source of water that can be used later. Most of the time, rainwater collected from green roofs is used to water plants, flush toilets, and do other things that don't involve drinking. When Carter and Rasmussen researched extensive sedum roofs, they discovered that during light storms (less than 25.4 mm of rainfall), 88% of the water was retained, whereas only 48% of the water was retained during huge storms (greater than 76.2 mm of rainfall).

A green roof can reduce thermal loading on buildings by retaining stormwater on the roof surface. Modern stormwater management approaches aim to control the quality and quantity of urban runoff in order to contribute to a sustainable urban environment by working in harmony with natural environmental processes.

It is optimal to manage the storm flow as close as possible to its source. According to Stovin (2009), a combination of green roofs with other sustainable stormwater mitigation methods perform better and more effectively. Installation of green roofs can help to solve the problem of the "urban stream syndrome" (Carter, 2006) which is defined by increased frequency of disturbances, increase in urban flooding, and rapid pollution transfer.

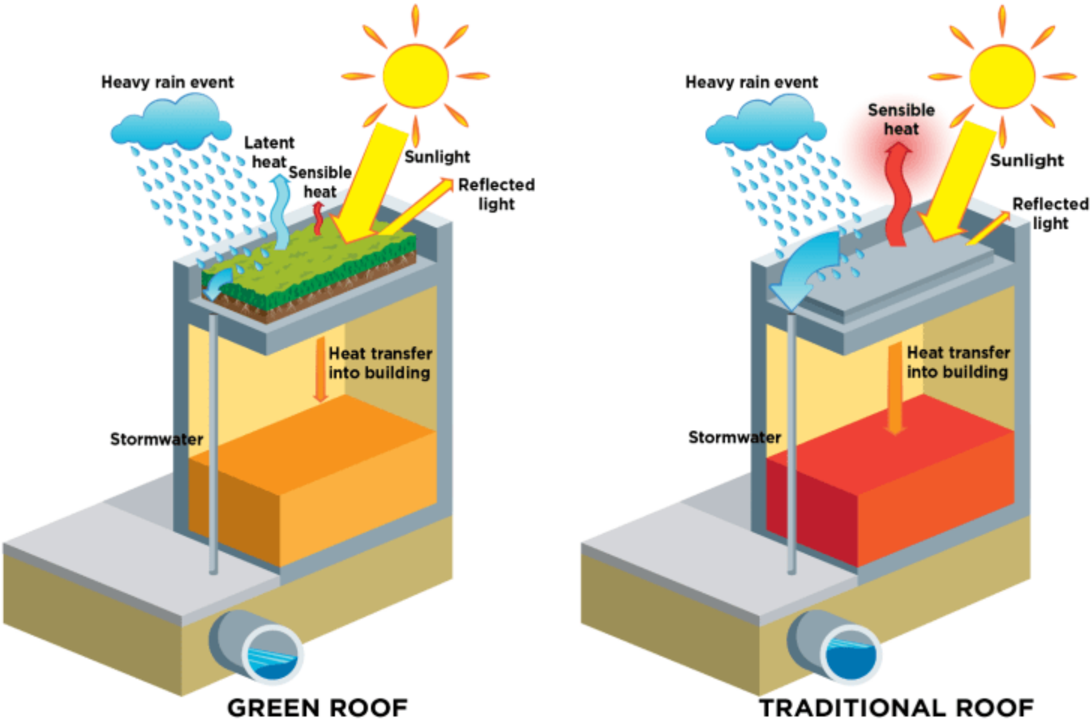


Figure 9. Heat exchange and water runoff of a green roof versus a traditional roof
Source: https://www.epa.gov/sites/default/files/2018-09/documents/greenroofs_casestudy_kansascity.pdf

Figure 10 below displays the runoff from the traditional roof and green roof during rainy events.

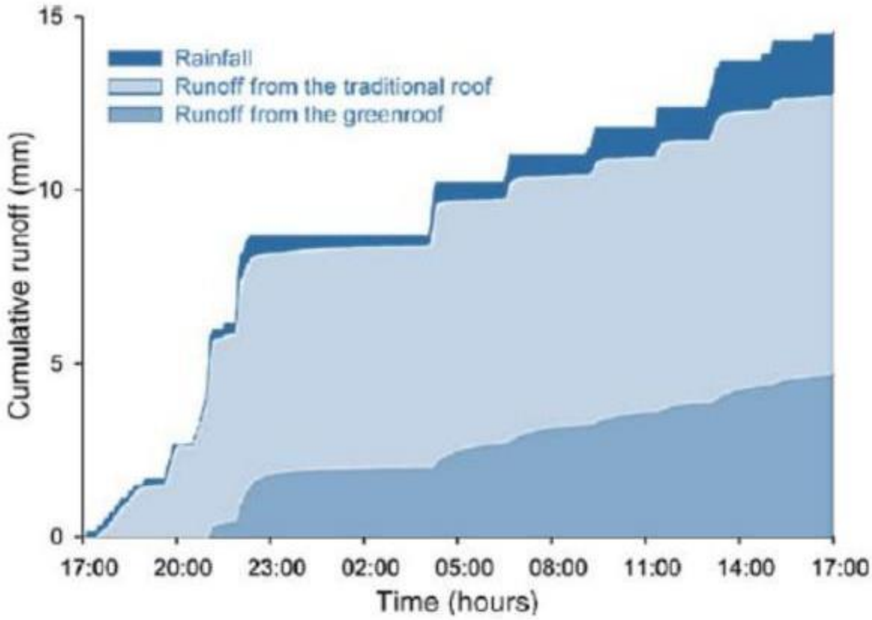


Figure 10. A comparison of a stormwater runoff between a traditional standard roof and a green roof
Source: Mentens et al. 2005

According to Mentens (2005) stormwater runoff reduction is dependent firstly on the type and design of the green roof systems, roof slope, and components, secondly on local climate conditions, and thirdly on the intensity and length of rainfall.

In terms of climatic effect, it has been demonstrated that the green roof is less efficient in the winter than it is in the summer due to the higher precipitation associated with winter, which saturates the soil and plants and thus reduces the technology's retaining capability, whereas in the summer, due to the lower precipitation usually verified, the retaining capability improves in comparison to the winter season (Silva 2012).

3.5.5 Urban biodiversity and aesthetic value

Urban biodiversity can provide a variety of ecological services that are beneficial to human well-being and health, enhancing people's access to nature (Sirakaya et al. 2018). According to a number of studies, urban biodiversity may improve the mental and physical health of residents by restoring concentration, lowering levels of stress, and reducing environmental pollutants (such as air and noise pollution) (Marselle et al. 2021).

Urban surfaces with skeletal substrates support the growth of biotic communities that resemble those found naturally on cliffs, outcrops, scree slopes, and gravely river edges (Dunnett, 2006). Birds and insects will be drawn to any green or brown roof that has weeds growing on it. For instance, flowering plants on rooftops provide vital food and shelter for bees, which have recently been in dire need of assistance. According to Dusty Gedge's research on the ecology of green roofs, accessories like logs, stones, and wads of balled-up hay can offer invertebrate species that inhabit skeletal substrate shade, windbreaks, shelter, and nesting habitat (Gedge, 2003).

Some of the same arthropods and birds were observed on green roofs as in the surrounding ground environment, representing a subset of species observed on ground locations (Bergeron et al. 2018). Green roofs with degraded habitat conditions can serve as ecological "sinks" or supplementary habitat for animal communities if they form a network of connected habitats with high-quality surrounding habitats (Eakin et al. 2015). Green roofs offer aesthetic benefits in addition to their ecological value.

In certain instances, such as in the Faroe Islands, sloping, grass-covered roofs have been utilized, which not only do not detract from the natural beauty of the surroundings but actually accentuate it. Rooftop gardens enhance the aesthetic value and diversity of urban environments. In the midst of all the concrete and glass, they surprise us with greenery. Several of them, like the top of New York's Rockefeller Center (Figure 1) or Jardim das Oliveiras (Fig.11), known as Porto's largest green roof — an oasis of 50 olive trees and lush grass are even popular residents and tourists destinations. They are a fascinating part of city planning and help mitigate some of the urbanization's drawbacks. The beautiful views of the city from these gardens are another attraction. An additional advantage of such solutions is that they delight the eyes of residents of neighboring houses. Green roofs can improve living conditions in built-up urban areas, thereby creating an open space where people can linger and interact with others. This, in turn, can promote social cohesion and strengthen communities.

Figure 11. A Historic Square Revitalized with an Olive Grove
Green Roof in Porto, Portugal
Source: Author

3.6 Disadvantages of green roofs

There are very few disadvantages of green roofs, but the main one is the initial cost of their installation (Getter et al., 2006). The current prices for the construction of green roofs in the Czech Republic and Portugal are discussed in more detail below.

Another disadvantage of green roofs is that they heavier comparing to traditional roofs and require special consideration and implementation of additional structural support. Intensive green roofs, in particular, require routine maintenance, while extensive roofs need roughly four annual inspections following the installation phase. Controlling vegetation growth and moisture levels, watering, cleaning debris, regular weeding, and fertilizing are all examples of general maintenance. According to Stovin, Vesuviano, and Kasmin (2012), extensive roofs have the drawback of having a lower retention capacity and drying more quickly than intensive roofs. Wind shear and negative wind pressures may compromise the resistance of the layers, especially on intensive roofs, so proper installation and consideration of these criteria are required.

Vulnerability to leaks is perhaps the most significant disadvantage. As previously stated, the waterproofing membrane is one of the most important components and after installation, a complete water flood test for leaks must be undertaken to assure quality control. Plant roots can occasionally break through the waterproofing membrane which might result in roof leaks that could harm the structure of the building. By conducting an annual inspection that includes the removal of problematic vegetation, the chance of leaks is reduced. Furthermore, it is particularly challenging to identify the source of a leak due to the multilayered base of green roofs.

Cost of green roof in the Czech Republic

Investment costs for building a green roof include project preparation, implementation work, and purchase of substrate, vegetation, and other materials. They range from 800 to 2,500 CZK/m ^{2} (33 €/m^2 to 106 €/m^2) for an extensive roof and 1,500 to 5,000 CZK/m ^{2} (63 €/m^2 to 211 €/m^2) with an intensive green roof. Other costs are mostly related to the verification of the statics and strengthening of the structure of the building, with the installation of air conditioning and irrigation. The operating costs of green maintenance must be taken into account. Decision-making, therefore, takes the form of cost-benefit analysis from the investor's point of view. To quantify the benefits, a combination of methods based on cost savings is used (energy prices for heating and cooling the building, for retention objects, for replacement of insulation), or costs for soundproofing indoor spaces. However, houses with green roofs gain a higher value in the real estate market.

According to Nádvorník, state subsidy prices will cover 69% of costs for extensive roofs and 62% for intensive roofs. However, some cities, such as Brno, add their own subsidy and the coverage of costs is then even higher.

Cost of green roof in Portugal

Each project is unique, and prices are always negotiated according to the solutions and different systems used.

According to the Portuguese National Green Roof Association, on average, an extensive green roof in Portugal can cost between 40 €/m^2 and 70 €/m^2, and an intensive roof can cost between 80 €/m^2 and 150 €/m^2. These values are merely indicative averages and may suffer very significant changes that relate to gains or losses in scale and logistical issues of access to the roof and means of distributing materials on the roof.

3.7 Green roof legislation

There are numerous laws that, in some cases, mandate the installation of green roofs. In certain countries, direct costs or maintenance costs for the installation of green roofs are financially supported.

For instance, Denmark has a culture of green roof culture that extends beyond the historical Faroe Islands. In 2010, Copenhagen became the first Scandinavian city to implement a mandatory green roof policy, that requires all newly built roofs both public and private to be vegetated. Earlier in 2009, Toronto became the first city in North America to approve a. bylaw requiring the construction of green roofs on all new industrial, commercial, and residential buildings larger than 2000m^2.

LEED and BREEAM are the most widely used green building certification standards in the world. Certification often leads to an immediate, measurable drop in how much water and energy a building uses, as well as a more efficient way of using it, which leads to cost savings.

LEED is an abbreviation for “Leadership in Energy and Environment Design”, and it is a certification program operated by the non-profit United States Green Building Council (USGBC). According to USGBC, LEED certification is based on eight categories: Location and Transportation (LT), site Sustainability (SS), Water Efficiency (WE), Energy and Atmosphere (EA), Materials and Resources (MR), Indoor Environment Quality (IEQ), Regional Priority (PR), Innovation (I).

Each of these has its own requirements and credits and the level of L.E.E.D. certification is based on the total number of credit scores earned.

BREEAM" was initiated in the UK in 1990 and stands for "Building Research Establishment Environmental Assessment Methodology" and it is Europe's most popular building certification. Since climate conditions and legislation differ by European country, a country-specific version is always required.

While BREEAM utilizes numerical standards, LEED uses percentage-based criteria. According to common consensus, LEED is simpler to understand and apply, whereas BREEAM is more academic and strict.

Green roof legislation in the Czech Republic

To encourage the use of green roofs in the construction industry, the Czech Environmental Ministry developed the New Green Savings Program to enhance the current environment, funds are available as of January 2017 and offer 24 €/m^2 (800 CZK/m^2). According to Beyer, the subsidy can cover the entire amount of eligible cost depending on the chosen type of green roof, vegetation, and method of installation. The Czech Green Roof Association developed a "Green Roof Code of Practice" prior to receiving the grant, green roofs are encouraged to be installed on both existing and new structures. For example, Brno supports green roofs with a direct subsidy for their implementation.

In 2019, the Czech Environmental Ministry supported 4,606 projects with a cost of over 2 billion crowns, and in 2020 it planned support in the amount of around 2.5 billion crowns. Based on data from the Czech Green Roof Association 195000m^2 of green roofs have been installed in the Czech Republic, which is equivalent to 4.3 times Vaclavke square. The green roof area has grown significantly by fifty percent year over year.

Both extensive and semi-intensive green roofs were subsidized under this program. In order to receive financial support, intensive green roofs must use a source of water other than the public supply for their irrigation (e.g. accumulated rainwater from surrounding surfaces or the use of grey water). Subsidy eligibility requirements for a green roof include:

- The minimum height of the vegetation layer must be $\geq$ 8 cm;
- Vegetation layer must be formed using the proper green roof substrate for the roof type;
- At least 5 sustainable plant species must be present;
- The applicant is in charge of the green roof's ongoing maintenance;
- For the whole 10-year sustainability period, at least two-thirds of the green roof area must be covered by vegetation in excellent condition;
- Green roofs must be designed in accordance with the Czech Green Roof Association's Standards for the Construction, Installation, and Maintenance of Green Roofs.

