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“Quantifying the Impacts of Vegetation Structures on the Climate Performance of Informal Green Spaces: A Case Study of Dresden, Germany”

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Abstract: The 2019 IPCC report highlights that anthropogenic activities have caused a global temperature increase of approximately 1.0°C, with Urban Heat Island (UHI) effects intensifying temperature rises in cities. Vegetation, particularly in Informal Green Spaces (IGS), mitigates UHI by providing cooling benefits and enhancing urban microclimates similar to Formal Green Spaces (FGS). This study addresses the knowledge gap regarding the microclimatic performance of IGS by examining their Vegetation Structures (VS) and air temperature regulation capabilities. The primary objectives of the dissertation are to highlight IGS's role in providing regulating services, quantify air temperature variations among different VS within IGS, investigate correlations, and propose integration strategies for IGS in greenspace planning. Three study sites in Dresden, Germany, were chosen based on criteria including Local Climate Zones (LCZ), size, IGS typology, and accessibility. The research employs a mixed-methods approach, including remote sensing, in-situ air temperature (AT) measurements via traverse study, and qualitative visual assessments of VS. The AT values are then compared to two variables: Vegetation Structure (VS) and Canopy Cover (CC). The findings indicate that IGS contribute to temperature regulation, with CC playing a crucial role in cooling. Correlations showed that lower and more stable afternoon temperatures were more associated with CC than VS. However, the low R² values suggest that other variables not examined in the study might have had more significant effects on the results. These may include vegetation health, built surfaces, and the surrounding urban form. The results also found that different types of vegetation and their spatial arrangement can provide both cooling and warming effects. For instance, grasslands and meadows can significantly reduce temperatures through the albedo effect and enhanced wind flow, while tall dense shrubs and grasses can trap heat, especially near anthropogenic heat sources. Furthermore, larger green spaces in less built-up areas are observed to offer more consistent cooling. Finally, the conclusions from the study have revealed directions for the management and integration of IGS in the greenspace planning of Dresden. This includes incorporating IGS into green space inventories, engaging stakeholders in management, and conducting further studies on Leaf Area Index (LAI) and thermal comfort benefits of IGS. In addition, future research should consider longer observation periods, consistent measurement timings, and a comprehensive evaluation of the diverse ecosystem services provided by IGS. Detailed studies of urban morphology around green spaces and microclimate simulations to compare with in-situ measurements are also suggested.		
Keywords Informal Green Spaces, Vegetation Structures, Canopy Cover, Air Temperatures, Microclimates		
Originality statement. I hereby declare that this Master's dissertation is my original work, does not contain other people's work without this being stated, cited and referenced, and has not been submitted elsewhere in fulfilment of the requirements of this or any other award.	Signature	

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LIST OF ABBREVIATIONS

AT: Air Temperature

CC: Canopy Cover

FGS: Formal Green Spaces

GI: Green Infrastructure

IGS: Informal Green Spaces

LAI: Leaf Area Index

LCZ: Local Climate Zones

LST: Land Surface Temperature

UHI: Urban Heat Island

VS: Vegetation Structures

CHAPTER 1. INTRODUCTION

1.1. Rationale

The Intergovernmental Panel on Climate Change (IPCC) 2019 report indicates that anthropogenic events have played a role in causing around 1.0°C of global temperature increase compared to pre-industrial levels, with a probable range of 0.8°C to 1.2°C (IPCC, 2019). The urban heat-island (UHI) effect exacerbates temperature increases within cities, leading to higher urban air temperatures compared to surrounding rural areas (Chang and Li, 2014). This poses risks to human health and thermal comfort in cities.

Vegetation, in all its forms, is considered the most effective approach for mitigating the UHI effect and improving the urban microclimate (Norton et al., 2015; Andersson-Sköld et al., 2015). Within the realm of urban vegetation, are “formal green spaces”—encompassing various elements such as urban parks, playgrounds, historical gardens, streetscapes, roof gardens, green façades, and other forms of green infrastructure (GI)—and Informal Green Spaces (IGS).

IGS are prevalent in many cities worldwide, particularly in those that have undergone post-industrial transformations. These spaces, including urban brownfields, wastelands, vacant lots, and former railways, host diverse spontaneous growth of tree and plant species. IGS provides residents with recreational opportunities and functions as natural habitats for urban biodiversity (Rupprecht et al., 2015). However, despite their significance, these spaces are often overlooked as components of GI, and their potential regulatory benefits remain unrecognized. Furthermore, while there has been considerable research on the ecosystem and biodiversity services provided by IGS, there is currently a knowledge gap regarding their impact on urban microclimates. In addition, several studies on both macro and micro-level cooling benefits of vegetation have been mostly represented by formal green spaces such as urban parks.

Several researchers have highlighted the significance of vegetation structure complexity in IGS (Gilbert, 1990; Fernandez-Juricic, 2000; Strauss and Biedermann, 2006; Carballido et al., 2011 in Rupprecht et al., 2015). In the context of assessing the

microclimatic benefits of green spaces in general, vegetation structures have been identified as a crucial factor in providing cooling effects.

To comprehend the benefits provided by vegetation within built environments, it is essential to conduct quantitative assessments to evaluate their associated microclimatic effects (Duarte, et al., 2015). Similarly, precise quantification of the cooling benefits provided by urban green spaces is of paramount importance for effectively integrating climate change adaptation strategies into urban planning and management (Gallay, et al., 2023). In line with this reasoning, examining the quantitative performance of informal green spaces (IGS) in temperature reduction within their surroundings can serve as a means to reinforce their significance as a crucial component of GI in cities to address the challenges posed by global warming. Accordingly, investigating the vegetation structures of Informal Green Spaces (IGS) may yield valuable insights into their cooling benefits.

1.2. Aims and Objectives

The main aim of this study is to address the knowledge gap regarding the microclimatic performance of Informal Green Spaces (IGS) in urban areas and investigate the air temperature cooling capabilities of different vegetation structures within IGS.

By the end of the study, the following two key questions must be answered: 1) “To what extent can vegetation structures help improve microclimates in specific urban environments?” and 2) “How can IGS be integrated as essential components of green infrastructure in cities?”. To achieve these goals, the study shall pursue the following objectives:

- To highlight the role of IGS in providing climate regulating benefits in urban environments.
- To explore various types of Informal Green Spaces and assess the characteristics of their respective Vegetation Structures.
- To measure air temperature variations caused by different Vegetation Structures (VS) within different IGS typologies.

- To explore potential correlations between VS and the cooling or heating effects within the selected IGS typology.
- To formulate management and integration strategies focusing on IGS as a component of Green Infrastructure (GI) in the urban planning system.

1.3. Methodological Framework

The dissertation's methodology presents a meticulously planned approach to investigate the cooling benefits of Informal Green Spaces (IGS) in Dresden, Germany. First, three study sites are selected based on strict criteria, including size, Local Climate Zone (LCZ) classification, and typological attributes, following the analytical framework for Informal Green Spaces (IGS) proposed by Rupprecht and Byrne (2014). Using the Canopy Height Model (CHM) of Dresden, Vegetation Structures (VS) are delineated at each site, leading to the creation of biotope maps through the ArcGIS Pro software. These maps guide the strategic placement of traverse points necessary for temperature measurements. Additionally, qualitative visual assessments of green cover and prevalent plant types are conducted to enhance the understanding of ecological characteristics.

To evaluate the microclimatic impacts of the selected IGS sites, temperature sensors are utilized for in-situ air temperature measurements through a traverse study. Factors such as the vertical elevation of measurement points, temporal variations, prevailing meteorological conditions, and wind dynamics are thoroughly considered during data acquisition to ensure methodological precision. The analysis focuses on identifying correlations, temporal trends, and complex relationships between temperature distribution patterns and VS at the selected IGS sites.

The insights from the study then inform the development of management and integration strategies for IGS within the planning system of Dresden, emphasizing their role in regulating microclimates and providing other ecosystem services comparable to those provided by Formal Green Spaces (FGS).

1.4. Outline of the Dissertation

The dissertation is structured into five (5) chapters, as follows:

Chapter 1 establishes the foundation of the dissertation by laying out its rationale, delineating the aims and objectives, and introducing the relevant concepts and methodologies.

Chapter 2 elaborates on the concepts outlined in the rationale, examining the existing body of knowledge and research gaps regarding the cooling benefits of vegetation and green spaces, as well as informal green spaces and vegetation structure. Additionally, it provides background information on the selected study site.

Chapter 3 explains the approaches and tools utilized to achieve the objectives, beginning with the selection of three (3) IGS sites through a specified. Additionally, it outlines the process of biotope mapping and visual assessment to delineate individual vegetation structures, which will serve as the basis for the field measurements. Furthermore, it describes the traverse study conducted to gather in-situ temperatures.

Chapter 4 delineates the outcomes and analyses derived from the amassed data, including the limitations of the study. A comprehensive account is provided of the principal findings.

Chapter 5 encapsulates the research by discussing the results in reference to existing literature and drawing conclusions, thereby addressing the overarching aim and objectives. Lastly, recommendations are provided for future studies and for stakeholders in Dresden's local governance, academia, urban planning, design sectors, and private enterprises, aimed at enhancing the safeguarding and management of Informal Green Spaces (IGS).

CHAPTER 2. LITERATURE REVIEW

2.1. Background

2.1.1. Overview of Urban Heat Island Effect (UHI) and the Role of Vegetation in Mitigating UHI

The Urban Heat Island Effect is a serious phenomenon that continues to pose a great risk to our cities. Heat islands refer to temperature variances observed between urban regions and their adjacent surroundings (Oke, 1995). The World Health Organization (WHO) emphasizes the importance of local adaptation and preparedness to mitigate heat-related risks. The build-up of heat from both external factors and internal processes can quickly contribute to severe heat-related ailments and worsen existing chronic health conditions, while also indirectly impacting behaviour. (World Health Organization, 2018).

Vegetation in urban areas plays a vital role in mitigating climate change impacts and reducing the urban heat island (UHI) effect. Through evapotranspiration, trees and shrubs prevent excessive heating of the local atmosphere during the day and provide cooling effects through evaporation at night (Heerwaarden et al., 2010, Zhang et al. 2007). They also create shade on streets and buildings, inhibiting heat accumulation and reducing the overall energy surplus in urban areas (Granero-Belinchón et al. 2020; Simon et al. 2019). Numerous studies have shown that vegetated spaces in cities contribute to lower microclimates, helping to reduce ambient temperatures nearby. Vegetation lowers daytime maximum temperatures by reducing radiant exchange at ground level and through evaporative cooling. (Simon et al., 2019; Dimoudi & Nikolopoulou, 2003; Duarte et al., 2015). Furthermore, research has emphasized that the existence of greenery, including trees and grass, has a beneficial impact on outdoor thermal comfort within urban environments, resulting in reduced air temperatures and mean radiant temperatures (Shashua-Bar et al., 2011; Taleghani & Sailor, 2016; Nasrollahi et al., 2020).

The cooling benefits provided by vegetation vary based on spatial and temporal factors, as well as unique characteristics inherent to each plant species (Feyisa et al., 2014). Salmond et al. (2016) suggest that the effects of trees on microclimate are dependent on certain factors, including tree layout, health, and age. Shinzato and Duarte (2012) determined that the temperature difference between green areas and adjacent streets, influenced by Leaf Area Index (LAI) values, can be mitigated by tree canopy shadow, depending on the type of plants and leaf density.

2.1.2. The Significance of Green Spaces

Studies have shown that urban green spaces provide cooling effects not only in their immediate vicinity but also in nearby areas (Aram et al., 2019; Jaganmohan et al., 2016; Huang et al., 2018). According to Shah et al. (2021), the cooling effects of green spaces in urban areas are influenced by a combination of factors related to the infrastructure of the green spaces themselves and the characteristics of the surrounding environment. Furthermore, according to Salmond et al. (2016), the effectiveness of green spaces in reducing local urban temperatures is also determined by broader regional climate conditions, the geographic location of the city, urban morphology and density, as well as ecological, technical, and social considerations. These include ecological, technical, and social considerations such as local stewardship which can enhance or diminish the cooling benefits provided by urban green spaces (Salmond et al., 2016).

Green spaces provide a wide range of ecosystem services besides climate regulation. These include water retention, stormwater run-off management, water purification, carbon sequestration, and reduction of atmospheric noise and pollution (Gallay, et al., 2023). Moreover, they play a multifaceted role by serving as recreational areas and contributing to placemaking initiatives, which facilitate social interaction within communities. This aspect enhances the overall liveability of cities and positively impacts the physical and mental well-being of individuals.

2.1.3. Formal (FGS) and Informal Green Spaces (IGS)

Formal Green Spaces (FGS) are designated areas within urban settings that serve recreational and aesthetic purposes, as described in the literature. These spaces, which are typically owned and managed by public entities, encompass various types such as parks, gardens, squares and playgrounds. During the planning phase of FGS, specific features and amenities are incorporated to meet the recreational needs and preferences of the community—including well-defined walking paths, sports facilities, seating areas, and landscaped gardens. Furthermore, these green spaces are characterized by clear boundaries, established regulations, and designated maintenance schedules enforced by relevant institutions or property owners (Pietrzyk-Kaszyńska et al., 2017)., whereas IGS are not formally recognized as greenspace by governing bodies or residents and are characterized by informal, unmanaged vegetation and transitional recreational use (Rupprecht and Byrne, 2014).

Formal Green Spaces have also been widely studied in terms of the thermal advantages that they provide in various scales (Yu and Hien, 2006; Chang et al., 2007; Chang and Li, 2014; Hwang et al., 2015). Meanwhile, there have been limited studies on the microclimate benefits of Informal Green Spaces.

2.2. Informal Green Spaces (IGS) in Urban Environments

2.2.1. Definition and Characteristics of IGS

The literature presents various definitions of IGS. In contrast to FGS, IGS encompass brownfield sites, unattended vegetated areas, abandoned spaces, or locations with limited vegetation maintenance and infrastructure, commonly found within urban parks (Sikorski et al., 2021). Scholars have used different terms, such as ‘urban wilderness,’ ‘urban wildscapes,’ ‘ambivalent landscapes,’ or ‘urban wasteland,’ to describe these spaces (Rupprecht and Byrne, 2014). IGS typically emerge as unplanned formations with uncertain legal, socio-economic, and ecological statuses, often existing unintentionally or accidentally (Rupprecht et al., 2015). The vegetation within IGS is spontaneous and not actively managed (Luo and Patuano, 2023). As a result, the recreational use of these spaces is informal and temporary due to the absence

of formal management (Rupprecht and Byrne, 2014). In addition, IGS are often perceived as problematic areas due to their perceived lack of aesthetic value, untidiness, and potential safety concerns arising from the composition of vegetation (Włodarczyk-Marciniak, 2020).

This literature review presents the following table to summarize the terminologies employed to define Informal Green Spaces:

Table 1 Summary of Associated Terminologies in the Literature Review

Terminologies	No. of References
Informal Green Spaces	9
Urban Vacant Land	1
Urban Wastelands	1
Urban Spontaneous Vegetation	1
Brownfields	2

Informal Green Spaces (IGS) exhibit distinct physical characteristics characterized by the prevalence of spontaneous vegetation comprising both native and invasive species (Riley et al., 2018). Vegetation in urban vacant lands typically exhibits a higher proportion of non-native tree species compared to residential land (Kim et al., 2018). These spontaneous types of vegetation provide a wide range of ecosystem services, such as supporting biodiversity and regulating ecosystems (Riley et al., 2018), which complement those provided by formal green spaces (Luo and Patuano, 2023). For instance, Lehmann et al. (2014) found, through ENVI-met simulations of urban vegetation structures, that urban wastelands can develop vegetation structures akin to those found in urban green spaces, thereby achieving comparable average cooling effects.

2.2.2. Lack of Recognition as a Component of Green Infrastructure

Green Infrastructure (GI), as articulated by (Monteiro, 2020), involves a variety of natural and semi-natural spaces, comprising both green and blue environments, that deliver diverse ecosystem services. GI can be incorporated into communities across various scales, encompassing urban, neighbourhood, and landscape or watershed

dimensions (United States Environmental Protection Agency, 2023). Pitman (2015) emphasizes the significance of green infrastructure in fortifying urban resilience against climate change and highlights its numerous advantages, encompassing enhanced human health, effective water management, economic well-being, and the preservation of biodiversity. The concept of GI involves various natural and semi-natural elements that offer environmental, social, and economic advantages (Rouse, 2013; Benedict and McMahon, 2012). Examples of such elements encompass parks, green roofs and green walls, urban forests, wetlands, raingardens, green streets, permeable pavements, bioswales, constructed wetlands and green corridors, which contribute to stormwater management, mitigate urban heat island effects, and promote biodiversity.

GI is vital for providing ecosystem services that benefit both the environment and urban communities in urban areas. While cities recognize the importance of green infrastructure and actively manage existing green spaces—integrating them into urban planning systems, informal green spaces, which constitute a significant portion of urban green spaces, often receive insufficient attention.

The literature review also reveals a lack of representation of Informal Green Spaces (IGS) in discussions of green infrastructure. Consequently, existing studies have primarily focused on formal urban green spaces, leaving Informal Green Spaces (IGS) relatively unexplored (Botzat et al., 2016). Unlike officially designated parks or gardens, IGS lack formal recognition by institutions or property owners for recreational purposes. Nevertheless, they constitute a substantial proportion of the overall green space within urban areas (Rupprecht and Byrne, 2014).

2.3. Research Gaps

2.3.1. Existing Knowledge Gap in the Cooling Benefits of IGS

From an ecological perspective, IGS play a vital role in regulating air quality, mitigating flood risks, managing temperatures, and promoting urban biodiversity (Brun et al., 2018). Despite their significance, IGS have been undervalued and understudied in comparison to formal urban green spaces. Recent studies have demonstrated that IGS can provide comparable ecosystem services and biodiversity preservation to urban parks but at lower maintenance costs (Sikorski et al., 2021). Notably, a comparative

study by Sikorski et al. (2021) found no significant differences in cooling benefits between sampled urban parks and IGS sites. The study also revealed the superior cooling benefits of woodlands compared to herbaceous vegetation and lawns. Moreover, a study by Kim (2015) on urban wastelands highlighted the promising effects of “unattended sites with vegetation” in delivering ecosystem services within urban environments, emphasizing the need to recognize and conserve the substantial ecological values associated with these areas.

Extensive research has been conducted on the societal aspects of Informal Green Spaces (IGS). Sikorska et al. (2020) investigated the role of IGS in enhancing the accessibility of green spaces for vulnerable communities, while studies by Kim et al. (2018), Rupprecht et al. (2015b), and Włodarczyk-Marciniak et al. (2020) focused on residents’ perception and awareness of IGS. Furthermore, studies by Sikorski et al. (2021), Luo and Patuano (2023), and Rupprecht et al. (2015a) underscored the significance of IGS in delivering ecosystem services and supporting biodiversity. Mathey et al. explored the potential of green spaces (2011) and urban brownfields (2015) in climate adaptation by utilizing climate modelling methods.

However, despite the extensive body of existing literature, the investigation of the micro-level potential of urban IGS in mitigating UHI through on-site temperature measurements, and the studies leveraging on IGS’ high species diversity such as the exploration of cooling effects relative to its vegetation structures, remain limited.

2.3.2. Limited Representation of IGS in the Quantitative Assessment of the Cooling Benefits of Vegetation and Green Spaces

The existing literature emphasizes the importance of quantifying the cooling benefits of vegetation in the urban environment. Accurately assessing the cooling impacts of green spaces is crucial for the development of successful urban planning initiatives and strategies for adapting to climate change (Gallay et al. 2023). By quantifying these cooling benefits, urban planners can strategically incorporate green spaces to enhance the overall cooling of urban environments and improve the quality of life for residents (Kong et al., 2016).

Much has been written on the cooling benefits of urban parks on varying scales through a combination of in-situ measurements and microclimate simulations (Yu and Hien, 2006; Aram et al., 2019; Al-Gretawee et al., 2016). The cooling benefits of various urban green infrastructure elements, such as green roofs and green façades, have also been quantified through methods like remote sensing and observational studies (Dong et al., 2020; Bakhshoodeh, 2023).

Peng et al. (2021) analysed a total of 24 urban parks in Shenzhen, China, and proposed indexes such as park cooling area, park cooling efficiency, park cooling gradient, and park cooling intensity to comprehensively measure the cooling effects of urban parks. Shah et al. (2021) utilized an even larger sample size, comprising 262 urban green spaces in Bengaluru, India. However, the study did not classify the specific functions (i.e., formal or informal) of the green spaces considered.

2.3.3. Current Methodologies in Quantitative Assessment of the Benefits of Vegetation in Cooling

Current methodologies in quantitative assessment of the benefits of vegetation in cooling include a range of approaches. Koc et al., (2018) in their systematic literature review of 165 papers on the cooling benefits of Green Infrastructure (GI), have identified three principal methodological strategies employed for examining the cooling impacts of green infrastructure: 1) Observational methods, encompassing in-situ measurements and remote sensing; 2) Simulations; and 3) Experimental techniques (Figure 1).

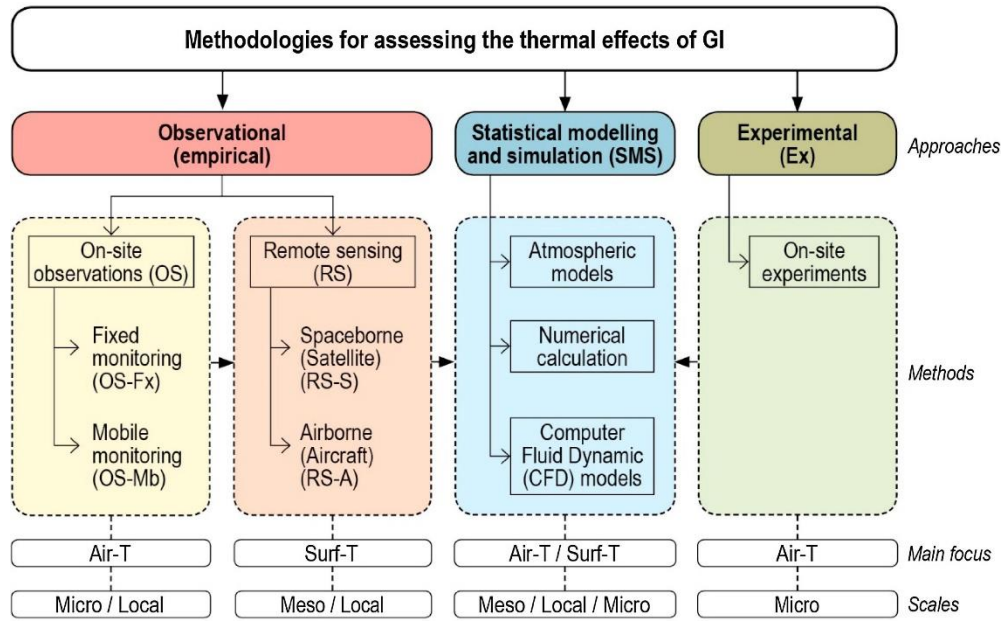


Figure 1 Methodologies for Assessing the Thermal Effects of Green Infrastructure (Koc et al., 2018)

In this systematic literature review, Koc et al. (2018) outlines the following research gaps in the methodological aspects of quantitative studies on the cooling benefits of green spaces: (1) most studies focus on land surface temperatures, leaving the impacts of the spatial organization of vegetation underexplored; (2) remotely-sensed estimates of air temperatures do not reflect the actual temperatures, thus highlighting the importance of in-situ measurements to validate the remotely-sensed data; and (3) there is a lack of a holistic approach in studying the collective impacts of vegetation and their surrounding built environment (Koc et al., 2018).

2.4. Vegetation Structures

2.4.1. Vegetation Structure in Existing Literature

Multiple authors have highlighted that the general configuration of green spaces—encompassing factors such as size, shape, and structure—influences surface heat flux and subsequently affects temperature mitigation (Gunawardena et al., 2017). Similarly, different categories of green spaces possess varying capacities for temperature mitigation (Sun & Chen, 2017). Furthermore, the composition of green cover—including lawns, meadows, shrubs, hedges, and trees—along with the height

classification of the vegetation layer, significantly influences the climatic effects observed in urban open spaces (Lehmann et al., 2014).