Portugal

The Portuguese government established the Environmental Fund in 2020, which provides funding for the building of vertical gardens and green roofs. Individuals who own existing and occupied residential buildings, single-family buildings, autonomous fractions in multi-family buildings, or multi-family buildings, built by the end of 2006, are eligible. Green roofs must be installed in accordance with the guidelines outlined in the Portuguese National Association for Green Roofs' technical guide for the design, construction, and maintenance of green roofs (ANCV).

ANCV is NGO-Non-Governmental Organization, which aims to promote green infrastructures in cities, especially those that can be installed in buildings (new or pre-existing) such as green roofs, highlighting their enormous importance, and the numerous contributions they can give to the possibility to create healthy, sustainable, biodiverse and resilient urban territories. In its mission, social bodies from different activities promote collaboration between companies, municipalities, and national and foreign research groups.

The first Portuguese municipality to establish a financial incentive for installing green roofs and walls was Barreiro. The municipality, which became a member of ANCV, was concerned to include in this document a set of requirements that may help to improve environmental performance.

3.8 Urban heat island effect

3.8.1 Urban heat island effect in Prague

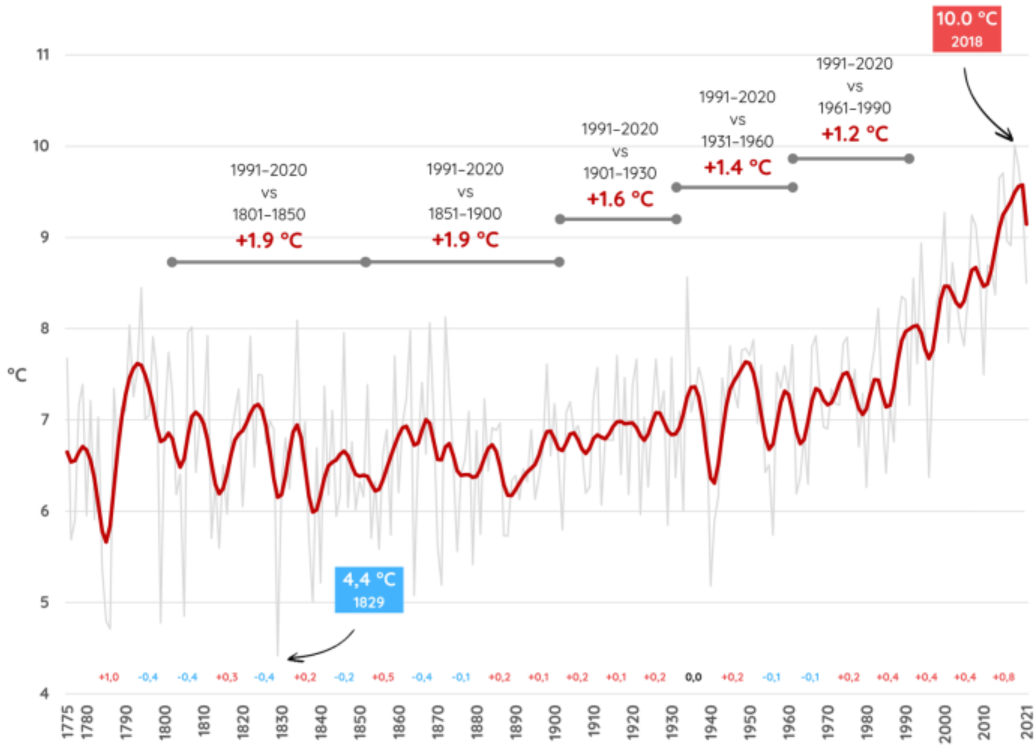


Figure 12. Mean annual air temperature in the Czech Republic between 1775-2021
Source: Global Research Institute CAS

According to measurements from the main meteorological station located in Klementinum which has the longest record of observation in the Czech Republic Prague's climate has changed over the past 200 years. Due to its central location of the station, it is affected by the UHI effect. The station has recorded an increase in the average air temperature between 1775 and 2021, shown in Figure 12, as a result of the city's growing urbanization, with rapid warming documented during the 1980s. The warmest year to date was 2018.

Table 7. Annual temperature from 1961-2020

Characteristic	1961–1990	1971–2000	1981–2010	1991-2020
Annual mean air temperature	+10.0 °C	+10.4 °C	+10.8 °C	+11.3 °C
Mean air temperature in January	-0.2 °C	+0.7 °C	+0.9 °C	+1.6 °C
Mean air temperature in July	+19.7 °C	+20.1 °C	+20.8 °C	+21.5 °C
Annual mean total precipitation	470.3mm	457.8mm	458.6mm	453.9mm

Source: https://www.chmi.cz/historicka-data/pocasi/praha-klementinum?l=en

According to data on the average annual air temperature recorded at the Klementinum station from the period 1775 to 2021, there was an increase in temperature at the end of the 18th century, which was followed by a reduction in the first half of the 19th century and since the second half the temperature has been gradually rising. .

As a result of built-up areas, a limited amount of green areas, and increasing population density, metropolitan areas became vulnerable and suffer from the UHI effect (Fig.13). In Figure 13, maximum temperature changes (T_{max}) are mostly greater than changes in minimum temperatures (T_{min}).

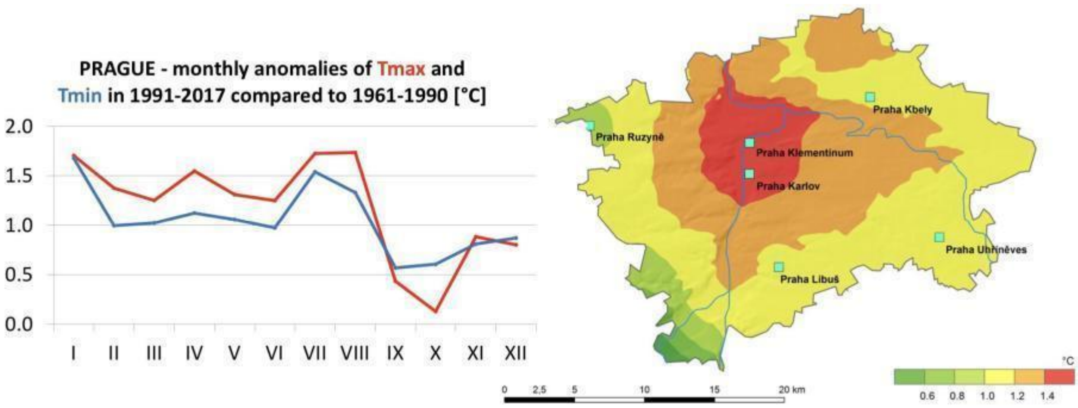


Figure 13. Monthly anomalies in Prague
Source: Global Change Research Institute

The increase in Tmax is similar across all stations in Prague (not shown), but the increase in T_{min} is occurs primarily in the city center, exacerbating the UHI effect in the city. Michal Zak from the Czech Hydrometeorological Institute states that Prague's annual average temperature is 2.5 °C higher compared to the countryside nearby, and in some cases, the difference in temperatures between urban and rural areas can reach 10 °C.

The number of tropical days, or days with temperatures above 30 °C, has increased dramatically in recent years, as has the number of tropical nights when temperature does not drop below 20 °C. However, this pattern is expected to continue in the future. According to estimations by experts from the Academy of Sciences using the improved ALADIN meteorological model, the number of tropical days is predicted to increase by 50% in the near future 2021-2050 (Prazakova, 2016). These heat waves have already had a negative impact on human health as well as the economy, and they could increase the number of fires.

On June 18, 2022, ECOSTRESS sensor from NASA aboard the International Space Station measured land surface temperature around Prague. The hottest surfaces are obvious, however the cooling impact of parks and plants is visible, shown in Figure 14. This image provides geographic information to mitigate the UHI effect in the future through better planning.

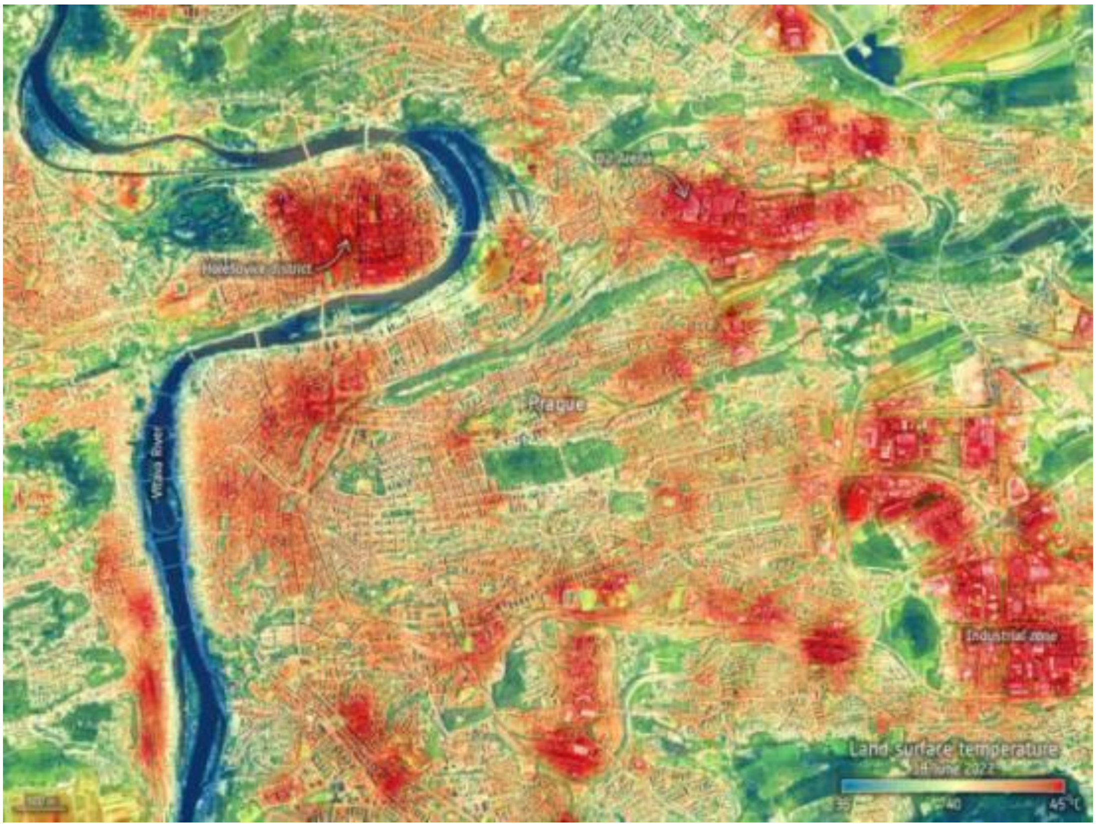


Figure 14. Map of LST in Prague 18 June 2022
Source: NASA/JPL-Caltech

Future development scenarios indicate that citizens will become more vulnerable, especially in the downtown area of Prague (Praha 1, 2, 3, 4, 7, 10, and 11 city districts).

Moreover, scientists predict that by 2050 the average air temperature in the Czech Republic would rise by 1.5 °C and 3 °C by the end of the century.

3.8.2 Urban heat island effect in Lisbon

Lisbon is located near the western coast of Portugal, on the bank of the Tagus estuary, which is 15 km wide eastwards from Lisbon. The city covers 84 km^2, has circa 600,000 inhabitants, and is the center of a metropolitan area with nearly 2.5 million people. The city's topography (including the city center) is hilly with steep slopes and altitudinal variations of over 100 m. Northwards, a plateau slopes gently to the North, and to the west the Monsanto Hill – a forested area – reaches 200 m. The old city center lies near the river and the highest buildings are not concentrated here, but rather on its northern and north-western fringes. Lisbon's climate is Mediterranean with mild and rainy winters and hot dry summers (Alcoforado, 1992).

Lisbon is a medium-sized city regularly affected by heatwaves with maximum temperatures >35 °C and is expected to grow and densify during this century.

UHI is more intense in summer in Lisbon (maximum hourly averages up to 6.3ºC) than in winter (up to 3.8ºC), and more intense during the night than during the day. In Lisbon, its causes are not only due to the modification of energy balance in urban areas but also to the shelter effect from the prevailing and cold/cool North winds, due to the topography and the buildings.

According to Andrade (2003), the urban heat island effect occurs normally in the south, with undefined boundaries. This thermal pattern is also influenced in Lisbon by a set of nonurban features, such as the relief and the proximity to the Tagus estuary and to the ocean. In Lisbon, the wind blows predominantly from the north and northwest throughout the year. Western and southwestern as well as eastern and northeastern winds are also frequent in the cold season. However, for 45% of the spring and summer days, a relatively strong north wind (the Nortada) dominates. This natural north ventilation is very important because it promotes pollutant dispersion and reduces natural and anthropogenic heat loads. However, in the last 20/30 years, Lisbon has been growing towards the north; the buildings create an enormous barrier to the north wind and environmental problems for the south of the city can occur.

4. Methodology

This chapter will provide a description of the methodology used as well as an explanation of why it was chosen. As previously mentioned, the goal of the research is to investigate the efficiency of green roofs as a supplement to the green spaces of the city to mitigate the negative impact of the increase of the maximum temperature due to climate change.

Fig.15 below shows a flow chart detailing the methodology followed. The proposed methodology is applied to green roofs located in Prague and additionally, a green roof site in Lisbon was observed, two cities with different climate conditions, density variations, and geometrical and typological characteristics. The effects of the built-up environment, the presence of vegetation and green roofs, and the urban morphology of the two cities have been assessed considering the land surface temperature distribution. The methodology may be considered as a base to estimate the potential of green roofs. Further research with a great number of green roofs is needed in the future in order to better quantify this effect.