Jupp (1997) describes vegetation structure as the organization of plant material in both vertical and horizontal dimensions within a plant community, a concept that extends to vegetation dynamics and the evaluation of resources and habitats. According to Lehmann et al. (2014), vegetation structure can be categorized based on shape, size, spatial arrangement, and soil coverage.

On the other hand, encompassed within vegetation structures of plants and trees is the Canopy Cover (CC). Literature has shown that an increase in CC generally lowers temperatures, as trees provide shade and enhance evapotranspiration, thereby cooling the microclimate. The literature also suggests that the cooling impact of tree canopies on both air and surface temperatures intensifies with increased CC—making it a critical factor in evaluating the potential of vegetation to mitigate urban heat island effects (Wang et al., 2023, Vasconcelos, 2020).

Understanding the factors influencing urban vegetation variation is crucial for managing ecosystem services such as climate regulation, carbon sequestration, biodiversity support, stormwater control, and recreational opportunities, as well as for preserving biodiversity (Mitchell, 2016). Consequently, when assessing ecosystem services, the focus primarily lies on the structural attributes of vegetation and land use configurations rather than their functional qualities, as emphasized by Lehmann et al. (2014). For instance, ecosystems with diverse structural elements typically offer a range of resources and support greater species diversity (Bergen et al., 2009; Beninde et al., 2015, in Threlfall, 2016).

It is important to clarify that within the context of this dissertation, the term ‘vegetation structure’ should not be conflated with the ‘Urban Vegetation Structure Types’ defined by Lehmann et al. (2014). The latter encompasses a comprehensive taxonomy comprising 13 principal categories and 57 distinct urban vegetation structure types (UVSTs), as shown in Table 2.

Table 2 UVSTs Mathey et al., 2011 in Lehmann et al., 2014

1. Residential sites, mixed-use sites as well as industrial, commercial and specialized sites	7. Grassland
1.1 Built-up land with richly structured, park-like gardens	7.1 Intensive grassland
1.2 Built-up land with richly structured gardens, medium to high proportion of deciduous trees	7.2 Grassland with little or no trees and shrubbery
1.3 Built-up land with poorly structured, intensively maintained gardens	7.3 Grassland with communities of tall herbaceous vegetation
1.4 Built-up land with little or no vegetation	7.4 Grassland with trees and shrubbery
1.5 Built-up land with no or few trees and shrubbery	8. Trees, shrubs and bushes
1.6 Built-up land with trees and extensive shrubbery	8.1 Bushes; pre-forest shrubbery
2. Transport facilities and infrastructure	8.2 Hedges; row of shrubs
2.1 Railway site and facilities, tracks, embankments	8.3 Row of trees; group of trees
2.2 Road site with bordering greenery	8.4 Meadow with scattered fruit trees
2.3 Transport facilities, transport area largely to completely sealed	8.5 Prominent individual tree
2.4 Transport area; car park; greened	9. Woodland (deciduous, coniferous and mixed)
3. Green spaces	9.1 Wood
3.1 Green space with trees and closed canopy	9.2 Reforestation; tree nursery
3.2 Green space with diverse amount of trees and shrubbery	9.3 Clearfelling; cleared corridor
3.3 Lawn and sports field	9.4 Clearing with herbaceous vegetation
3.4 Green space with little or no vegetation	9.5 Clearing with meadow, wildflowers
3.5 Green space with young trees and partly with dense woodland	9.6 Developed edge of the wood
3.6 Green space with a lot of trees and extensive shrubbery, fruit trees	10. Near-natural wetlands
3.7 Green space with few trees and shrubbery, primarily decorative function	10.1 Near-natural wetland with reed beds, reed-, bulrush- and sedge-marshland
3.8 Green space with few trees and shrubbery, primarily lawns	10.2 Near-natural wetland with communities of tall herbaceous vegetation
4. Urban wastelands	10.3 Near-natural wetland with shrubbery
4.1 Urban wasteland with ruderal and other herbaceous plants, early stage of succession	10.4 Near-natural wetland with trees
4.2 Urban wasteland with pioneer trees, groves and woodland, middle stage of succession	11. Waterside zones
4.3 Urban wasteland with mature trees, groves and woodland, late stage of succession	11.1 Waterside zone with reeds, bulrushes and sedges
5. Landfills and quarries	11.2 Waterside zone with tall herbaceous vegetation, trees and shrubbery
5.1 Partly or fully overgrown; restored landfill or quarry	11.3 Waterside zone with grassy banks
5.2 Landfill or quarry with little vegetation, partly overgrown	11.4 Waterside zone with little or no vegetation
5.3 Landfill or quarry with no or little vegetation	12. Arid grasslands, heathland
6. Agricultural sites	12.1 Arid and semi-arid grassland; heathland
6.1 Arable land	12.2 Bushy to wooded dry grassland and heathland
6.2 Land for fruit cultivation, orchard	13. Open sites
6.3 Horticultural site, commercial use	13.1 Rocky area
6.4 Horticultural site, private use	13.2 Sandy area
6.5 Vineyard	13.3 Dune

2.4.2. As an Approach to Assess the Microclimatic Benefits of IGS

Numerous studies have been conducted to assess the microclimatic benefits of green spaces, particularly urban parks by investigating vegetation structures. In Vieira et al.'s (2018) investigation into the climate regulation and air purification advantages of urban parks, it was determined that vegetation structure, composition, and management play pivotal roles in maximizing the effectiveness of urban green spaces. The study highlighted that different vegetation types display varying capacities to provide ecosystem services, with more complex and naturally occurring forms demonstrating superior abilities in air purification and climate regulation (Vieira et al., 2018). Wei et al. (2021) explored the relationship between plant community structure parameters such as canopy density, porosity, greening coverage, and spatial types of urban green infrastructure, and their cooling and humidifying effects within urban green spaces, which can inform the design of future urban green spaces to enhance temperature regulation. Gallay et al. (2023) investigated variations in cooling impacts across urban green spaces in Zvolen, Slovakia, considering factors such as vegetation composition and size, while also evaluating the extent to which the cooling effect disperses from the perimeter of these green spaces.

Lehmann et al. (2014) used microclimate modelling software, ENVI-met, to estimate the climatic impacts of individual vegetation structure types across various urban structure types. Through the simulations, the study found that the cooling benefits are primarily influenced by factors such as vegetation coverage, building composition, and the extent of soil sealing (Lehmann et al. 2014). Tan et al. (2021) utilized a similar approach using ENVI-met to assess the cooling effectiveness both horizontally and vertically of different compositions of vegetation structures, concluding that the combination of trees and grass yields optimal cooling benefits.

2.5. Study Site

The city of Dresden, Germany ($51^{\circ} 02' 55'' N$, $13^{\circ} 44' 29'' E$), situated in the southeast of the Free State of Saxony, encompasses a land area of 328.48 km^2 , according to data from December 31, 2020 (Landeshauptstadt Dresden, 2020). Presently, it has an estimated population of approximately 567,375 individuals (Landeshauptstadt Dresden, 2021), resulting in a population density of approximately 1,708 inhabitants per km^2 .



Figure 2 Dresden, Saxony, Germany (Britannica, 2024)

The city experiences a warm and temperate climate, characterized by substantial rainfall throughout the year even in the driest months (Climate Data, n.d.). Based on

the Köppen and Geiger climate classification system, Dresden's climate is categorized as a temperate oceanic climate (Cfb). Areas categorized under this classification commonly encounter overcast skies, precipitation, and sporadic snowfall, while thunderstorms are infrequent (SKYbrary, n.d.). Temperature variations are limited, characterized by warm yet moderate summers and relatively mild winters (SKYbrary, n.d.).

2.5.1. Formal and Informal Green Spaces in Dresden

The World War II profoundly altered the urban landscape of Dresden, Germany, causing extensive damage and notable changes in its physical surroundings. According to Toit et al. (2021), the city experienced a 51% reduction in its street tree population during this period, underscoring the significant impact of the destruction (Toit et al., 2021). Following the war, initiatives were undertaken to reconstruct the urban landscape, aiming to conserve its historical essence while integrating contemporary features (Britannica, 2024). Simultaneously, there was a notable expansion in manufacturing activities in Dresden driven by the limited availability of raw materials (Britannica, 2024).

The presence of abandoned lots and brownfields with spontaneous vegetation in Dresden, Germany, is influenced by various factors outlined in the literature. Schug et al. (2022) attribute this phenomenon to significant migration in Eastern Germany, resulting in the abandonment and underutilization of buildings and infrastructure. This demographic shift reflects the characteristics of shrinking societies and presents both challenges and opportunities for the region, as noted by Schiller et al. (2017, cited in Schug et al., 2022), urging a transition toward a more circular built environment. Despite facing population decline, deindustrialization, and economic restructuring, Dresden has recently experienced a resurgence in population and economic growth (Mathey et al., 2018). Nevertheless, numerous brownfield sites, remnants of past structural changes, remain undeveloped and undergo natural succession, as highlighted by Mathey et al. (2018).

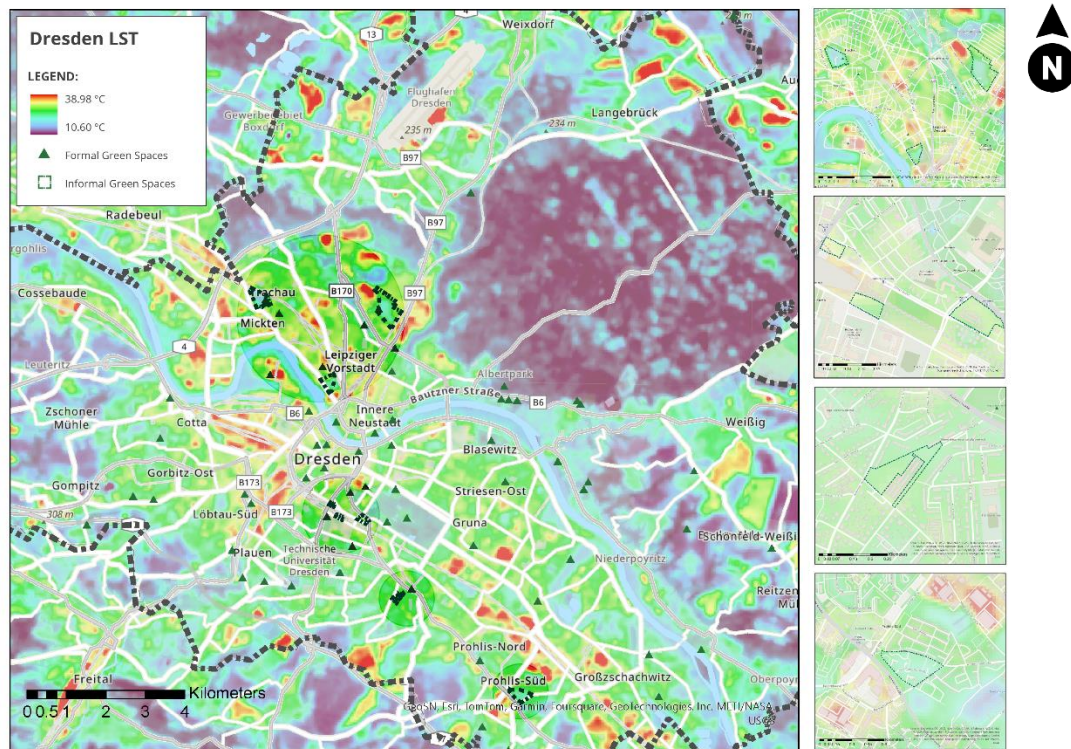


Figure 3 Land Surface Temperature Map, Dresden, May 2023

Figure 3 displays the Land Surface Temperature Map of Dresden, obtained from Earth Explorer (Landsat U.S., Geological Survey, 2023) on a cloudless day in May 2023. This map includes the Formal Green Spaces in the city (Dresden Office for Urban Greenery and Waste Management, 2023). In the absence of a comprehensive database for Informal Green Spaces (IGS) in Dresden, eight known IGS sites were overlaid on the map. This overlay demonstrates that these IGS sites exert similar surface cooling effects on the city as the Formal Green Spaces. Therefore, suggesting that IGS sites could play a comparable role in moderating urban temperatures, and in mitigating urban heating.