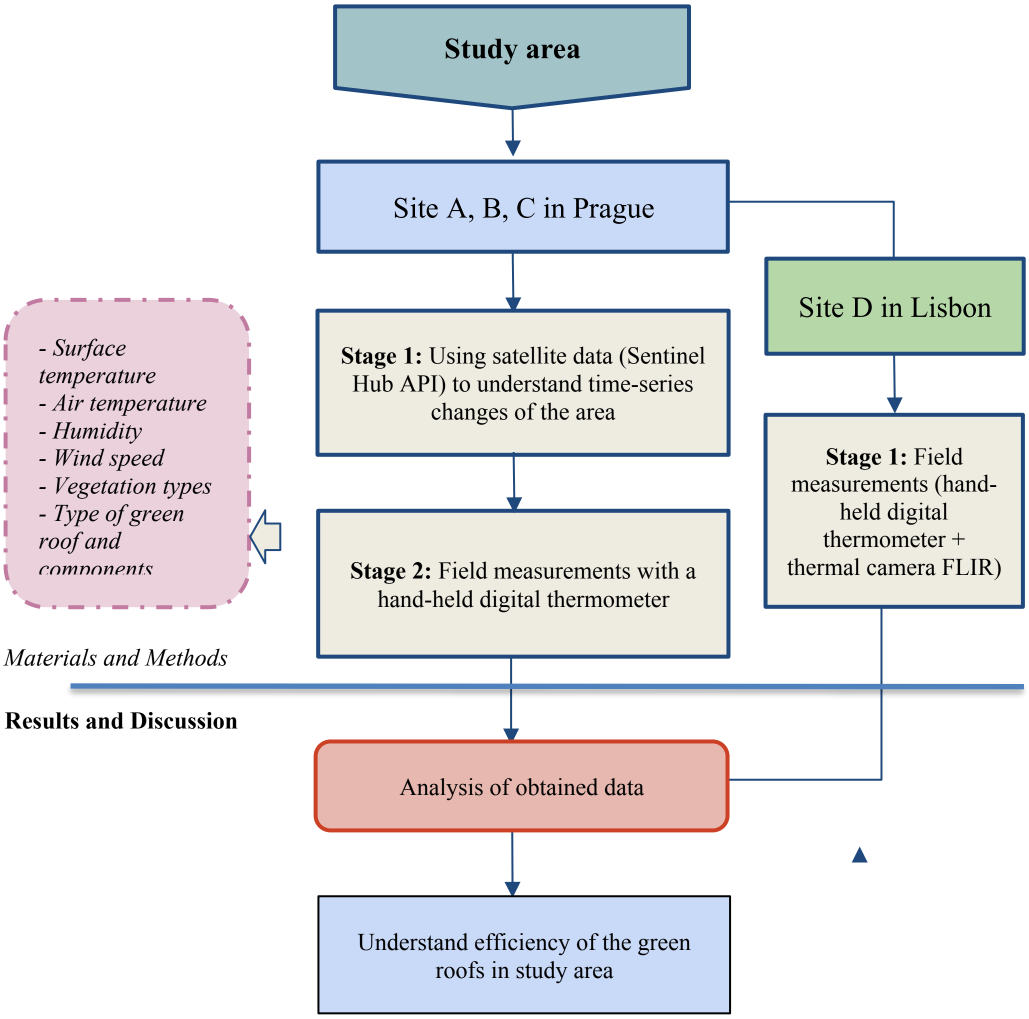


Figure 15. Overall research flow chart (Sites A, B, C, D)
Source: Author

The purpose of the research will be achieved through different methods of approach over a long-term investigation. The first part of the research involves satellite images, in order to understand time-series changes in vegetation cover in the study area. NDVI images were obtained from January to December 2022 period using satellite data. Current missions to monitor Earth are being carried out by NASA and ESA using sensors that can detect red and near-infrared reflectance. Sentinel-2 (Sentinel Hub API), an ESA satellite, was chosen for this investigation because it has a spatial resolution of 10x10m, which is higher than NASA's Landsat-8 mission (30x30m).

The initial analysis is based on measuring the land surface temperature (LST) of green roofs with a hand-held digital thermometer (YM-6688, emissivity: 0.95) shown in Fig.16,17. For this model, the temperature ranged from 0 to 40 °C and the temperature accuracy is ±1.0% with high accuracy, a low error value of 0.2 °C. A hand-held thermometer was chosen as a more accurate measure and lower-cost instrument solution for conducting the fieldwork.

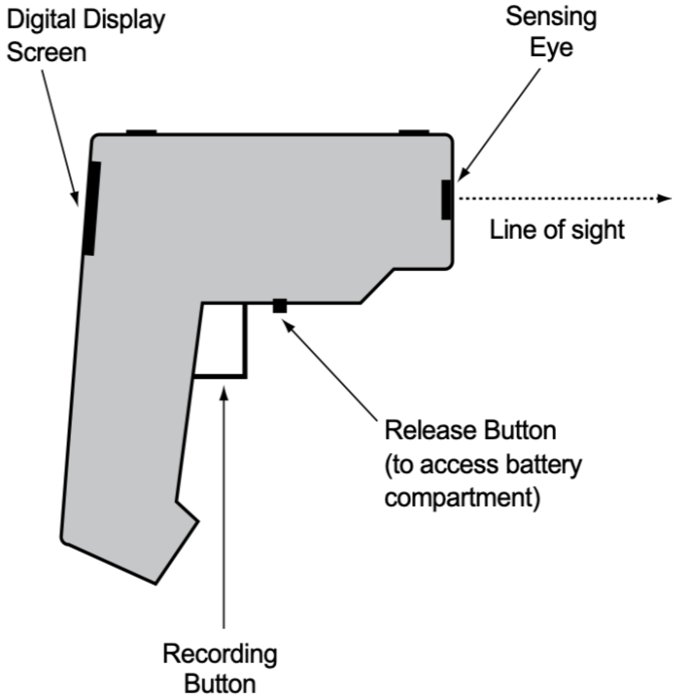


Figure 16. Hand-held digital thermometer
Source: GLOBE® 2014

The calibration of the hand-held digital thermometer is checked once a month. According to the Global Learning and Observations to Benefit the Environment (GLOBE) Program, to perform a check, an ice water solution in a bowl was prepared. The digital thermometer was pointed directly at the water with the end of the instrument approximately 5 cm away from the water; then press the recording button. If the thermometer accurately reads, the ice water measurement will read 0 ˚C. Note, the thermometer reading must be between -2 and 2 ˚C, otherwise, the thermometer is not calibrated.

The instrument is pointed at the ground to take the surface temperature. Daytime air temperature changes and other weather data such as wind speed, humidity, dew point, and UV was recorded using an accurate weather forecasts application (Clime: NOAA

Weather Radar Live). LST is one of the crucial factors that are important in this study of climate change and the UHI phenomenon in Prague.

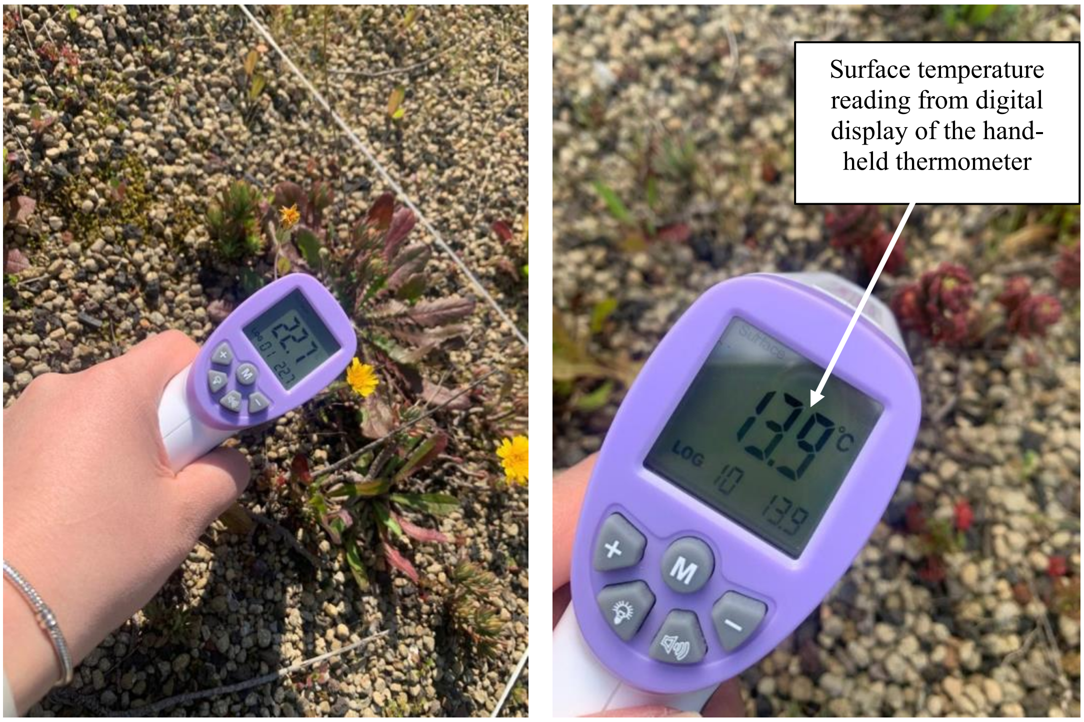


Figure 17. Hand-held digital thermometer (YM-6688)
Source: Author

Field data collection started in December 2021 till June 2022 once a month in the Prague study location by selecting a sunny day or at least partly cloudy. Temperatures were collected during the warmest time of day, between 13:00 p.m. to 15:00 p.m. in winter and 12:00 p.m. to 16:00 p.m. in spring. Fieldwork was finished by June due to being naturally overgrown creating a dense vegetation cover on two green roofs out of three that made it impractical to walk through the roof space without damaging and squashing vegetation (Fig.18).

Figure 18. Condition of the observation fields on May 31
Source: Author

As a result, data was collected in the winter-spring season, despite the fact that the winter LST was substantially lower than the summer LST. The period of time from June to November 2022 was devoted to the analysis of the collected data.

Additional field data collection continued in Lisbon from December 2022 to February 2023. A thermal camera (Fig.19) was used in the study area in addition to a hand-held digital thermometer. The UAV TIR LST images were captured with a FLIR B425 camera shown in Fig.19. These results may depend on various factors, such as the field of view and performance of the thermal camera, as well as the weather and atmospheric conditions

Figure 19. FLIR B425 camera
Source: https://www.teledynedalsa.com

4.1 Study area in Prague

Prague is the capital and the largest city of the Czech Republic. The city is located on the Vltava River in the northwest of the country with a population of around 1.32 million (Official Census, 2023) in an area of 496 km^2. Prague has an oceanic continental climate with humid continental influences. Two distinct air masses pass over the city and exchange rapidly, resulting in varied weather. Erosive action has formed a rugged topography with the lowest point at Suchdol is 177m above sea level and the highest at Telecek Peak is 399m above the sea. The average annual air temperature is 9.8 °C with the lowest temperature in January and the highest in July. The average rainfall in Prague is 525mm. The predominant average hourly wind direction is from the west throughout the year.

Figure 20. Aerial map of Prague
Source: mapy.cz

This study was conducted in an area of the Czech University of Life Sciences (CULS) Campus (Fig.20). CULS (50° 7' 48.792" N, 14° 22' 24.9096" E) is located on the outskirts of Prague and it is the center of research and development in such fields as agrobiology, forestry and wood sciences, environmental sciences, tropical agrisciences, engineering, economics, and management.

The University creates and shares knowledge to promote eco-friendly and sustainable programs and policies. For instance, not many educational institutions have adopted green policies and sustainability. In this sense, CULS is the most sustainable university in the Czech Republic**.** Campus sites offer many green technologies that mitigate adverse impacts on the environment and contribute to a better climate. The result reflects the green roofs, covered with plants and small trees, green walls, meadows, parks, ponds, and water filtration devices implemented by the efforts of the academic community.

The campus of the University is a good case study and the potential use of green roofs will be studied there. The study area was chosen for several reasons: 1) being a university property, 2) having different types of green roofs in the same area, 3) easy access, and 4) the possibility to collaborate with others.

In this study, a total of three sites with different types of green roofs were chosen to observe and explore the changes in surface temperatures that occur due to the differences between these sites: Aula Hall, Pavilion of Tropical AgriSciences, and High-tech Educational Pavilion (Figure 21).

Figure 21. a) Aerial view of the CZU campus with green roofs locations
Source: google.map

Site A. Aula Hall

The green roof of Site A designed to give the impression of a stylized prairie meadow and construction was finished in 2019-2020 (Fig.22). According to the designers of the project, the green roof and the selection of specific types of plants were based on the desire to harmonize with the surrounding landscape of the area.

Site A has a relatively small area of 34.8x11.4m compared to other sites. It was chosen because it is an extensive green roof, and the rooftop is fully covered with vegetation. A total of 15,522 plants were chosen for planting on an area of 397 m^2, and the flowering alternates throughout the year. The emphasis is mainly on the pre-spring,

spring, and summer seasons. Examples of plants in spring are shown in Fig.23. In autumn, various types of grasses are fully used.

The green roof of Site A is irrigated by a rainwater retention system that uses the properties of the water storage and water retention layer. Excess rainwater is directed to storage tanks, from which it is used to flush toilets in the building.

Figure 22. Aula green roof
Source: https://gaudeamus.cz/seznam-skol/detail-skoly/schoolHash:b560adc2e2f8bff11e62428576eac8e9

Figure 23. Vegetation growing on the rooftop
Source: Author

The construction of the green roof consists of the following layers (from the top to the bottom):

a) Vegetation cover
b) Growing medium layer, extensive substrate for multi-layer vegetation roofs: 100-320 mm, mulch - round aggregate 30 mm
c) Secondary drainage layer, expanded clay: 30 mm
d) Filter layer – filter fabric (type 105)
e) Hydro accumulation and drainage layer – stud foil (drainage and waterproof panel FNK 60 UK-BO) – 60 mm

f) Protective layer – separation and water accumulation fabric geotextile RMS 500 (500 g/m2)
g) Waterproofing layer – PVC roofing film BauderTHERMOPLAN T20

Site B. Pavilion of Tropical AgriSciences

The operation of the new building of the Faculty of Tropical AgriSciences started at the end of September 2020. The green roof with an area of 590 m^2 (Fig.24). The University's own botanists maintain this green roof.

Figure 24. Green roof
Source: https://www.ftz.czu.cz/cs/r-8683-aktuality-home/praha-jako-centrum-evropy-pro-vzdelavani-a-vyzkum-v-oblasti-.html

Site B, unlike site A, is covered with a combination of gravel and crushed stones on the top layer and partly with short vegetation, mostly succulents, and sedum, which are drought-resistant plants and store water in the leaves, stems, or roots, and require low maintenance. Some examples of vegetation are shown in Fig.25. The rooftop is walkable and has seating areas with benches.

Rainwater is collected from the surrounding land and the roof through an infiltration system behind the building and drained into storage tanks having a volume of 60 m^2. If the storage tanks are full, an emergency overflow leads to an infiltration gallery, where the excess water seeps into the ground through 4 large-volume boreholes filled with coarse gravel. After being purified and mixed with tap water, the rainwater is used to flush toilets, as well as to irrigate green roofs and creepers. In the future, the creepers will cover the metal structure on the south side of the building and cool the facade.

Figure 25. Vegetation growing on the rooftop
Source: Author

Site C. High-tech Educational Pavilion

In the autumn of 2019, the Faculty of Forestry and Wood Sciences (FFWS) opened a new building - the High-tech Educational Pavilion (Fig.26) with the most modern technologies. Site C differs from the other two by the presence of trees planted on one side and a meadow on the other.

A roof garden or intensive green roof with an area of 880 m^2 has a thicker profile that enables small trees and a variety of other plants to grow in the soil, following vegetation was chosen to plant: thermophilous grassland (consisting of grasses, legumes, and forbs) is cultivated in the southern half of the green roof, the northern half of the green roof is covered by thermophilous woody species (combination of shrubs and trees) with a low layer of grassland.

Roof construction:

- 40 cm thick layer of specialized substrate mimicking shallow and calcium-rich soils (soil type: rendzina). The substrate name is VULKAPLUS EXTENSIV (mixture of lava, pumice, and organic material; contains augite, olivine, limonite, magnetite, and biotite), a German brand (producer: VULKATEC), with physical features as follows: granularity 0-12mm, dry volume weight 0.95t/m^3, water-saturated volume weight 1.5t/m^3, maximum water-holding capacity 35-45% of weight, volumetric concretion (shrinkage ratio) 15-20%, weight load on the roof ~600kg/m^2.
- Tree individuals are anchored into a welded wire mesh sunken within the substrate layer.

Maintenance: grassland is regularly mown just after the seeding of the majority of grasses and forbs. Irrigation by a dropping system with water being distributed via a superficial hosepipe, both grassland and trees, with watering intensity ~5% of max. intensity during the summer months.

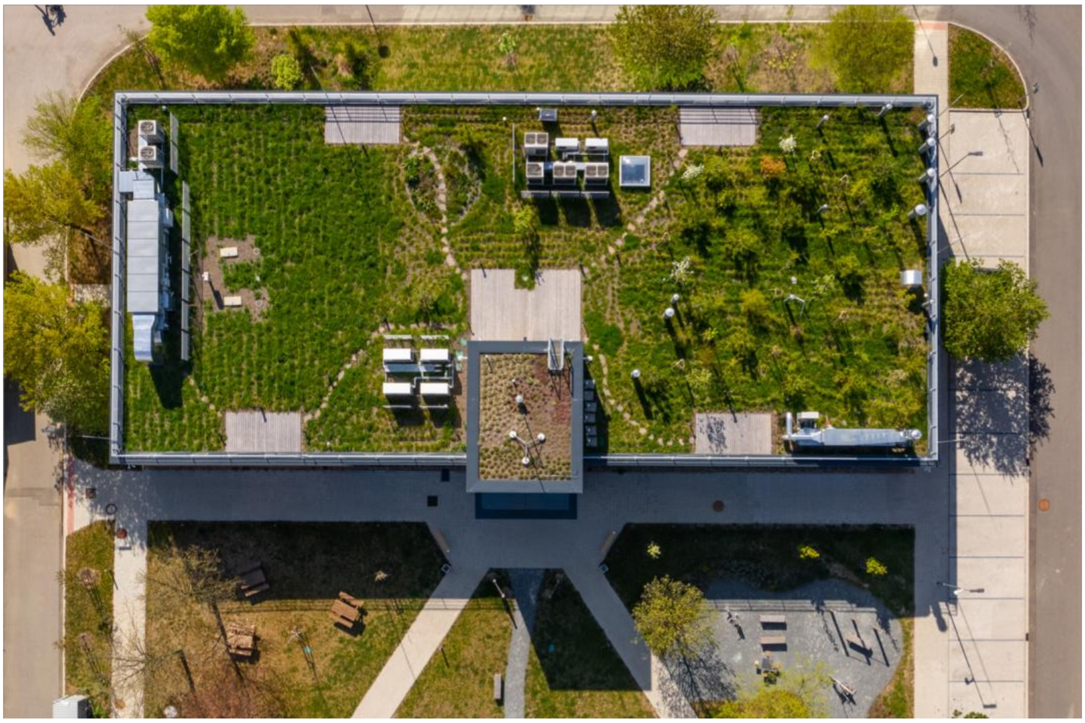


Figure 26. Aerial view of the green roof of the High-tech Educational Pavilion
Source: internet

4.1.1 Analysing NDVI to extract vegetation cover along the year

A widely known vegetation index “Normalized Difference Vegetation Index” (NDVI) was used in this study. The goal of using NDVI was to obtain data about vegetation cover for 2022 from remote sensing. Moreover, NDVI is beneficial since it requires only two spectral bands from a satellite with a light sensor. This index is based on the idea that green, healthy vegetation reflects near-infrared light and absorbs red light as a result of photosynthesis.

NDVI measures the ratio of the reflective difference in the red and near-infrared portions of the spectrum to the sum of red and near-infrared reflectance. According to Tucker (1979), the index is calculated using the formula below:

$$NDVI = (NIR - Red) / (NIR + Red),$$

where “NIR” means the Near-Infrared (Band 8) and “Red” means the red (Band 4).

Sentinel-2 uses these bands B$ and B8 as a result of the sensor on the satellite to calculate NDVI value:

$$NDVI = (B8 - B4) / (B8 + B4)$$

The NDVI values vary from -1 to +1 (Table 8), where negative values refer to surfaces other than vegetation areas, such as snow, water, or clouds (Jones and Vaughan, 2010). For urban areas, near-infrared and red have the same reflectance, and therefore NDVI value is close to 0 (Jones and Vaughan, 2010). Plant formations have positive NDVI values, generally between 0.1 and 0.7, and the highest values correspond to dense green covers (Jones and Vaughan, 2010).

For NDVI images were used twelve Sentinel-2 scenes from January 2022 to December (Table 8). Areas highlighted in green are green roofs and in blue are buildings without vegetation shown in NDVI images of the University Campus (Fig.27).

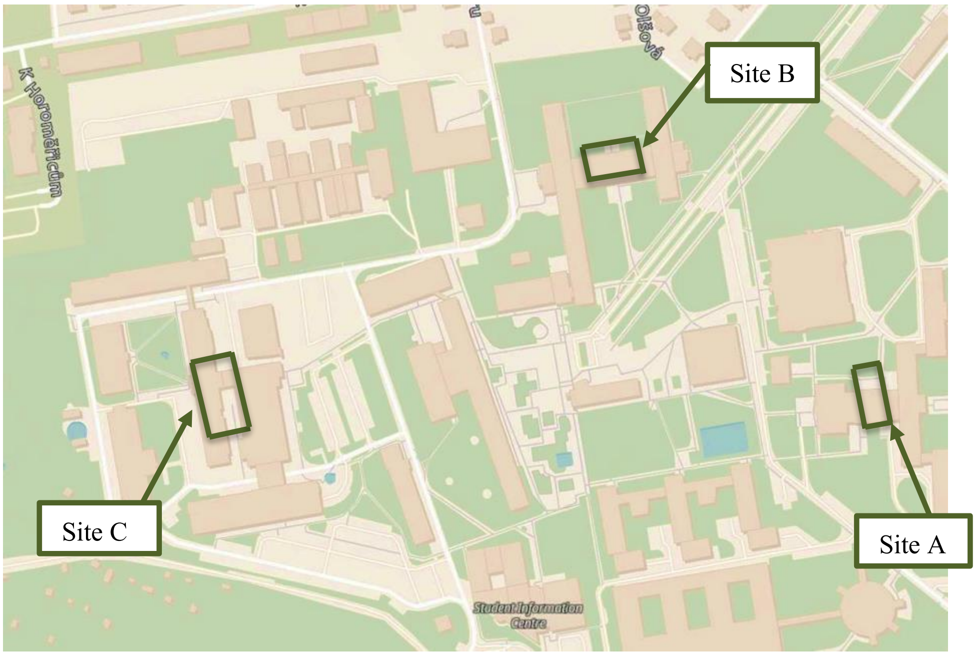
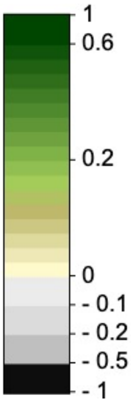
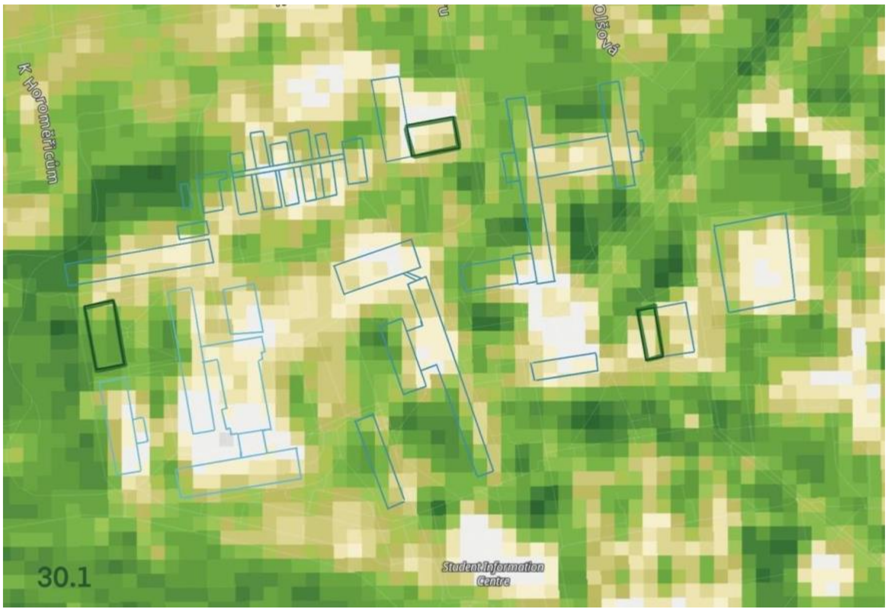
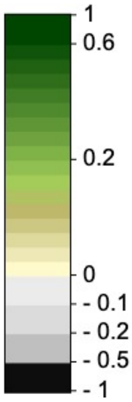
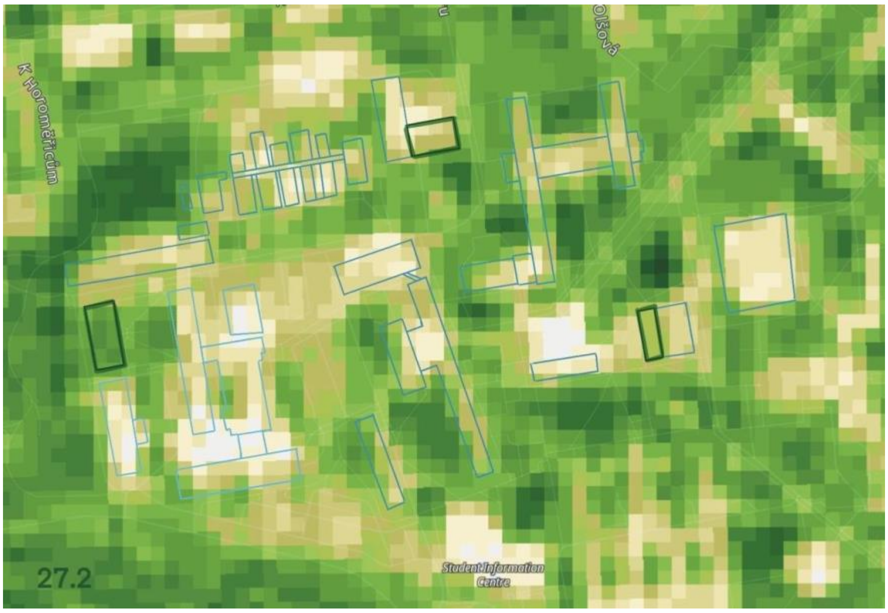
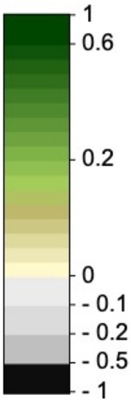


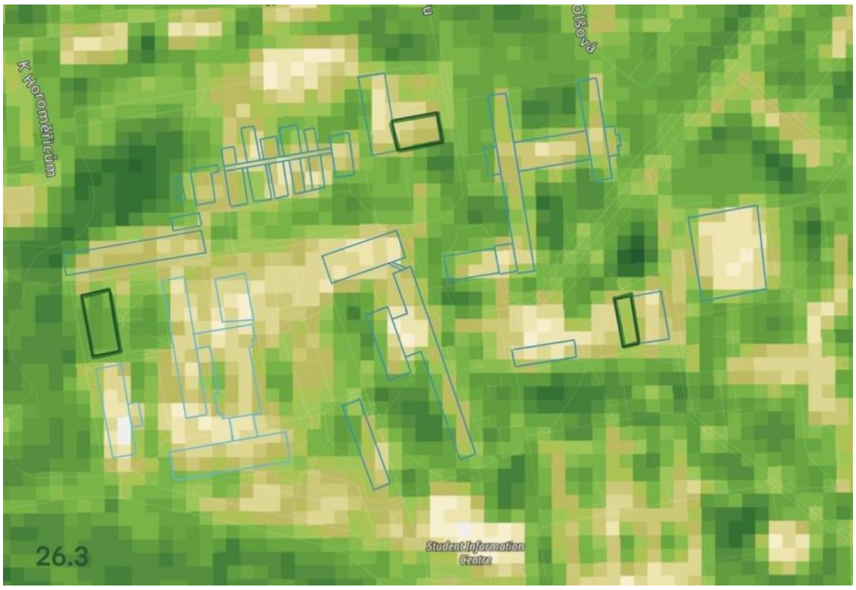
Figure 27. Map of University campus with green roofs
Source: https://www.sentinel-hub.com/