2.5.2. Greenspace Planning Instruments in Dresden

- **Dresden Model (Dresdner Modell, 2018)**

The Dresden Model is a comprehensive framework designed to evaluate and manage urban and natural landscapes in Dresden, promoting sustainable development and environmental protection. This model employs a numerical scoring system to assess various environmental factors, including biotope and land use types, biotope

connectivity, soil quality, water balance, floodplain functionality, urban climate, recreational value, and landscape aesthetics. Each factor is assigned point values reflecting its ecological importance and impact, allowing for uniform and objective evaluations. Data for these assessments are sourced from landscape plans, environmental reports, GIS-based tools, and field surveys (State Capital of Dresden, 2018).

The model supports land-use planning and decision-making by integrating environmental considerations into urban development plans. It outlines methods for calculating and implementing compensation for environmental impacts, ensuring that negative effects are mitigated or offset through appropriate measures, such as creating or enhancing green spaces. The overarching goal of the Dresden Model is to balance ecological, social, and economic factors, ensuring long-term environmental health and quality of life for residents. Continuous monitoring and evaluation are emphasized to adapt to changing environmental conditions and urban development needs, maintaining the model's relevance and effectiveness over time (State Capital of Dresden, 2018).

Notably, the Dresden Model does not explicitly mention informal green spaces or associated terms. Recognizing the ecological and social functions of IGS, it is therefore recommended to incorporate these greenspaces into the compensatory measures and overall urban planning process.

- **Dresden Landscape Plan (Landschaftsplan Dresden)**

The Dresden Landscape Plan, approved on May 17, 2018, covers the entire city area of 32,800 hectares and focuses on goals and measures for nature conservation and landscape management. It emphasizes enhancing structurally poor landscapes, improving the urban climate, and boosting the ecological functions of water bodies. The plan maps all existing areas, both developed and undeveloped, and outlines future development measures. Areas are considered in connection and interaction with each other, supporting the concept of a compact city within an ecological network (Landeshauptstadt Dresden., 2021).

It consists of four main steps:

1. *Analysis of Protective Goods*: Assessment and evaluation of soil, water, urban climate, species/biotopes, landscape aesthetics/recreation, human health, cultural and other assets.
2. *Sectoral Target Concepts*: Development of specific goal concepts for soil, water, urban climate, species/biotopes, and landscape aesthetics/recreation.
3. *Strategic Guiding Concept*: Formulation of an integrated long-term strategy for Dresden as a compact city within an ecological network.
4. *Development and Action Concept*: Implementation of the strategic goals through a development and action plan over a 15-year period.

Similar to the Dresden Model, the Landscape Plan of Dresden (See Appendix) does not explicitly account for informal green spaces or any associated terms including brownfields, urban wilderness, etc.

CHAPTER 3. METHODOLOGY

3.1. Research Approach

This study employs a mixed-methods research approach to evaluate the microclimatic impacts of Informal Green Spaces (IGS) in Dresden, Germany, utilizing vegetation structures as a key evaluative factor. Quantitative data collection includes the use of classified LiDAR data, satellite imagery and temperature sensors to measure vegetation structures and air temperatures, complemented by qualitative observations that provide detailed descriptions of on-site conditions and vegetation, including shape, canopy cover, species density, and maintenance levels. Descriptive methods systematically document the characteristics of the selected study sites, while explanatory methods identify correlations and trends between air temperature variations and vegetation structures.

3.2. Overview of Methodology

In line with the stated objectives, this study aims to select three distinct study sites in Dresden, Germany, utilizing the analytical framework developed by Rupprecht and Byrne (2014) regarding Informal Green Spaces (See Figure 6). The selection process will be refined based on specific criteria, namely size, Local Climate Zone (LCZ) and typology. Dresden was chosen as the research location due to the existing research on its vegetated urban brownfields, wastelands, and wilderness areas, as well as the availability of biotope maps and previous studies on urban vegetation.

Figure 4 presents a summary of the steps to be undertaken for the study.

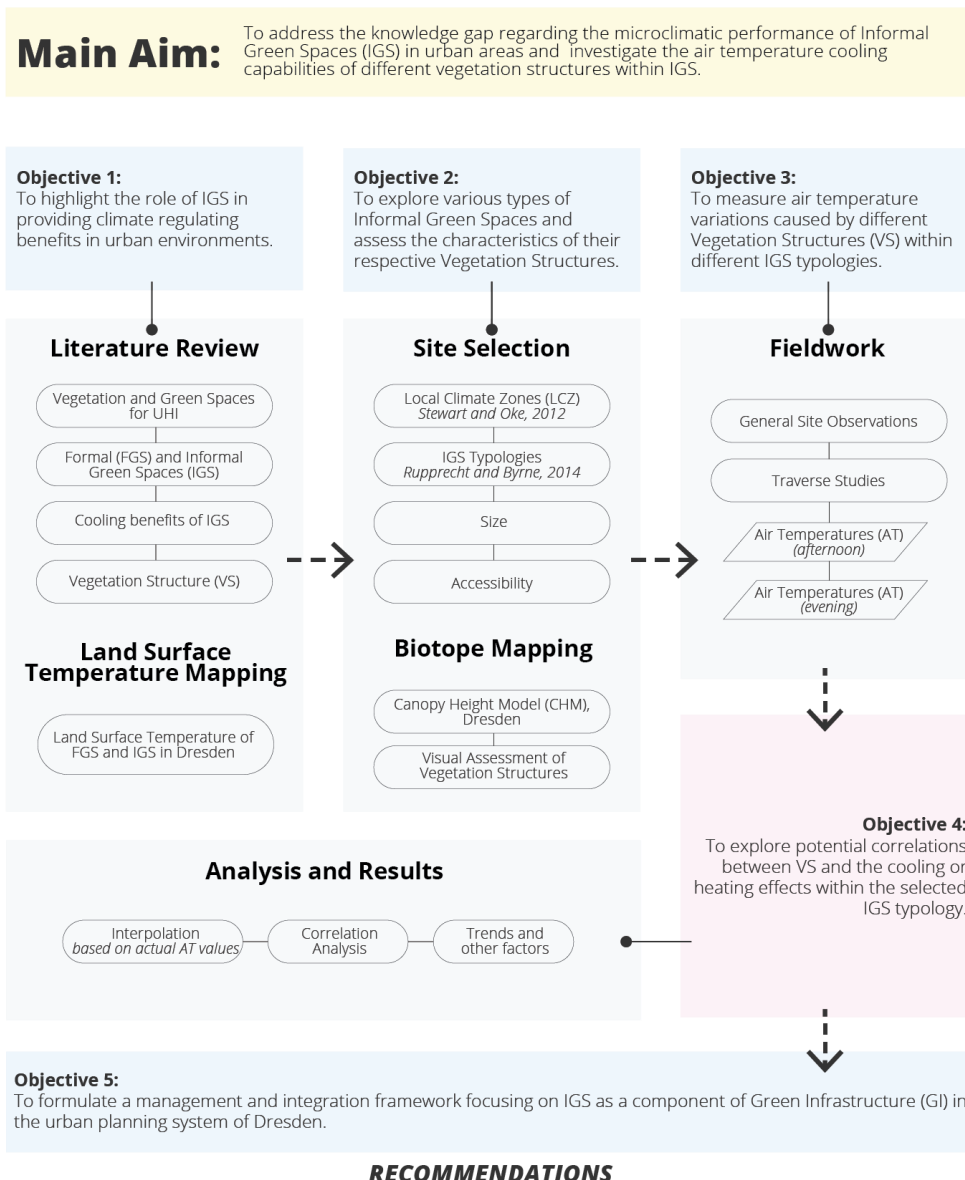


Figure 4 Process Methodology Overview

The individual vegetation structures of each selected site shall be derived from the Canopy Height Model (CHM) of Dresden, which shows the elevation of vegetation. This data will then be processed using ArcGIS Pro software to generate biotope maps, which will guide the traverse points for conducting temperature measurements in the field. By producing these biotope maps, informal green spaces can be further classified based on the extent of their green cover and the heights of the plant types. Due to restrictions on the timeframe of available datasets, it is necessary to further qualify the conditions of green cover at each site, such as prevalent plant types, shapes, canopy cover, plant health, and unique features like paved and built surfaces. These characteristics can significantly enhance the analyses' appropriateness, relevance, and

accuracy. Therefore, a visual assessment of existing vegetation structures at each site shall be conducted based on the vegetation structure assessment matrix by Lehmann et al., 2014.

To evaluate the microclimatic impacts of the selected Informal Green Spaces (IGS) sites, a quantitative research design approach will be employed. This approach entails collecting in-situ measurements of air temperatures using temperature sensors. It must be noted that sensors must be protected to prevent interference from solar radiation and obtain more accurate measurements. Several variables will be considered, including the height of the measurement point, the time of day, the prevailing weather conditions and wind speed during the measurement process.

After the data-gathering process, the actual points and air temperature values shall be utilized to interpolate new points in each site through ArcGIS Pro, to increase the sample points. Each point shall be assigned with their corresponding values based on Vegetation Structure (VS) and Canopy Cover (CC).

Subsequently, the data analysis shall be conducted to identify correlations, trends, and relationships between air temperature variations and the existing vegetation structure of the selected IGS. Since the biotope maps are derived from vegetation heights, which do not account for the vegetation's shading abilities, the analyses will also examine the correlations between air temperatures and canopy cover. The results will be visualized using boxplots and scatterplots to show data distribution, variability, correlations, and trends.

The findings from this analysis shall be the basis for proposed management and integration strategies involving IGS as a component of green infrastructure in the planning system of the city of Dresden.

3.3. Definitions

For the purpose of this study, the term “**Vegetation Structure (VS)**” is defined as “the physical arrangement and characteristics of plant species within the IGS”. It is qualified by the canopy height levels (low, medium, high), spatial organization of plants

(ie., estimated proportion of shrubs, trees and groundcover), density and sparseness and predominant plant types.

On the other hand, the term “**Canopy Cover (CC)**” shall be employed as defined by Jennings, (1999), ‘as percentage of ground area occupied by the vertical projection of the plant canopy’. It is represented in three levels—no shade, partial shade and deep shade, as observed through a visual assessment (See Appendix).

3.4. Site Selection

3.4.1. Site Selection Criteria

The following factors are taken into account during the site selection process:

- **Criteria 1: Local Climate Zones (LCZ)**

The extent of the urban heat island phenomenon is contingent upon both macroscopic climatic factors and microscale urban morphology (Manoli et al., 2019 in Egerer et al., 2024). The Local Climate Zone (LCZ) scheme, proposed by Stewart and Oke, 2012, has emerged as an asset in examining urban heat island phenomena in the neighbourhood level. This classification system categorizes field sites based on urban structure and land cover characteristics, offering a standardized method for investigating heat islands (Stewart et al., 2014; Zhao et al., 2021). It prioritizes the examination of physical attributes that directly impact climatic behaviors (Oke, et al., 2017).

It facilitates the categorization of landscapes according to surface cover, urban configuration, construction materials, and anthropogenic heat flux and offers a standardized approach for examining fluctuations in urban air temperature (Hashemi et al., 2020). By distinguishing the thermal characteristics of urban regions, the scheme allows for a more independent classification of urban and rural land covers based on their impact on local air temperature (Kwok et al., 2019).

The LCZs of each site have initially been guided by the Global Map of Local Climate Zones by Demuzere et al. (2022), and then validated through the 3D Building

Model of the City of Dresden by the Geoinformation and Surveying Saxony (2023), as well as actual site conditions to classify in accordance with the LCZ criteria by Stewart and Oke (2012).