Table 8. NDVI images for study area along the area 2022

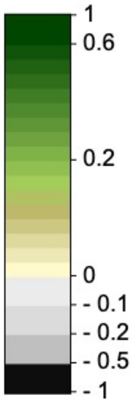
Month	Images
January 2022  	
February 2022  	

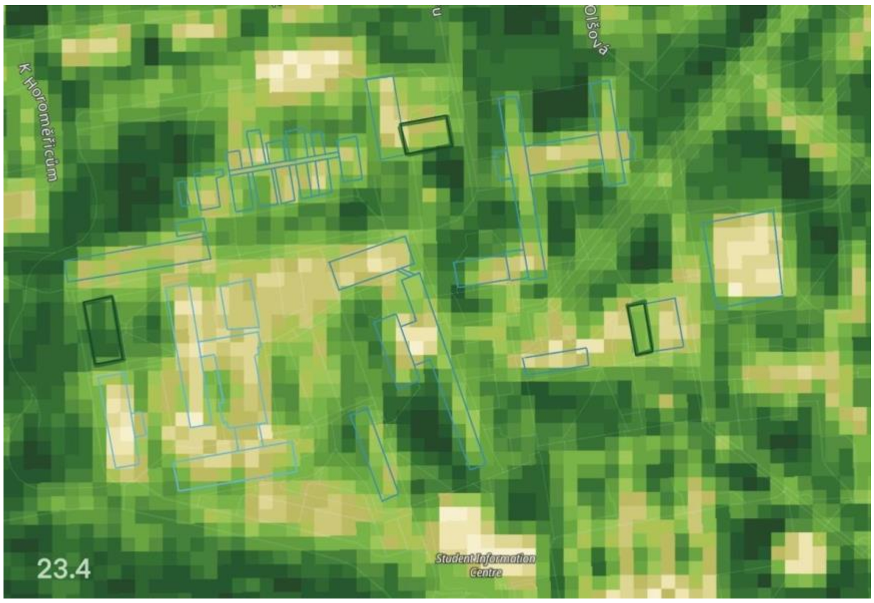
March
2022



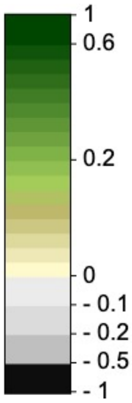


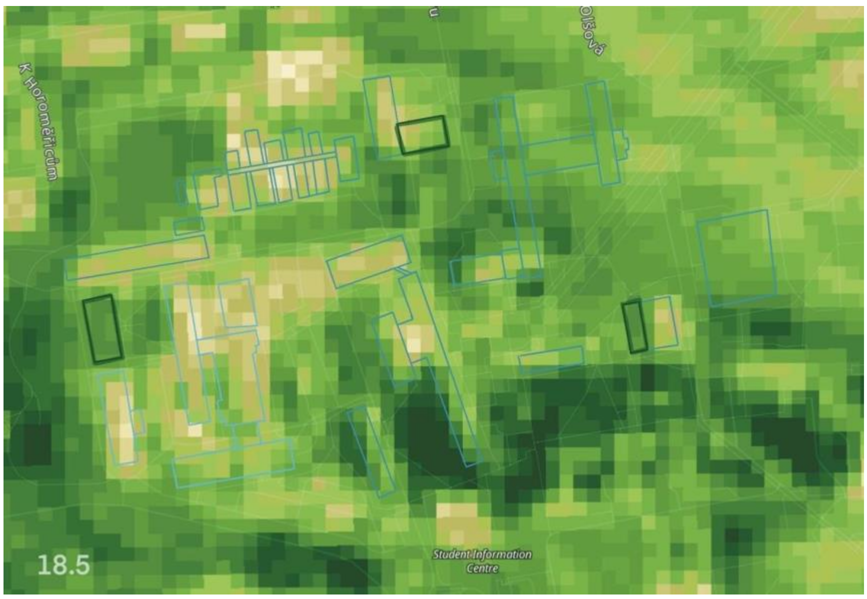
April
2022



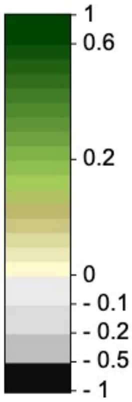


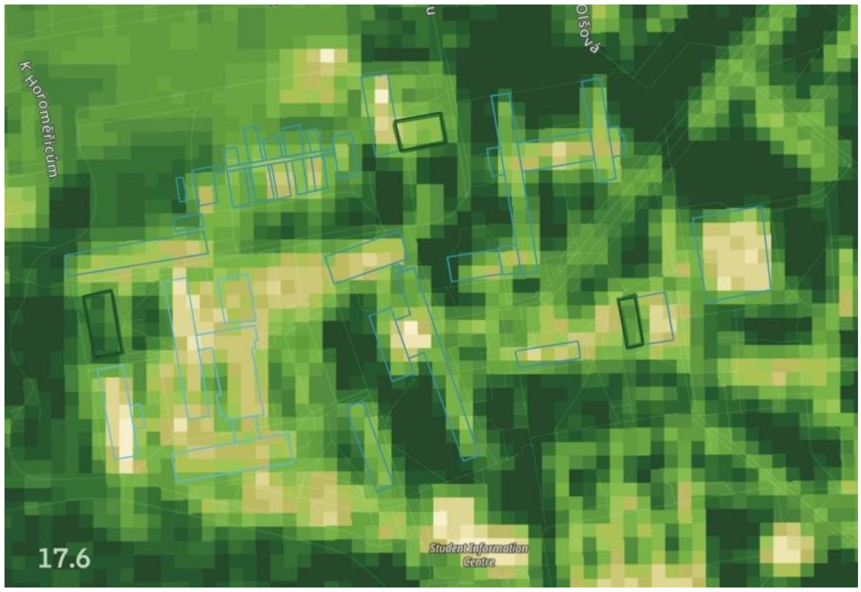
May
2022



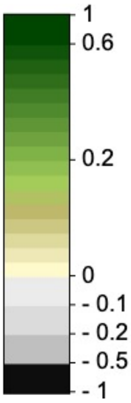


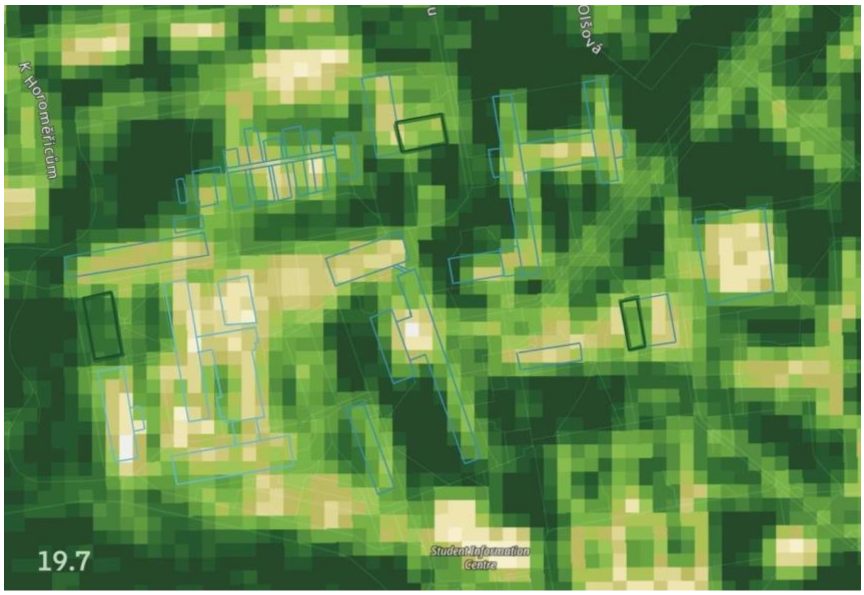
June
2022





July
2022





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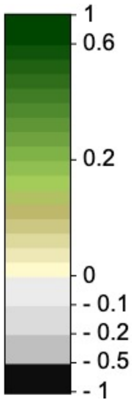

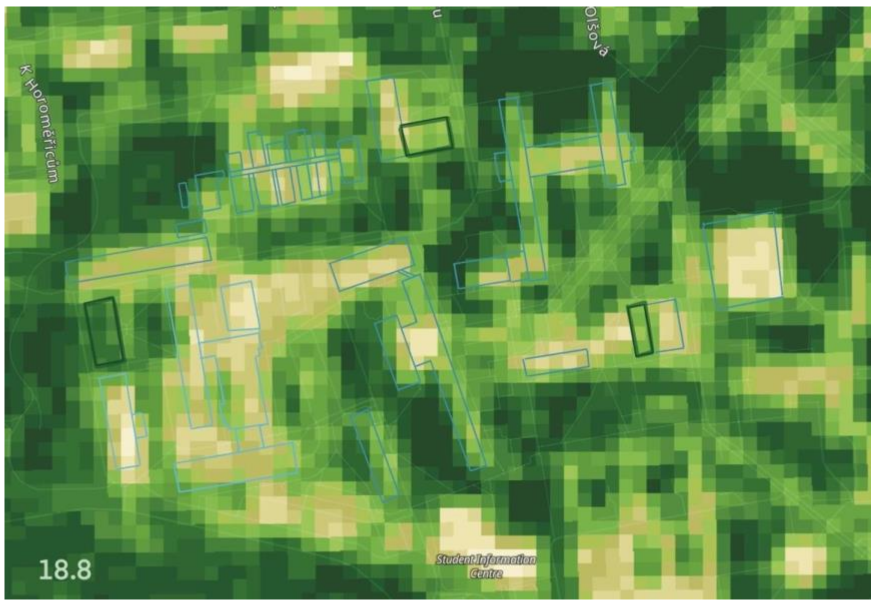

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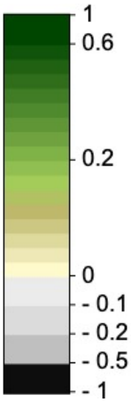
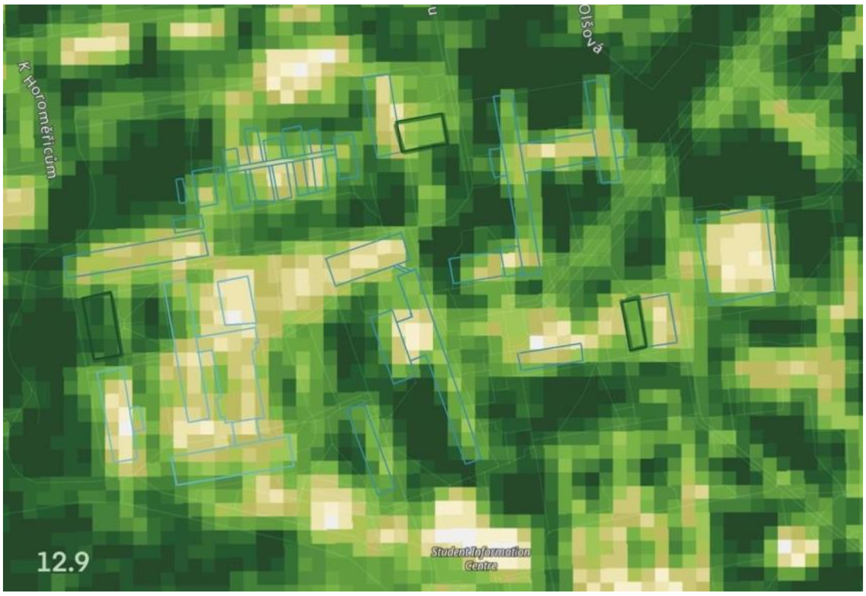
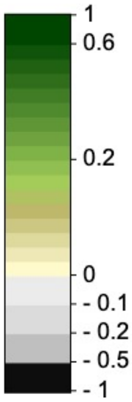
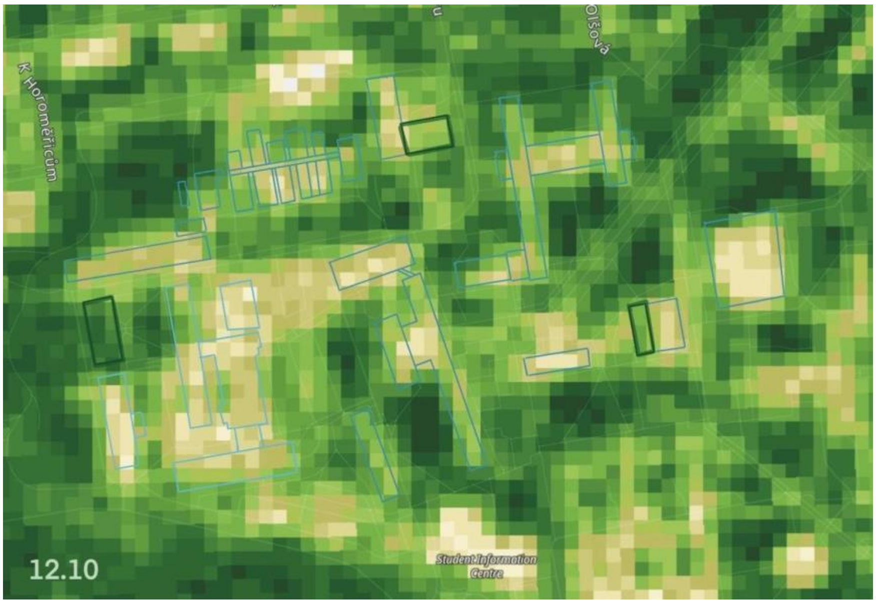