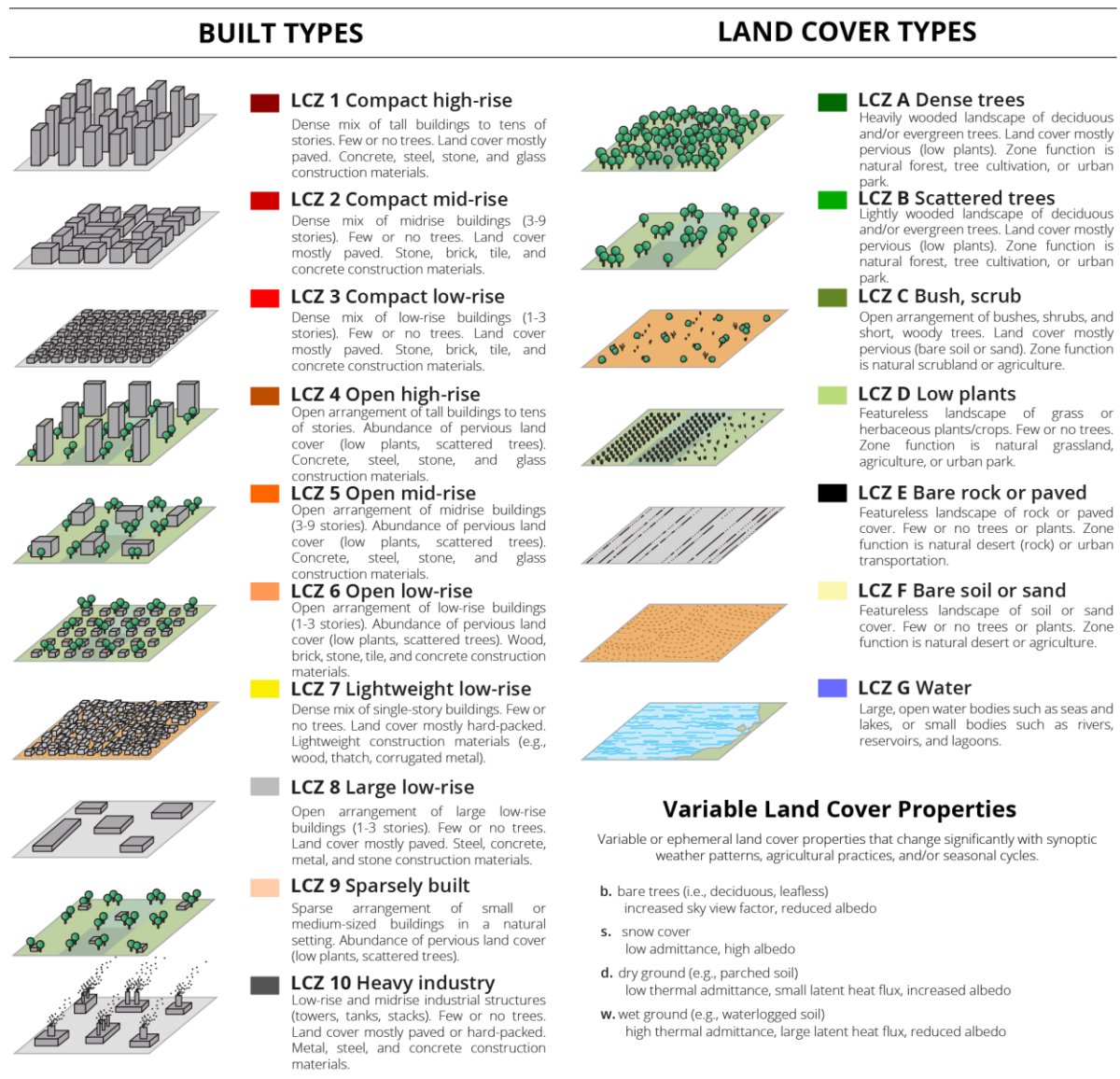


Figure 5 Local Climate Zones (LCZ) Scheme (adapted from Stewart and Oke, 2012)

• Criteria 2: Size

Size is another crucial factor in the site selection process. As illustrated in Figure 6 of the IGS typologies by Rupprecht and Byrne (2014), certain spaces, such as Gaps, Structural, and Microsites, exhibit minuscule sizes that might not encompass the interesting variety and combinations of vegetation structures important for this research. Most studies conducted on the cooling benefits of green spaces have focused

on large-scale areas of < 5 hectares. While there is no formally defined optimal size to achieve cooling benefits in an urban setting, it has been suggested that green spaces with dimensions of at least 1 hectare or 10,000 m² have the capacity to contain a diverse range of vegetation structures, support biodiversity, regulate temperatures, and enhance human comfort levels (Egerer, 2024).

- **Criteria 3: IGS Typology**

Due to the absence of a universally accepted definition of Informal Green Spaces (IGS), the typologies delineated by Rupprecht and Byrne (2014), depicted in Figure 6, have been employed to provide a framework and rationale for site selection. In order to effectively compare and contrast the various IGS typologies presented, it is imperative that the selected sites exhibit diverse typological characteristics.

- **Criteria 4: Accessibility**

Accessibility is one of the factors considered during the site selection process. While there are several potential sites for further investigation, some are privately owned and therefore not readily accessible to the public. These sites may be gated and fenced, with no contact information available to request permission for access. The accessibility of the potential sites is assessed through street images available on Google Maps and site visits.

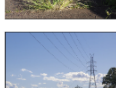
INFORMAL GREEN SPACES (IGS)	EXAMPLES	DESCRIPTION	MANAGEMENT	COMMON SUBSTRATES	
	a. Street verges	Roadside verges, roundabouts, tree rings, informal trails and footpaths	Vegetated area within 5 m from street not in another IGS category; mostly maintained to prevent high and dense vegetation growth other than street trees; public access unrestricted, use restricted	Regular vegetation removal (≥ once per month); governmental and private stewardship	Soil, gravel, stone, concrete, asphalt
	b. Lots	Vacant lots, abandoned lots	Vegetated lot presently not used for residential or commercial purposes; if maintained, usually vegetation removed to ground cover; public access and use restricted	Irregular veg. removal, medium to long removal intervals; private stewardship	Soil, gravel, bricks
	c. Gap	Gap between walls or fences	Vegetated area between two walls, fences or at their base; maintenance can be absent or intense; public access and use often restricted	Irregular veg. removal; variable removal intervals; private stewardship	Soil, gravel
	d. Railway	Rail tracks, verges, stations	Vegetated area within 10 m adjacent to railway tracks not in another IGS category; usually herbicide maintenance to prevent vegetation encroachment on tracks; public access and use mostly restricted	Regular veg. removal (monthly to yearly); corporate or governmental stewardship	Soil, gravel, stone
	e. Brownfields	Landfill, post-use factory grounds, industrial park	Vegetated area presently not used for industrial or commercial purposes; usually no or very infrequent vegetation removal and maintenance; public access and use mostly restricted	Irregular veg. removal, long removal intervals; corporate and governmental stewardship	Soil, gravel, concrete, asphalt
	f. Waterside	Rivers, canals, water reservoir edges	Vegetated area within 10 m of water body not in another IGS category; occasional removal of vegetation to maintain flood protection and structural integrity; public access and use often possible with some restrictions	Irregular veg. removal, long removal intervals; governmental stewardship	Soil, stone, concrete, bricks
	g. Structural	Walls, fences, roofs, buildings	Overgrown human artifacts; often vertical; occasional removal of vegetation to maintain structural integrity; public access and use mostly restricted	Irregular veg. removal, medium to long removal intervals; varying stewardship	Soil, stone, gravel, wood, metal
	h. Microsite	Vegetation in cracks or holes	Vegetation assemblages in cracks, may develop into structural IGS; maintenance can be absent or intense	Irregular veg. removal, variable removal intervals; variable stewardship	Deposits, soil, stone, concrete
	i. Powerline	Powerline rights of way	Vegetated corridor under and within 25 m of powerlines not in another IGS category; vegetation removed periodically to prevent high growth; public access and use mostly unrestricted	Regular veg. removal (less than yearly); utility or governmental stewardship	Soil

Figure 6 Typologies of Informal Green Spaces (adapted from Rupprecht and Byrne, 2014)

3.4.2. Selected IGS for In-situ Measurements

This study examined a total of eight Informal Green Spaces (IGS) situated around Dresden, Germany, as illustrated in *Figure 7*.

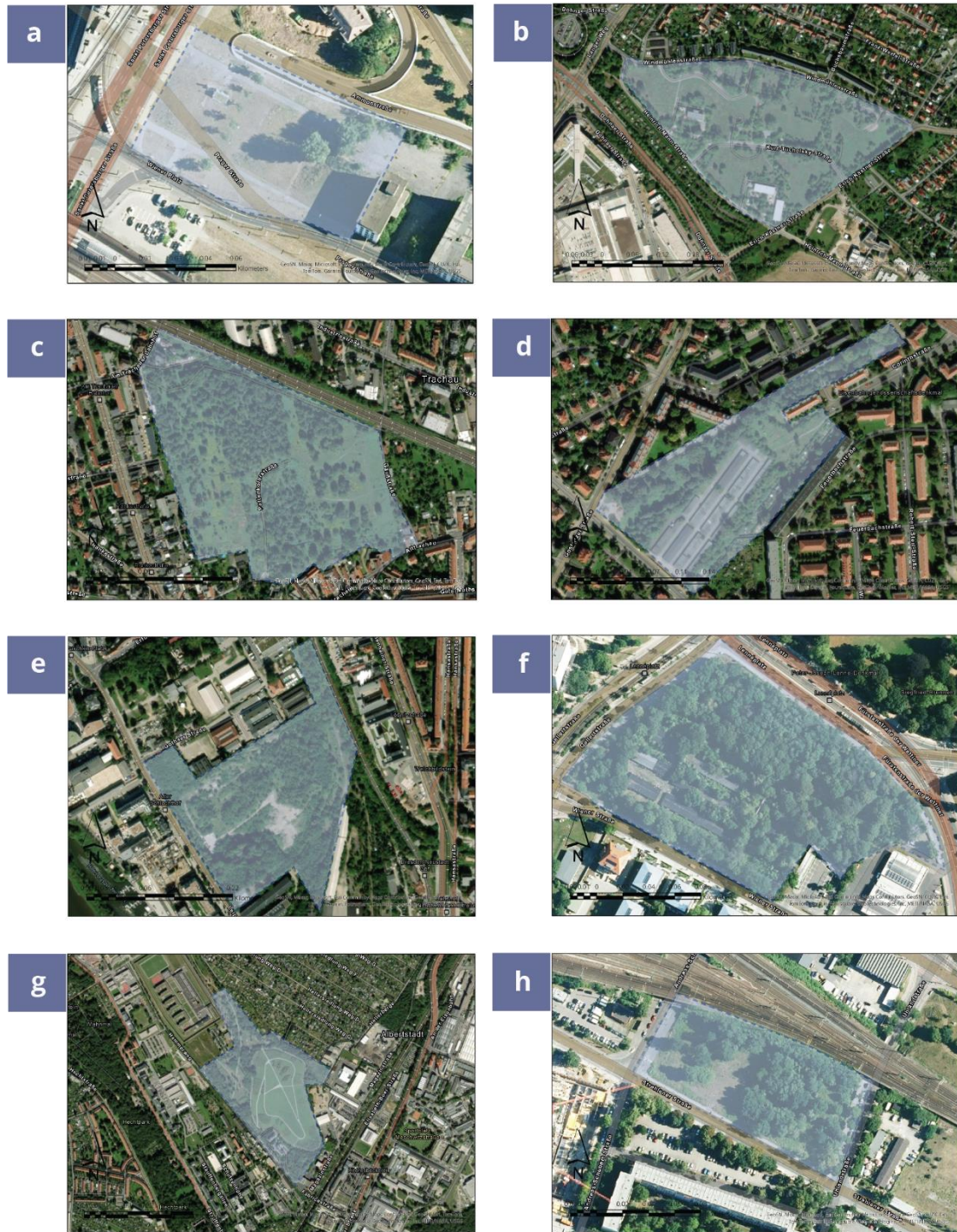


Figure 7 Informal Green Spaces (IGS) in Dresden, Germany

Following the consideration of the aforementioned factors—namely IGS Typology, Size, LCZ, and Accessibility, as presented in Table 3—sites **B**, **D**, and **H** were ultimately selected for further investigation.

Table 3 Summary of Site Selection

Site	Geolocation	Criterion 1: Local Climate Zone (LCZ)	Criterion 2: Size	Criterion 3: IGS Typology	Criterion 4: Accessibility
A	51°02'26.4"N 13°44'07.1"E	Compact midrise	~ 6,675.45 m ²	Vacant lot	Accessible
B	50°59'52.4"N 13°48'21.4"E	Open lowrise	~106,050.62 m ²	Brownfield (former demolition site)	Accessible
C	51°05'11.6"N 13°42'33.2"E	Compact lowrise	~ 114,671 m ²	Vacant lot	Inaccessible
D	51°01'12.4"N 13°45'39.3"E	Open midrise	~30,989.50 m ²	Waterside	Accessible
E	51°04'05.7"N 13°44'04.4"E	Compact midrise	~ 92,925.68 m ²	Railway (former Leipzig station)	Inaccessible
F	51°02'14.8"N 13°44'49.1"E	Open midrise	~ 27,450.39 m ²	Brownfield (former housing site)	Inaccessible
G	51°05'05.9"N 13°45'15.3"E	Open midrise	~ 245,645.63 m ²	Brownfield (former housing site)	Inaccessible
H	51°02'16.3"N 13°44'18.5"E	Large lowrise	~ 11,733.75 m ²	Railway	Accessible

In terms of Local Climate Zones (LCZ), the majority of potential sites are situated within LCZ 5, categorized as Open midrise, and generally, most locations are surrounded by green spaces. In relation to their spatial extent, these sites vary from small to medium-scale. Conversely, the sites exhibit a diverse range of Informal Green Spaces (IGS) typologies, with the majority being Brownfield sites. Criterion 4, Accessibility, emerged as the predominant determinant, given that half of the sites are inaccessible to the public. Therefore, sites B, D, and H were selected due to their accessibility, representation of different LCZ categories, size exceeding 1 ha, and distinctive IGS typological characteristics.

3.4.3. Background of Selected IGS Sites

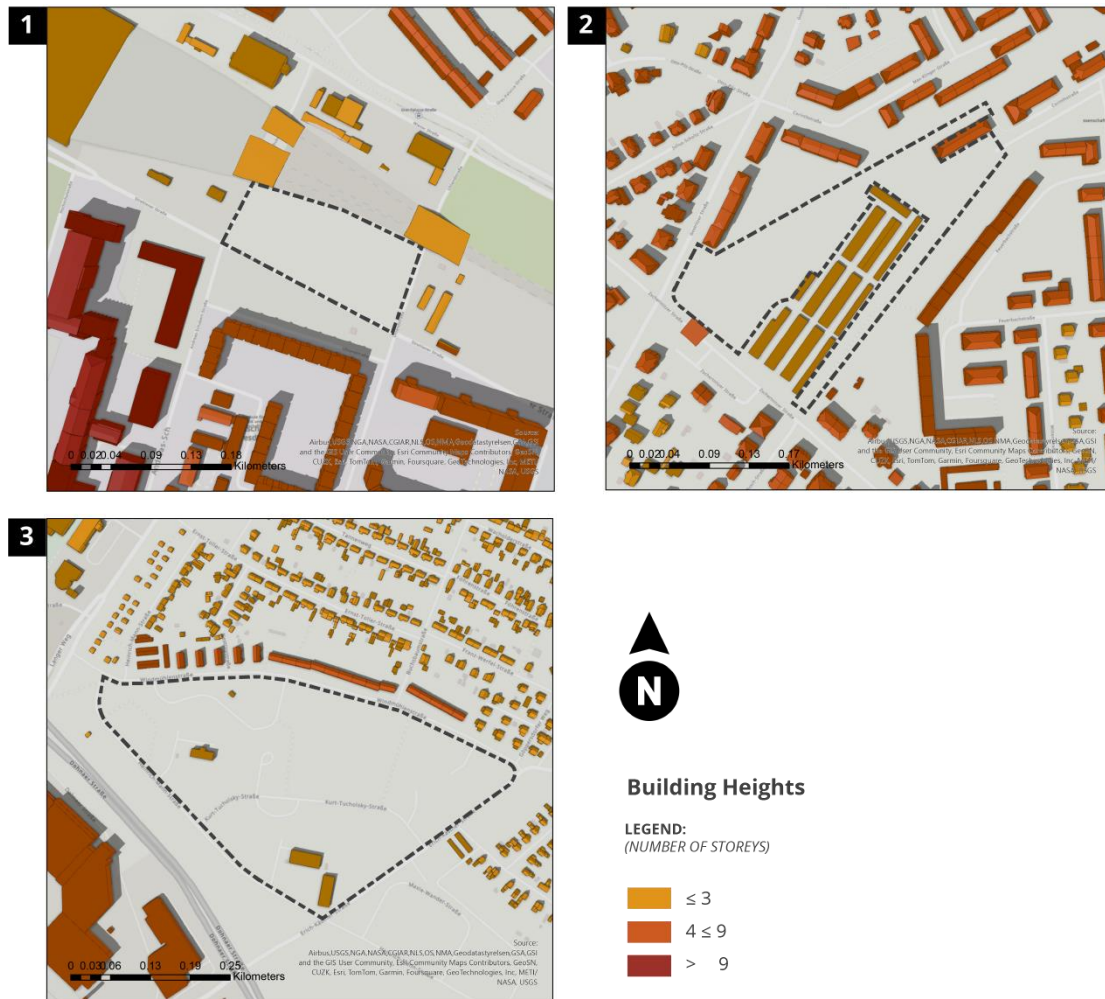


Figure 8 Surrounding Building Heights derived from the 3D Building Model of Dresden (Geoinformation and Surveying Saxony, 2023)

Figure 8 illustrates the immediate urban morphology surrounding the three selected IGS sites. Site 1 is identified as a railway IGS, whereas Site 2 is categorized as a waterside IGS and Site 3 is designated as a brownfield site (formerly a demolition site). All three sites are predominantly surrounded by an open layout of built spaces, albeit the surrounding buildings vary in heights. It is noteworthy however, that the area to the north of Site 1 presents a more compact urban morphology, attributed to its location within the city center of Dresden. Historical satellite images of each site can be found in the Appendix.

The following briefly describes the context of each site:

- 1) **Site 1** (Strehleener Str.) is part of the Dresden Hauptbahnhof, owned by DB InfraGO, and lacks legal status or protection. It is bordered by the railway to the north and a mix of medium to high-rise buildings and parking spaces to the south.
- 2) **Site 2** (Kaitzbach) is a green space intersected by the Kaitzbach River, surrounded by predominantly medium-rise residential buildings. A central parking lot serves the residents of these buildings.
- 3) **Site 3** (Kaufpark) is a former demolition site of the "Star Houses" in Dresden-Prohlis, now a developed and greened area where 10-storey prefabricated buildings from the 1980s were demolished between 2005 and 2009.

3.4.4. General On-site Observations

All three sites despite not being formally managed or maintained, have been observed as transit spaces or corridors that facilitate the movement of pedestrians from one point to another. Pedestrians of various ages, from teens to the elderly, individually, in pairs, or groups, have been observed passing by, riding bicycles, or walking their dogs. Sites 1 and 3 were also observed to serve as resting spaces to sit, drink, chat and smoke a cigarette. While all sites have been observed to have a high level of species richness, this is particularly apparent in Site 1, which serves as a research location for urban ecology studies and a venue for plant photography. Researchers and photographers have been observed visiting the site at least twice during the traverse campaign.

Of the three sites, Sites 2 and 3 have paved pathways utilized by pedestrians. In contrast, Site 1, being the smallest in land area, lacks paved walkways and instead features desire lines. These desire lines are informal paths created by the natural foot traffic of individuals taking the most direct route across open ground. Among the three sites, Sites 2 and 3 also have the most paved surfaces. Site 2 encompasses a large, completely impervious parking area of approximately 1 hectare that serves the nearby

residences. On the other hand, Site 3 features a mix of pathways, roads, residential spaces, and parking areas.

The following Table summarizes the social functions observed in each site:

Table 4 Social Functions of Selected IGS Sites

Site 1 Strehlehnstrasse	Site 2 Kaitzbach	Site 3 Kaufpark
• Venue for activities such as dog walking • Resting space to sit, drink, consume snacks and smoke a cigarette • Venue for studying urban ecology due to its complex vegetation structure and proximity to HTWD • Venue for plant photography, particularly due to the richness of meadow planting	• Transit space for pedestrians. • Venue for activities such as dog walking, biking. • Large central parking lot	• Transit space for pedestrians and occasionally for vehicles • Venue for activities such as dog walking, biking • Resting space to sit, drink, chat and smoke a cigarette • Features park-like elements in certain areas such as benches, trellises and pathways • Temporary residences built on container trucks • Parking lots

3.5. Individual Vegetation Structures (VS)

3.5.1. Biotope Mapping

Unlike the more common practice of using Landsat spatial imagery to derive individual Vegetation Structures (VS) in existing literature, this study utilized highly detailed LiDAR data acquired from the Saxony Open Geodata website. Airborne LiDAR technology has demonstrated its effectiveness in furnishing precise and comprehensive three-dimensional data regarding terrains, building elevations, and vegetation (Koc et al., 2018). As outlined on the Saxony Open Geodata website, laser scanner measurements are employed to generate elevation and urban models through the recording of terrestrial surfaces. The data is captured through laser scanner measurements at a minimum point density of 4 points per square meter, utilizing the DHHN2016 height reference system and the ETRS89_UTM33 (EPSG: 25833)

coordinate reference system. The laser scanner measurements yield data with a height accuracy of ± 0.15 m (State Office for GeoBasic Information Saxony, n.d.).

The biotope maps were created using the 2017 Canopy Height Model (CHM) of Dresden, which provides detailed spatial data on tree canopy heights in a 0.5-meter resolution GeoTIFF format (Münzinger, 2023). The CHM was derived from the 2017 LiDAR data of Dresden, combined with multispectral imagery and a 3D building model, achieving a 95% accuracy (Münzinger, et al., 2022). The classification process employed an object-based data fusion approach, which involved first filtering buildings from the LiDAR point clouds and then identifying trees by integrating the filtered point clouds with aerial images through an object-based image analysis (OBIA) method (Blaschke, 2010 in Münzinger, et al., 2022), followed by applying watershed segmentation to differentiate tree crowns from other objects (Koch et al., 2014 in Münzinger, et al., 2022).

The CHM raster file was then loaded into ArcGIS Pro (Esri, 2016) for further processing following these geoprocessing steps: 1) New Feature Class, to draw and specify the boundary of each site, 2) Clip Raster, to limit the CHM raster to the selected sites, and 3) Reclassify (Spatial Analyst), to reclassify the values of the CHM raster file into low (0 to 1m), medium (1m to 3m), and high (3m and above) levels of vegetation. A more detailed description of the vegetation height classification is discussed in Section 3.6.2, Visual Assessment of Individual Vegetation Structures.

The resulting polygons from the biotope maps were used to quantify the percentages of the three levels of VS as well as the other built elements in the site.