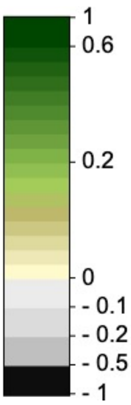


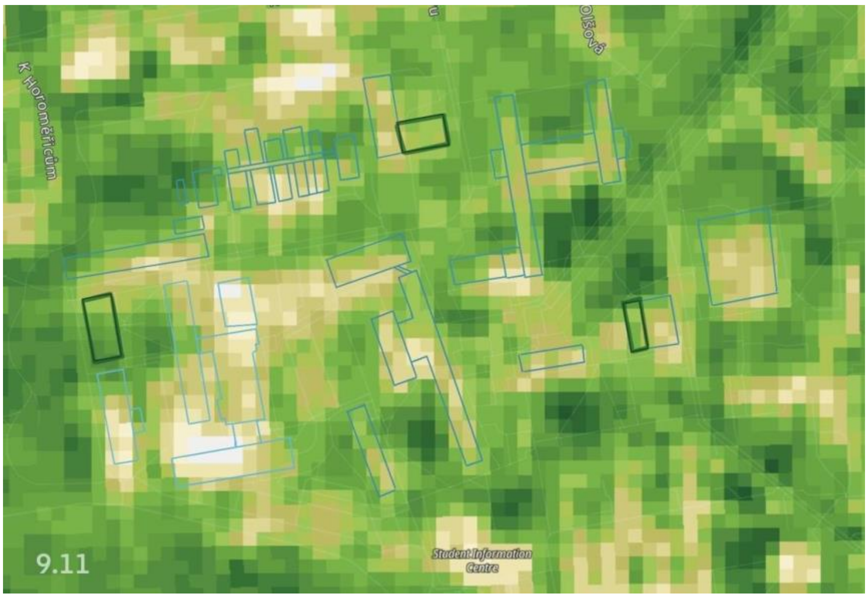
<u>October</u>
2022

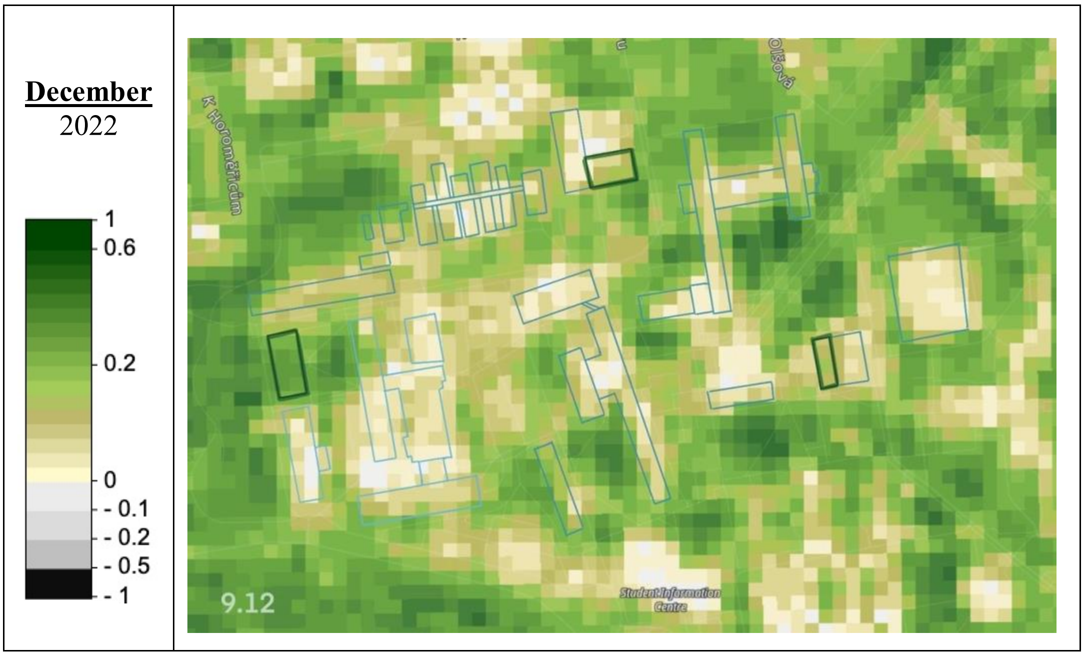




<u>November</u>
2022







Source: https://www.sentinel-hub.com/

4.1.2 Field Measurements

The whole area of each green roof is divided into squares, taking into consideration the type of green roof, size, and vegetation cover in the study area. LST was measured at two levels: a 5 cm height and a 2 m height above the surface using a hand-held digital thermometer (YM-6688). The field measurement was performed by one person and the temperature was measured in Celsius and recorded on a touchscreen tablet at the same time. At each measurement point, measurement was performed two times and the average value was calculated to determine the LST of the point. Weather information of the day is recorded as well, including wind speed, air temperature, heat index, dew point, and humidity.

The year 2022 was an above-normal temperature in the Czech Republic and the average annual air temperature was 9.2°C. According to the Czech Hydrometeorological Institute, 2022 was recorded as the fifth warmest in the period since 1961. It was warmer in 2014 and 2015 (9.4 °C), 2019 (9.5 °C), and 2018 (9.6°C).

The warmest months included June with an average air temperature of 18.7 °C (deviation +2.2 °C) and October with an average temperature of 10.7 °C (deviation +2.5 °C). The months of January, February, May, and August were also among the above-normal temperatures. April was very cold with an average temperature of 6.4 °C (deviation -2.1 °C). The following months were rated as normal in temperature.

In terms of precipitation, the year 2022 was normal in the Czech Republic. The preliminary mean annual precipitation of 629 mm represents 92% of 1991–2020 normal.

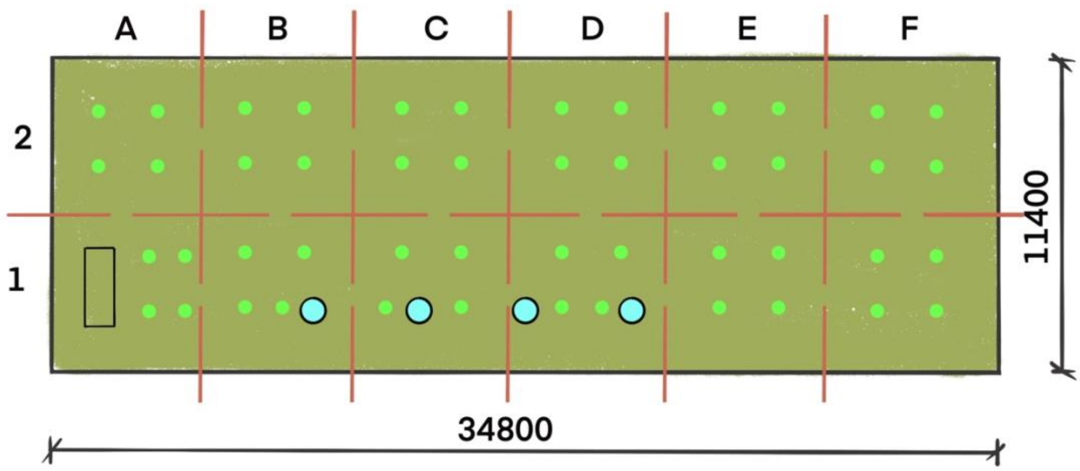
Sites A, B, C

A total of 48 squares (Site A – 12, Site B – 15, Site C - 21) are shown below in Figure 27, and one square approximately equals 6.0x6.0m. A total of 186 points were selected for the field measurements, in each square 4 points.

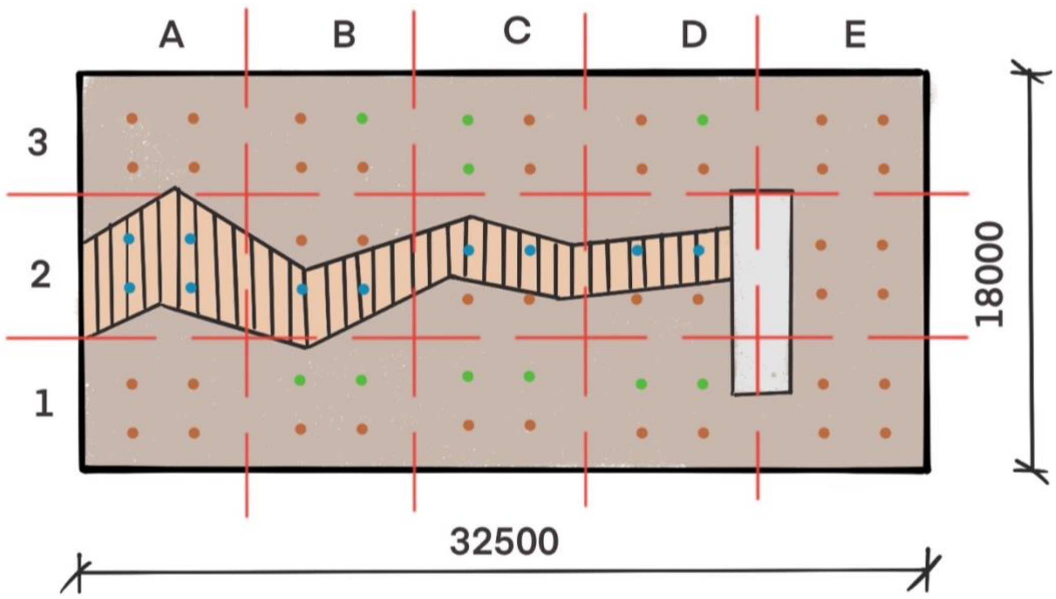
LST on green roofs was measured between 12:00 – 16:00 h local time. The measurement was completed within 30 - 45 min on each site to minimize changes in LST with time.

During the fieldwork different surfaces on the green roofs have been measured based on their land cover. Site A has a total of two land covers (vegetation cover, soil with small stone particles on the top), Site B has a total of four land covers (vegetation cover, gravel mixture with stones on the top of soil, walkway surface), and Site C has a total of three (vegetation cover, soil, and walkway surface).

Site A



Site B



Site C

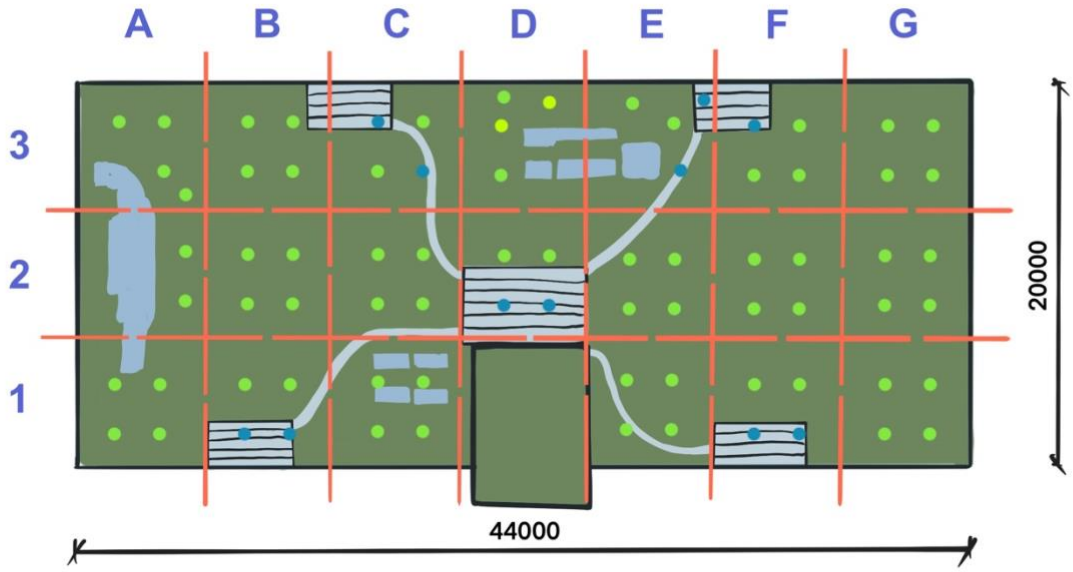


Figure 27. Green roofs: Site A, Site B, Site C
Green points – vegetation cover, brown points – gravel, stones,
blue points – walkway surfaces
Source: Author

4.4 Study area in Lisbon

Lisbon has a temperate climate, with a moderate winter and the hot season is the driest period of the year since precipitation concentrates between October and April. According to Alcoforado and Andrade, this type of climate (Köppen Csa) is modified by the rough relief and the proximity to the Tagus estuary and the Atlantic Ocean. These features, along with the latitudinal position, give the city a certain thermal amenity.

Due to the geographical distribution and special climatic conditions in the Mediterranean area, the development of green roof technology differs from the Czech ones. The period from October to December was devoted to finding a study area in Lisbon similar to the Prague study location. However, most of the green roofs had a large area located in museums, galleries, or were a part of public spaces, while others had a dense vegetation cover that didn't allow walking on it, or were pitched green roofs. or commercial buildings.

Site D

Site D (Fig.28) was selected due to the possibility to apply the proposed methodology. It is also an interesting case study to observe the condition of the green roof. Compared to the previous three green roofs in Prague, this roof is significantly smaller 10x10m and it was installed in 2013. This extensive green roof is located at the Faculty of Sciences of the University of Lisbon with a total area of 100m^2.

It is lightweight with a thin vegetative cover green roof (Fig.29) that is not suitable for constant use activities, only for maintenance. Four different species of the Sedum genus (Sedum/Petrosedum), a total of 1560 plants were planted. In the last few years, the green roof has not been irrigated due to technical issues which greatly affected the vegetation. In addition, native plants brought by the wind and birds started colonizing the roof (Fig.30).

Figure 28. Faculty of Sciences of the University of Lisbon
Source: Author

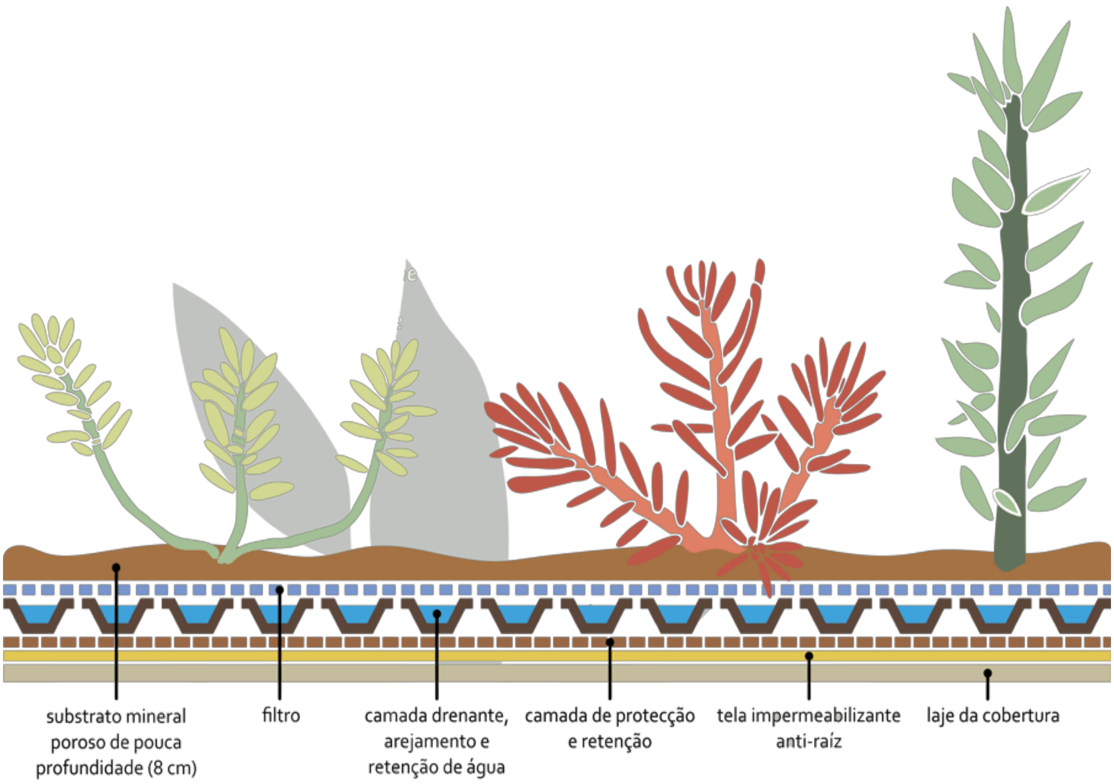


Figure 29. Different layers of the green roof structure
Source: https://ciencias.ulisboa.pt/en/green-roof

Figure 30. Vegetation growing on the rooftop
Source: Author

4.4.1 Field measurements

The whole area of the green roof is divided into 25 squares, and one square equals 2.0x2.0m. Due to the small size of the roof a total of 75 points were selected for the field measurements shown in Fig.31, in each square 3 points.