Figure 9 Biotope Map of Site 1 Strehlener Straße

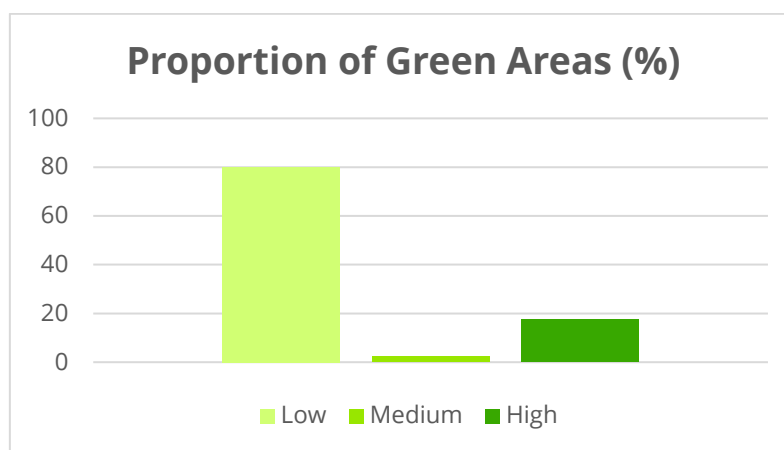


Figure 10 Proportion of Green Areas, Site 1

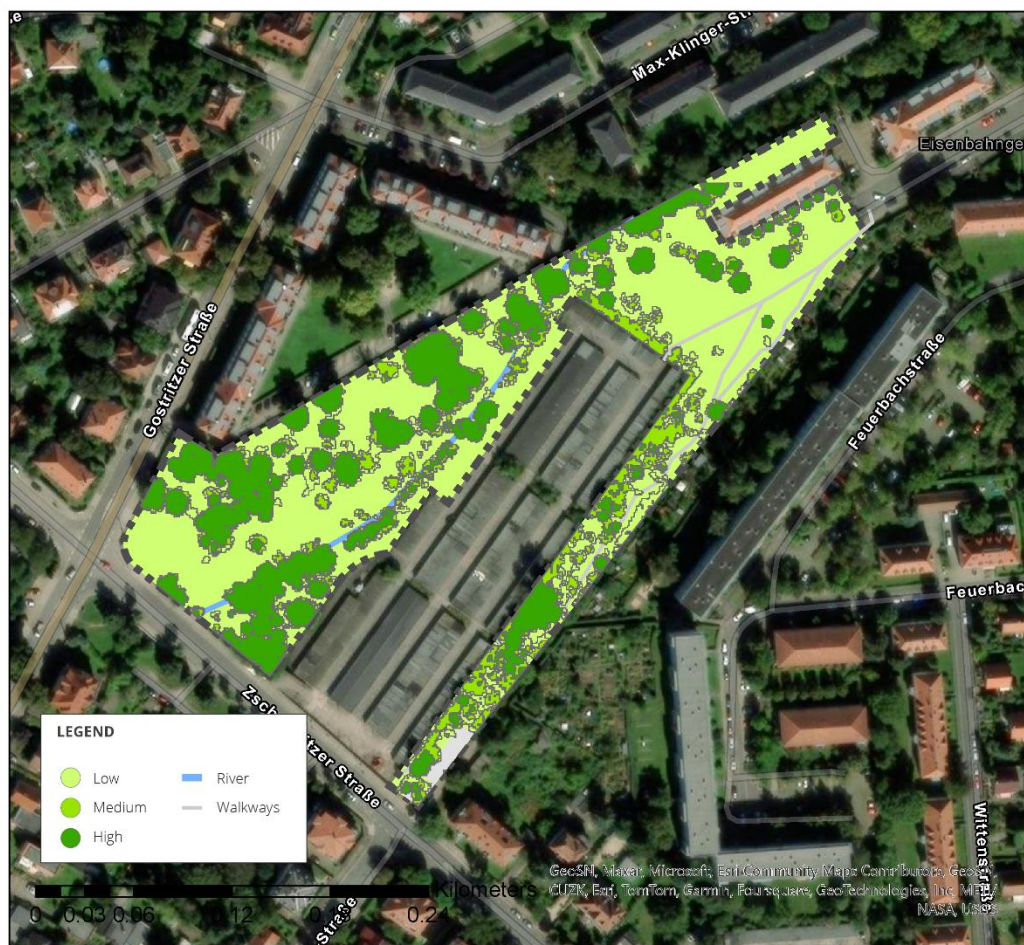


Figure 11 Biotope Map of Site 2 Kaitzbach

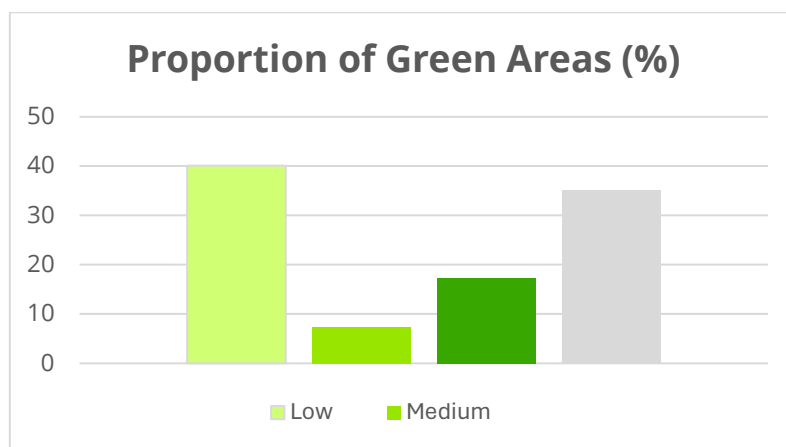


Figure 12 Proportion of Green Areas, Site 2



Figure 13 Biotope Map of Site 3 Kaufpark

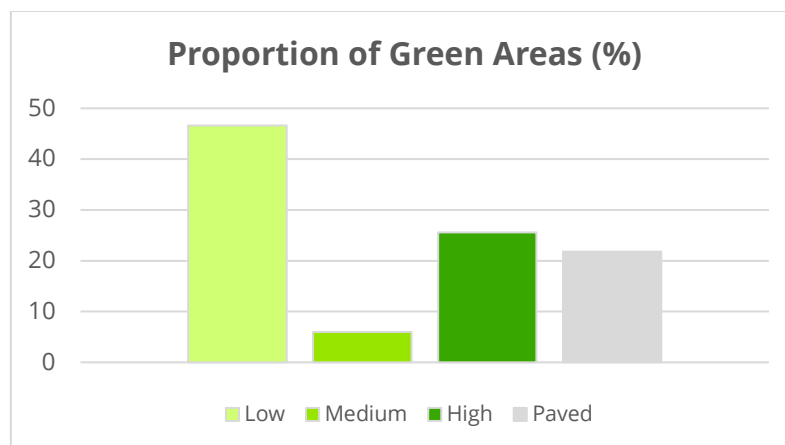


Figure 14 Proportion of Green Areas, Site 3

3.5.2. Visual Assessment of Individual Vegetation Structures

A visual assessment was conducted to further qualify the existing vegetation structure at each site. To aid the visual assessment, a vegetation structure matrix was

adapted based on Lehmann et al. (2014) and Arlt et al. (2005). The matrix categorizes vegetation by height and includes qualitative features such as spatial coverage, level of maintenance, and unique characteristics of each site.

The vegetation structure matrix for each site is presented in Tables 5-7.

Site 1: Lawns are sparse, located only in the middle section of the area near the road. Meadows, on the other hand, dominate the middle to northern portion with very dense coverage. The site also features medium to tall trees, densely clustered on the east side and sparsely scattered on the west side. The understory consists of grass, shrubs, and bushes ranging from 1 meter to around 2 meters in height, characterized by complex, broad-leaf structures. Low shrubs and hedges are observed along the wall separating the site from the railway. However, a more detailed assessment of the vegetation structures along this portion was difficult to verify due to inaccessibility.

The health of the trees at the time of the recordings was noteworthy, as the canopies of most tall trees on the site were dry and shedding, except for a few clusters in the northern section and towards the southeast. Most of the tall shrubs were also dry, while only the grasslands and meadows appeared relatively healthy. Notable special features included stone benches and desire lines.

The site is entirely comprised of vegetation, with approximately 80% classified as Low VS, 18% as High VS, and 2% as Medium VS. However, it is immediately adjacent to the railway and lacks tall screening.

Site 2: According to the visual assessment, Site 2 exhibits a low density of low-level vegetation, such as meadows and lawns. The predominant accessible vegetation structure at the site comprises tall grass up to 1.50 meters in height along the western portion, hedges, and medium-tall shrubs above 1.50 meters in height along the man-made pathways. Except for the man-made pathways, portions of the site are inaccessible due to dense, multi-stem tall shrubs, particularly along the perimeter of the parking lot in the southeastern part of the site. Shrubs characterized by complex, thorny leaf structures, similar to the species found in Site 1, are also observed mostly along the pathways (See Appendix). Clusters and rows of tall trees are found on the western side, which are also inaccessible due to the tall, undisturbed grasslands.

Notable features of the site include frequently utilized man-made pathways, a narrow stream approximately 300 mm to 400 mm wide along the western part, and a parking area in the center that occupies approximately 35.15% of the site. The remaining 64.85% is vegetated, with approximately 40.12% classified as Low VS, 7.34% as Medium VS, and 17.39% as High VS.

Site 3: According to the visual assessment, the Low VS in Site 3 is predominantly composed of grassy shrubs and clusters of bushes distributed throughout the location. The dense structure of the grass and bushes serves as a shelter for wildlife, particularly hares and wild rabbits, as observed during the traverse campaign. Medium to tall hedges line both sides of the narrow-paved paths and rows of medium to tall street trees dominate the perimeter of the site. Meanwhile, complex shrubs are mainly found in the understory of the trees.

Among the three sites, Site 3 features the most variety of paved elements, including man-made park features such as walkways, benches, and play structures, as well as parking lots and residential areas. A residential area made of container trucks was observed on the site, situated in the central-eastern section. However, its exact extent could not be determined due to obstruction by tall vegetation and steel fences, and it was not visible in satellite images. Based on the generated biotope map, paved areas comprise approximately 21.80% of the site, while Low, Medium, and High VS comprise approximately 46.60%, 6%, and 25.60% of the site, respectively.

The vegetation in all three sites was observed to be wild, without any signs of maintenance. Therefore, the most used vegetation structures were those found along man-made paths, paved surfaces and desire lines. All three sites exhibit spontaneous vegetation and species richness; however, Site 2 was found to exhibit greater diversity in its VS compared to Sites 1 and 3.

Table 5 Visual Assessment Matrix, Site 1

Height class of vegetation layer	Site 1 Strehlenstraße																
	Selected structural characteristics <i>(adapted from Lehmann et al., 2014)</i>																
	Spatial coverage and assessment					Intensity of maintenance		Leaf characteristics				Special features					
	sparse	of low density	in clusters	in rows	dense	low	high	broad	fine	grassy	compound	waterbody	border greenery (i.e., vegetation beside pathways, roads and sidewalks)	man-made pathways i.e., desire lines or paved walkways	parking	residences	park-like elements i.e., boulders, benches, play structures
Lawn	x						x			x							
Meadow					x	x				x							
Shrubs, grass and herbs ≤ 45cm					x	x		x		x	x						
Low hedges ≤ 1m		x				x			x		x						
Shrubs, grass and herbs > 1m			x			x		x		x	x						
Bushes ≤ 2m			x			x		x	x		x			x			x
Medium hedges >1 ≤ 2.5m				x		x		x	x		x						
Tree hedges > 2.5m		x				x			x		x						
Small trees ≤ 3m	x					x			x		x						
Medium trees > 3 ≤ 5m			x			x		x	x		x						
Tall trees > 5m			x			x		x	x		x						

Table 6 Visual Assessment Matrix, Site 2

Height class of vegetation layer	Site 2 Kaitzbach																
	Selected structural characteristics <i>(adapted from Lehmann et al., 2014)</i>																
	Spatial coverage and assessment					Intensity of maintenance		Leaf characteristics				Special features					
	sparse	of low density	in clusters	in rows	dense	low	high	broad	fine	grassy	compound	waterbody	border greenery (i.e., vegetation beside pathways, roads and sidewalks)	man-made pathways i.e., desire lines or paved walkways	parking	residences	park-like elements i.e., boulders, benches,play structures
Lawn		x				x				x		x	x	x	x		
Meadow	x					x				x							
Shrubs, grass and herbs ≤ 45cm					x	x				x							
Low hedges ≤ 1m				x		x			x		x						
Shrubs, grass and herbs > 1m					x	x			x	x	x						
Bushes ≤ 2m				x		x		x	x		x						
Medium hedges >1 ≤ 2.5m				x		x			x		x						
Tree hedges > 2.5m				x		x			x		x						
Small trees ≤ 3m				x		x		x	x		x						
Medium trees > 3 ≤ 5m			x	x		x		x	x		x						
Tall trees > 5m			x			x		x	x		x						

Table 7 Visual Assessment Matrix, Site 3

Height class of vegetation layer	Site 3 Kaufpark																
	Selected structural characteristics <i>(adapted from Lehmann et al., 2014)</i>																
	Spatial coverage and assessment					Intensity of maintenance		Leaf characteristics				Special features					
	sparse	of low density	in clusters	in rows	dense	low	high	broad	fine	grassy	compound	waterbody	border greenery (i.e., vegetation beside pathways, roads and sidewalks)	man-made pathways i.e., desire lines or paved walkways	parking	residences	park-like elements i.e., boulders, benches, play structures
Lawn		x				x				x							
Meadow	x					x				x							
Shrubs, grass and herbs ≤ 45cm					x	x				x							
Low hedges ≤ 1m				x		x			x		x						
Shrubs, grass and herbs > 1m	x					x			x		x						
Bushes ≤ 2m		x				x		x	x		x		x		x	x	x
Medium hedges >1 ≤ 2.5m				x		x			x		x						
Tree hedges > 2.5m				x		x			x		x						
Small trees ≤ 3m	x					x		x	x		x						
Medium trees > 3 ≤ 5m				x		x		x	x		x						
Tall trees > 5m				x		x		x	x		x						

3.6. In-situ Air Temperatures

In this study, air temperature measurements were obtained by utilizing a fixed station and by conducting the traverse method. Traverses are efficient for detecting spatial variations in air temperature, humidity, surface temperature, radiation, and air pollutants, and they offer a comprehensive view of microclimate diversity in urban areas, serving as a cost-effective complement to fixed station networks (Oke et al., 2017). Due to the predominantly vegetated nature of the sites, the traverses were conducted on foot. Temperature and humidity data were recorded at each location using a Tinytag data logger, while the Survey 123 mobile application was utilized to record the geolocation, date, time, and general observations of the vegetation structures at each point.