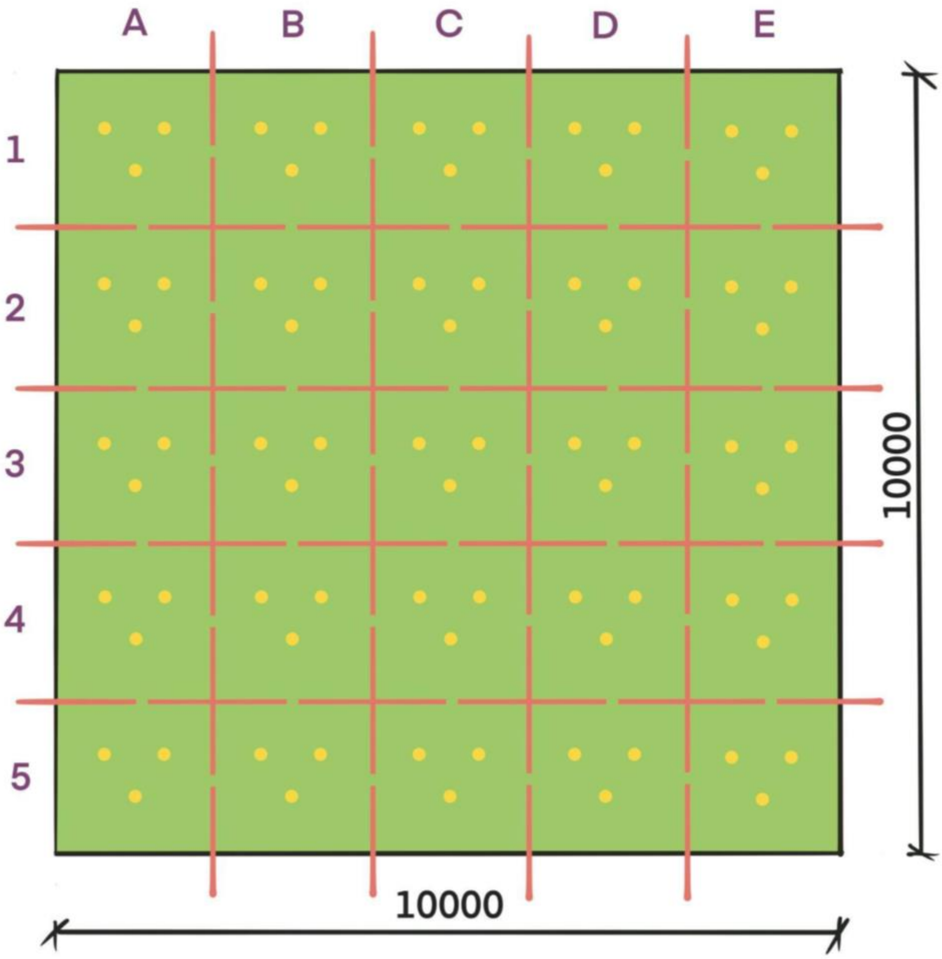


Figure 31. Site D with selected points
Source: Author

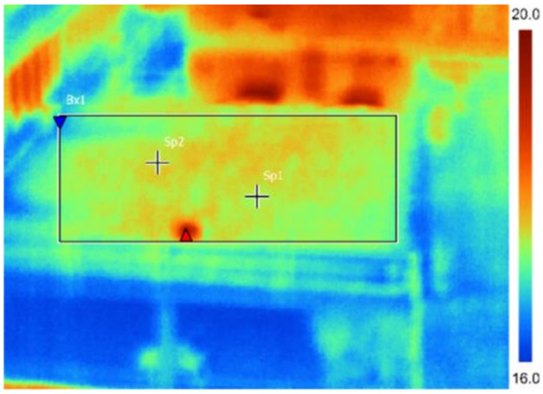
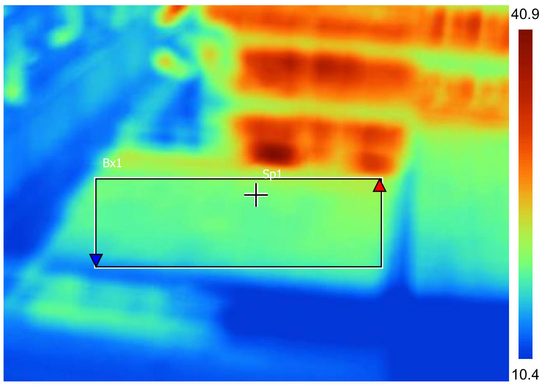
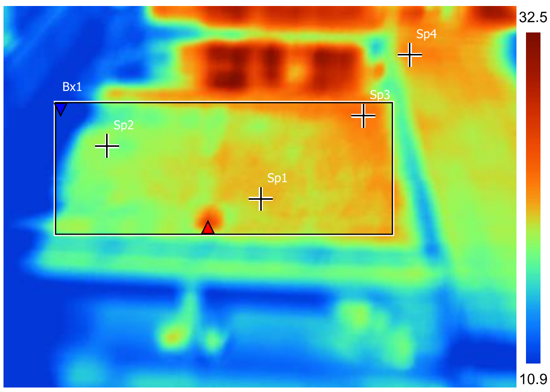
The on-site measurement of LST using a hand-held thermometer and thermal camera was carried out from December 2022 to February 2023 once a month choosing a sunny or partly cloudy day with no precipitation between 11:30 and 12:00 h local time when the influence of shadow was minimal due to the highest solar altitude.

TIR images were taken from the rooftop of another building (Fig.32). The measurements were completed within 45 min to minimize changes in LST with time. From the study area, climatic data was collected (wind speed, temperature, heat index, and humidity).

Figure 32. High-angle view from the rooftop of the faculty building
Source: Author

Data from thermal images were extracted using FLIR Builder Tools software, including maximum, minimum, and average surface temperatures for a selected area of green roof. Table 9 summarizes obtained weather data and LSTs which are measured in Celsius first using a hand-held thermometer and FLIR camera.

Table 9. Surface Temperature Data Sheet

Surface temperature measurement (°C) in December 21 / partly cloudy day					
11:30 a.m.					
Eq	**weather condition**	**T_{min1} T_{min2}**	**avg_1 avg_2**	**T_{max1} T_{max2}**	
thermometer	Temp.17°C Hum. 81.7% Wind 14 km/h UV index 1	15.5°C	17.4 °C	18.2°C	
		T_{min}	**avg**	**T_{max}**	
FLIR		16.4 °C	17.4 °C	19.4 °C	
January 12 / sunny day					
12:00 p.m.					
thermometer	Temp. 15°C Hum.75% Wind 7 km/h UV index 1	15.5 °C	21.6 °C	24.6 °C	
FLIR		14.2 °C	19.4 °C	24.1 °C	
February 7 / sunny day					
11:30 a.m.					
thermometer	Temp. 12°C Hum. 68% Wind 22km/h UV index 2	13 °C	18.0 °C	23.5 °C	
FLIR		10.9 °C	20.0 °C	26.4 °C	

5. Results

In this section, the difference between the LSTs of each green roof in Prague obtained from fieldwork by using a hand-held thermometer was compared. At different measurement points the same land cover types displayed different LSTs. Measuring LST at 2 m above the surface was far more accurate in comparison to 5 cm. Table 10 below summarizes the minimal, average, and maximum LSTs of three sites and weather information of the observation day.

Table 10. Surface Temperature Data Sheet

Month	**Surface temperature measurement (°C)**								
	Site A			**Site B**			**Site C**		
	T_{min}	**avg**	**T_{max}**	**T_{min}**	**avg**	**T_{max}**	**T_{min}**	**avg**	**T_{max}**
January (25)	**13:00**			**13:30**			**14:00**		
Partly cloudy day *Temp. 2-3°C* *Humidity 74%* *Wind 11 km/h* *Dew point 1°*	1.1 °C	2.1°C	3 °C	1.2 °C	2.3 °C	3.1 °C	0.9 °C	1.4 °C	2.1 °C
February (24)	**12:30**			**13:00**			**13:40**		
Sunny day *Temp. 9-11°C* *Humidity 51%* *Wind 11 km/h* *UV 1* *Dew point -2°*	7.2 °C	12.2°C	13.8 °C	8.5 °C	13.5°C	14.7 °C	5.2 °C	11.9°C	15.8 °C
March (29)	**15:00**			**16:00**			**16:30**		
Partly cloudy day *Temp. 12-14°C* *Humidity 56%* *Wind 7 km/h* *UV 2* *Dew point 4°*	12.4°C	17.6°C	19.3 °C	11.1°C	15.2°C	17.8 °C	10.4 °C	13.1°C	18.9 °C
April (26)	**13:30**			**15:00**			**12:30**		
Sunny day *Temp. 14-15°C* *Humidity 44%* *Wind 11 km/h* *UV 4* *Dew point 2°*	13.3°C	19.6°C	24.2 °C	11.9°C	18 °C	21.4 °C	12.3 °C	17.5°C	22.1 °C
May 31	**12:00**			**12:30**					
Sunny day *Temp. 19-21°C*	20.4°C	23.4°C	28.5 °C	24.1°C	27.6°C	33.5 °C	-	-	-

Humidity 36% *Wind 8 km/h* *UV 7* *Dew point 4º*										

During the investigation, it appears that surface temperatures would decrease on cloudy days due to the fact that clouds can block light and heat, and increase when the skies are clear and the sun is shining. The monthly measurements show the variance between surface temperatures throughout the time tested. Notice the air temperature is lower than the surface temperature during the warm months (March-May). There was a partly cloudy day in March and sunny in April with similar air temperatures, but different wind speeds, which directly affected the surface temperatures.

Through comparison, the temperature differences between the LSTs of green roofs were quantitatively analyzed, and it was found that the temperature of vegetation is significantly lower than the surface temperature on a sunny warm day. The highest temperature value of 36°C was recorded on Site A (May 31) which was small stones on the roof surface, the walkways on Site B had temperatures between 33 and 37.5 °C (May 31), a mixture of gravel with stone particles also on the Site B ranges between 31.1 and 33.5°C. On the other hand, the land cover type with the lowest LSTs was measured in places dominated by dense vegetation cover ranging between 19.0 and 24°C (May 31). For instance, the temperature of dark green vegetation was lower than other vegetation.

The average LSTs of Site C were lower during the studies compared to Sites A, and B. The building is situated in an open area and is more sensitive to wind flow which affects the surface temperature on the roof. For instance, Sites A and B are in the middle of the University Campus and have less influence of wind.

The average temperature difference between Site A and B is around 4.2°C on May 31, assuming the actual effect of gravel mulch layers as the top layer which increased the LST on Site B, while on Site A vegetation cover is actively growing (Fig.31). Based on the literature review the facts such as plant height, color, leaves, coverage, and stomatal resistance are the most important vegetation characteristics that influence heat transfer on a green roof.

From the NDVI images shown above in Table 8, we can see Site A and B had values between 0 and 0.1 in winter and positive changes in NDVI started from March-April 2022 on Síte A and B. The vegetation led to an increase in NDVI values, which corresponds to the start of the growing season shown in Fig.32 below, and the period of maximum NDVI approximately corresponds to the end of vegetative development or the beginning of the flowering stage in the summer period with maximum vegetation dense cover.

Site A is fully covered with various types of vegetation, shown in Fig.32, and the NDVI value in May runs from 0.2 to 0.6, which is greater than Site B, which is between 0 to 0.3, and the roof is partly covered with low vegetation (succulents and sedum). Results of field data collected in May showed that the average LST in Site A is 4.2°C (Table 9) lower than in Site B. This difference in NDVI values and temperatures indicates the influence of vegetation cover on LST. The link between LST and NDVI is demonstrated by the result: the higher the NDVI, the lower the LST.

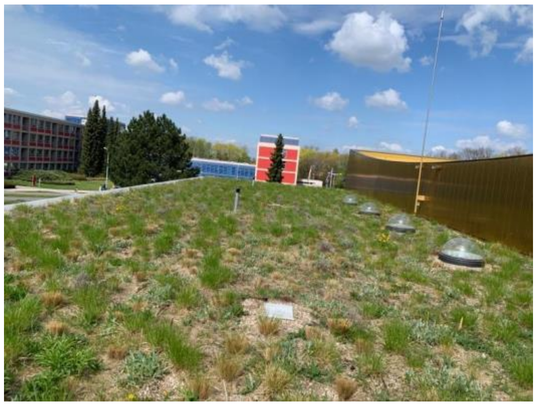
On the other hand, Site C has similar values as the NDVI of the gardens and surrounding green areas. The value started to increase during the vegetation growth season and reached a maximum of 0.6 to 1 in June-August. In November it significantly decreased but still was higher than Site A, B values.

January

February

March

April



May

Figure 32. Vegetation growth on Site A during fieldwork
Source: Author

Due to the limited timeline of fieldwork in the Prague study location which was carried out only during the winter-spring season in 2022 and since LST in winter is much lower than that of summer, NASA's Landsat-8 mission with spatial resolution (30x30m) and QGIS was used to retrieve LST data. Satellite data was acquired for June 2022 (Fig.33) to identify UHI effects on the city scale.

June 18 was selected because it was one of the hottest summer days in Prague and many European cities in 2022 with air temperatures that were more than 10°C above the seasonal average. The LST map below shows clear high temperature ranges from 36°C to 42°C in the city center, with the hottest surface being 42°C to 46°C suffering from heat (Fig.33), but also the cooling effect of green areas, parks, and water (20°C) is visible.

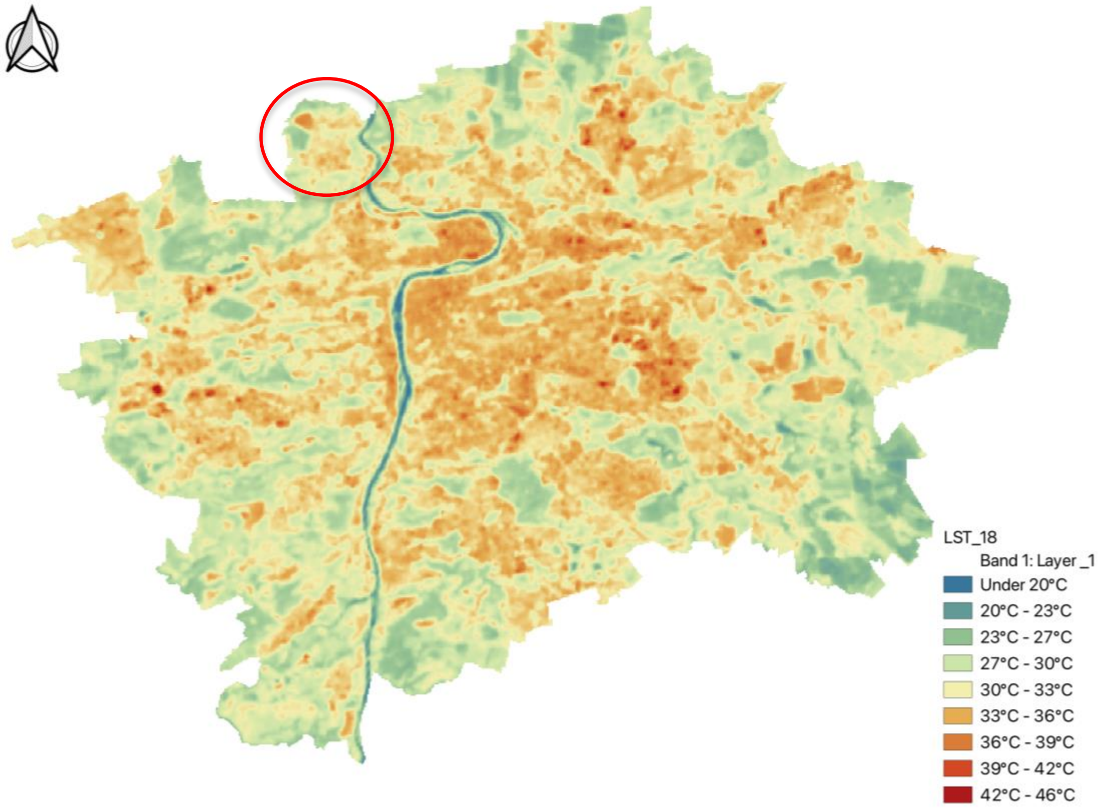


Figure 33. Land surface temperature map in Prague on June 18, 2022
Source: Author

In order to gain a deeper insight into LST at the University Campus level, the following map (Fig.34) was prepared with highlighted green roofs on it.

According to the results, the LST map of the University Campus area shown in Figure 34, LST values range from 32.3 to 37.2°C. It is clearly visible that the lowest temperature 32.3°C belongs to the area with a high density of tree cover between the Faculty of Tropical AgriSciences and the Faculty of Economics and Management, the highest temperature 37.2°C was on the roof surfaces of the Faculty of Engineering and Library.

For instance, the difference between the maximum (37.2°C) LST of the area and Site A (34.4°C) was observed to be 2.8°C, and Site B (33.0°C) and C was 4.2°C.

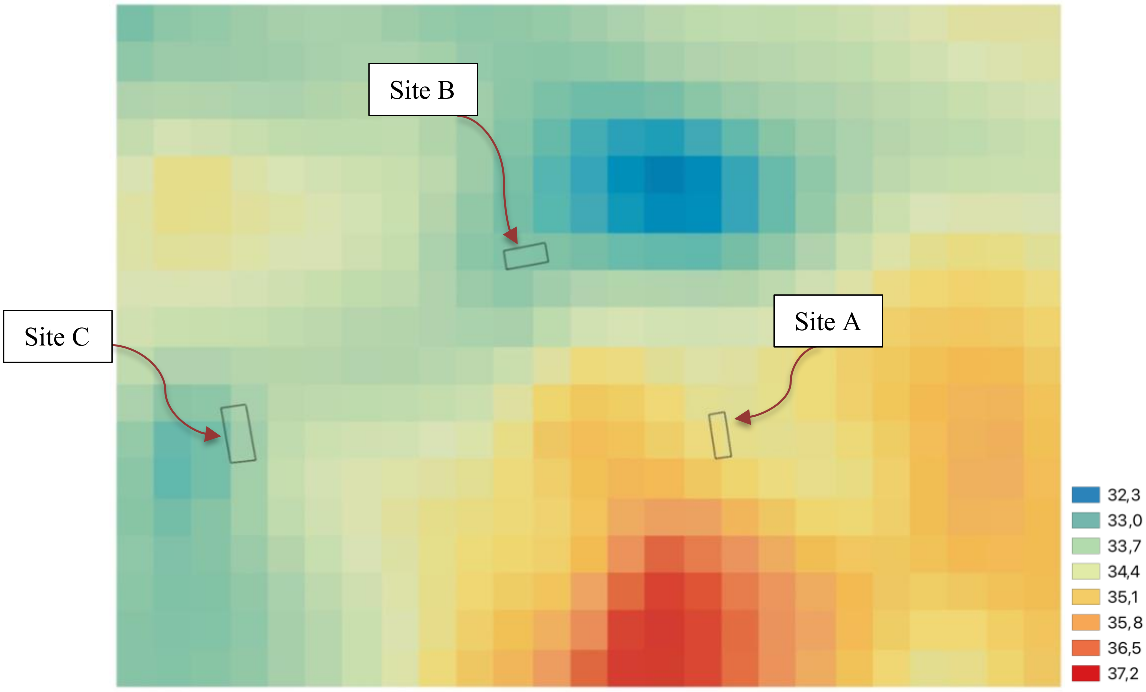


Figure 34. LST map of CULS Campus on June 18
Source: Author

Figure 35. Map of CULS Campus
Source: Google Earth

Table 11. The temperature of different land cover

LST	Land cover
32.3°C	Area with a high density of tree cover, botanical garden
33.0°C	Site C, Site B, botanical garden, greenhouses
33.7°C	Site C, Faculty of Environmental Sciences,
34.4°C	Site A, Faculty of Environmental Sciences, Faculty of Economics and Management
35.1°C	Dormitory ABC, Canteen, Rectorat, Faculty of Agrobiology, Food and Natural Resources
35.8°C	Dormitory JIH, impervious surface in front of the main entrance Faculty of Agrobiology, Food and Natural Resources,
36.5°C	Faculty of Engineering, Library
37.2°C	Faculty of Engineering, Library

Obtained data from the map are shown in Table 11 which helps to identify vulnerable areas and assess the cooling impacts of green areas.

Site D

The result of experimental data collected from the green roof in Lisbon using a thermal camera in addition to a hand-held thermometer showed that this green roof does not meet the necessary requirements to be able to mitigate the UHI effect for the following reasons:

- Site D is an extensive roof with a thin layer profile and a small area of 100 m^2 (In accordance with the legislation adopted in most countries such as Linz, Austria (Maurer, 2006), Brussels, Belgium (RRU, 2007), and Munich, Germany (Ansel and Appl, 2015) green roof area must be equal to or greater than 100 m^2).

- Being significantly covered by the shadow of a nearby building from the afternoon, make the roof not viable.

- Non-irrigated green roof due to technical issues with drainage, the roof has no access to water last couple of years which greatly affected the growth of vegetation.

- This green roof needs additional maintenance care at least twice a year to remove weeds carried by the wind and birds, including weeding, fertilizing, and replanting plants.

6. Discussion and conclusion

The objective of my study was to determine the potential contribution of green roofs in the selected study area at the Campus of the Czech University of Life Sciences in Prague as a supplement to green spaces as a means of mitigating the associated impact due to increasing surface temperatures caused by the UHI effect and explore if there is any relationship between green roof type, vegetation cover, and LST. Although some questions regarding the type and components of green roofs, the UHI effect had already been confirmed by the literature review.

In order to examine more accurate data different methods were applied including measuring with a digital thermometer, satellite data, QGIS, and thermal camera.

According to the fieldwork, the surface temperature of the green roof varies according to the different kinds of vegetation. This field result was compared with NDVI images and vegetation cover was found to have a significant effect on the surface, which also has been well-documented by other researchers (Givoni, 1998; Shashua-Bar and Hoffman, 2000; Wong and Chen, 2009; Bowler et al., 2010; Erell, 2008; Qiu et al., 2013; Adams and Smith, 2014; Coutts, 2015; Duarte et al., 2015; Li et al., 2011). This finding supports the literature review that plants and vegetation cover shade the roof and simultaneously absorb sunlight and reduce surface temperature. In addition, a relationship was studied between average LST and vegetation index NDVI, the higher the NDVI, the lower the LST.

Satellite images were obtained and the LST map was prepared using QGIS on June 18, one of the hottest days in summer demonstrating that the land-surface temperature in Prague tends to decrease as the green areas increase. According to the results, the LST map of the University Campus area, LST values range from 32.3 to 37.2°C, while in the city center temperature is between 36 to 42°C and in some areas, the temperature reached 42°C - 46°C suffering the burden of heat. According to Carleton and Hsiang, (2016), on days when air temperatures rise above 32.2 °C, the mortality rate can increase by at least 2%. This data helped identify vulnerable areas of the University Campus scale and assess the cooling impacts of green infrastructures and green areas there. The highest temperature 37.2°C was observed in the southern part of the campus, the center with an impervious surface cover in front of the main entrance of the Faculty of Agrobiology, Food and Natural Resources, as well as in the southeastern part area of the Dormitory JIH, the surface temperature reached 35.8°C. LSTs are much lower in the northern and southeastern parts ranging between 32.2 to 33.7°C, where green areas such as intense tree cover, a botanical garden, green roofs, and greenhouses are located.

The performance of a green roof is also dependent upon its type and design, such as substrate depth and vegetation species (Coutts et al., 2013). LSTs were lower in Site B and C than in Site A.

Site A is a non-walkable extensive green roof and has the smallest size 11.4x34.8m compared to other green roofs in the study area. The observed LST is 34.4°C. The cooling effect of Site B (18x32.4m) and Site C (20x44) is visible and 1.4°C lower than LST at Site A. For instance, Site C is considered as a roof garden with a thicker profile that enables small trees and a variety of other plants to grow in the soil. The roof creates a unique ecosystem that provides food for wildlife (bees, butterflies, birds).

This means that the results showed a very positive of green roofs on microclimate performance in the Prague study location. Concerning both the vegetation cover and the building characteristics can provide inputs for architects and urban planners to better design cities, effectively mitigate the urban heat island (UHI) effect, improve the livability of the city, gain thermal comfort conditions, and identify policies and incentives to promote green roofs.

Conditions of Site D in the Lisbon study location could be improved to meet standard green roof requirements by fixing the irrigation system, providing access to water, regular maintenance care, fertilizing, and monitoring plant growth by selecting drought-tolerance species.

Green roofs have demonstrated numerous social, environmental, and economic benefits.

Limitation of study

The fieldwork started in January and was finished by June 2022 in Prague. LSTs were collected by using a hand-held thermometer since it was an accurate instrument and low-cost. The proposed methodology was time-consuming and required walking through the roof space measuring temperatures in 186 points and recording it at the same time. Intense vegetation growth made it impractical to continue measurements without damaging vegetation in May. As a result, field data were collected only for five months, despite the fact that the winter-spring LST was substantially lower than the summer LST.

LST maps are limited by the spatial resolution of the Landsat-8 product with spatial scales of 30x30m.

Future directions

Future work can focus on improving the accuracy of the LST map of the University Campus with a better resolution to avoid the problem of scale.

For further research, it is recommended to carry out on-site measurements of the surface temperature of green roofs and different surfaces in the summer season. Several possibilities that will help to obtain more accurate data have been found during the investigation:

- Firstly, to better quantify the effect of green roofs to mitigate UHI corrective studies are needed with a great number of green roofs.
- Secondly, it would be useful to use unmanned aerial vehicles such as Infrared Drone Camera that takes thermal images with a spatial resolution from the air to be able to monitor temperature changes on the green roof surfaces in the summer period. Moreover, a handheld weather station (Kestrel Weather Meters) or air temperature sensors would provide accurate weather parameters of the area such as wind speed, air temperature, humidity, and heat stress information, and record the data for later analysis.

- Thirdly, a more comprehensive approach to green roofs could be studied through collaboration with other students and experts.

Conclusion

The conclusions of this analysis are summarized as follows:

- The surface temperatures of green roofs fluctuate according to the different types of flora. Lower temperatures have been recorded in areas covered with dense dark green plants, while higher temperatures have been recorded in areas with bare soil, less vegetation, or covered with gravel.
- The height and density of the vegetation cover are important in boosting the cooling function of green roofs, as they provide shade. The intensive green roof in Site C performed better than the extensive green roof in Site A,
- Green roofs with a low greening coverage ratio are not effective to improve the thermal environment. The cooling performance increased with the increasing coverage ratio.

The results of this study confirm the hypothesis that green roofs can be a more beneficial addition than a standard conventional roof in terms of reducing surface temperature. The data may alter in a larger study.

However, enough evidence is present that merits further study.

In conclusion, the large-scale implementation of green roofs as a supplement to green areas is likely to have a positive impact on Prague's resilience to climate change.

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