According to Meteostat, during May, Dresden typically experiences an average maximum temperature of approximately 20.5°C and an average minimum temperature of around 12.6°C. It receives an average of 63.8mm of rainfall throughout the month and has an average cloud cover of approximately 69%, based on a 10-year dataset (DWD Climate Data Center, 2024). Due to the frequency of precipitation and cloudy skies throughout the month, selecting the days for the traverse study has been particularly challenging.

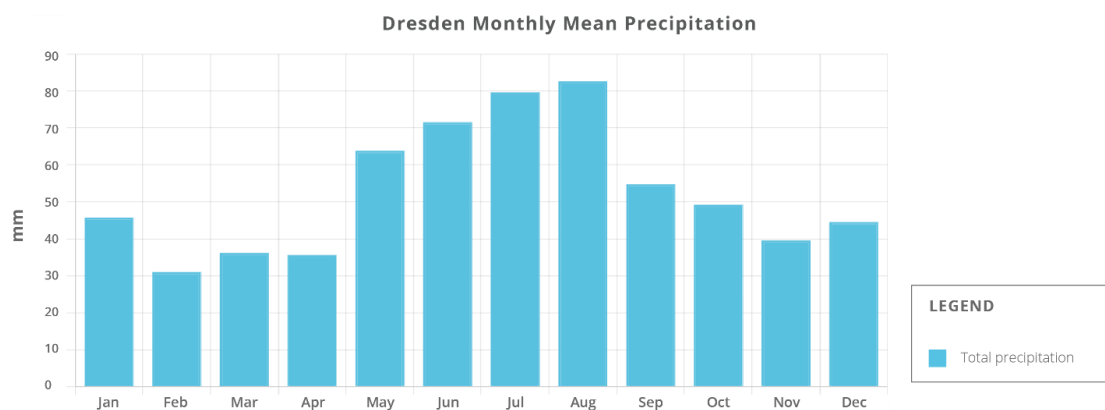


Figure 15 Dresden Monthly Mean Air Temperature

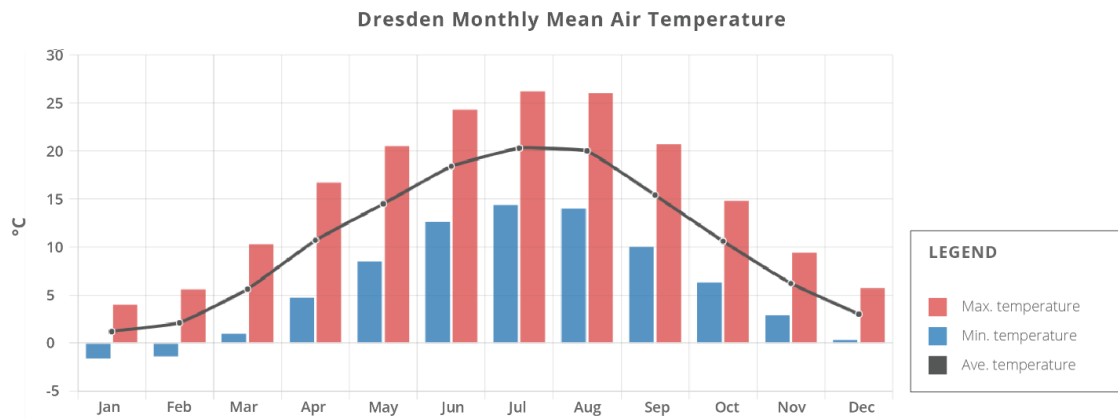


Figure 16 Dresden Monthly Mean Precipitation

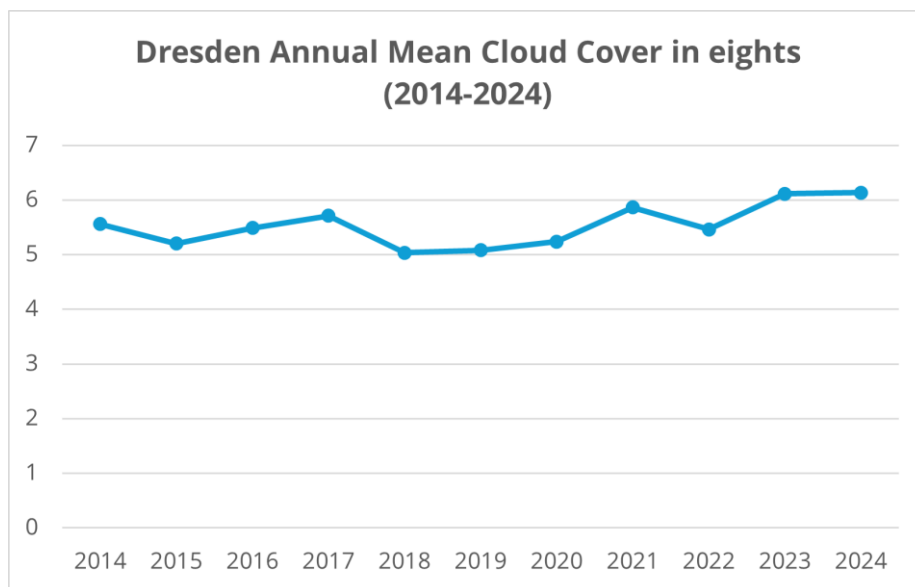


Figure 17 Dresden Annual Mean Cloud Cover (2014-2024)

The measurements were conducted during the 2nd to 4th weeks of May 2024, over seven (7) non-consecutive days. During the day, solar heating warms the ground, storing heat in the morning and releasing it into the air in the afternoon, while at night, the ground cools more under clear skies, causing heat to move upward from below the surface (Oke et al., 2017). According to Oke (1981) and Grimmond and Oke (1999), the most significant temperature variations typically occur a few hours prior to sunset. Accordingly, the traverse studies were conducted twice per day: in the afternoon between 14:30 to 16:30, and in the evening between 19:00 to 21:00. Each traverse campaign was completed within 40 minutes to 1 hour. Two Tinytag Plus 2 (TGP-4500) data loggers were employed, one for the traverse study: and the other to serve as the fixed station.

3.6.1. Fixed Station

The weather station located near the Dresden University of Applied Sciences (HTWD) was assigned as a fixed station. The first Tinytag logger was installed on a mound 2 meters above ground level (AGL), in a shaded, quiet green space, housed within a naturally ventilated inverted cone-shaped aluminum foil to safeguard it from rain and direct sunlight. The fixed station recorded the entire traverse campaign, specifically Air Temperature (AT) and Relative Humidity (RH) values. Information on Wind Velocity, Wind Direction and Cloud Cover were obtained from the German Weather Service (Deutscher and Wetterdienst, 2024).

Table 8 summarizes the details of the weather conditions for all 7 (seven) days in the campaign.



Figure 18 Images, Fixed Weather Station, Dresden

Table 8 Weather Conditions, Traverse Campaign

Site	Image	Date	Time	Air Temperature (AT) Fixed °C	Air Temperature (AT) Traverse °C	AT Difference °C	Humidity	Mean Hourly Wind Velocity	Wind Direction (Cardinal)	Cloud Cover
1		10-May	Afternoon	24.9	26.4	1.5	33.2%RH	3.07m/s	SW	87.5%
		10-May	Evening	21.2	23.9	2.7	37.7%RH	0.9m/s	SW	91.6%
		13-May	Afternoon	28.1	32.5	4.4	21.6%RH	5.13m/s	NW	0.0%
		13-May	Evening	21.5	22.3	0.8	29.2%RH	4.93m/s	NW	0.0%
2		14-May	Afternoon	28.2	30.3	2.1	23.9%RH	6m/s	NW	0.0%
		14-May	Evening	23.6	26.3	2.7	27.6%RH	4.23m/s	NW	0.0%
		20-May	Afternoon	25.7	30.8	5.1	40.4%RH	2.87m/s	SW	50.0%
		20-May	Evening	21.1	23.4	2.2	61.7%RH	1.37m/s	SW	20.9%
3		15-May	Afternoon	28.8	29.6	0.8	23.0%RH	8.5m/s	NW	8.4%
		15-May	Evening	24.8	26.2	1.4	26.5%RH	5m/s	NW	0.0%
		26-May	Afternoon	25.1	29.0	3.8	51.9%RH	5.47m/s	NE	100.0%
		28-May	Evening	16.1	20.5	4.4	99.6%RH	2.6m/s	SE	45.9%

Due to variations in weather conditions during the campaign, only the measurements from May 13, 2024, to May 15, 2024, shall be expounded upon and processed. The weather conditions on these dates are relatively similar, with little to no cloud cover and similar temperature ranges.

3.6.2. Traverse Study

The second Tinytag device was securely attached to the proponent's backpack, approximately 1.4 meters above ground level, recording temperature and humidity every 10 seconds. An inverted cone-shaped piece of aluminum foil was used to shield the device from direct sunlight. To ensure data precision, a two-minute pause was implemented at each traverse point to allow the logger to stabilize.

Thirteen (13) traverse points were plotted at Site 1 while twelve (12) traverse points were plotted at Sites 2 and 3 based on on-site observations of vegetation structure complexity, accessibility of vegetation types (e.g., tall, impenetrable thorny shrubs), and the intention to minimize disturbance to untouched flora. Consequently, most points in areas with medium and tall vegetation were placed nearby or along man-made paths such as paved walkways and 'desire lines,' while points in low vegetation or grasslands, which were more accessible, were mapped more conveniently.

Figures 19-21 show the traverse points for each selected IGS site. Each point is qualified by the type of Vegetation Structure (VS) as well as the Canopy Cover (CC),

described as: *no shade, partial shade, and deep shade*. Images and field notes were taken at each traverse point to support the visual assessment and the representation of each vegetation structure (**See Appendix**).



Figure 19 Site 1 Strehleener Straße, Traverse Points

Among all vegetation structures present at **Site 1** (Figure 19), only the low levels were mainly accessible, particularly at points A, B, and C, as well as along the desire lines between tall trees at points D, E, F, G, and H. Of the thirteen points assessed, four were categorized as Low VS, four as Medium VS, and four as High VS. The vegetation structures on site have been observed to be complex, with the presence of understory leafy bushes, grass and other types of ground cover.

During the visual assessment, it was noted that most of the trees were not in good health at the time of the traverse; consequently, only points H, I, and L were classified as ‘deeply shaded,’ whereas the remaining points were either non-shaded or partially shaded.

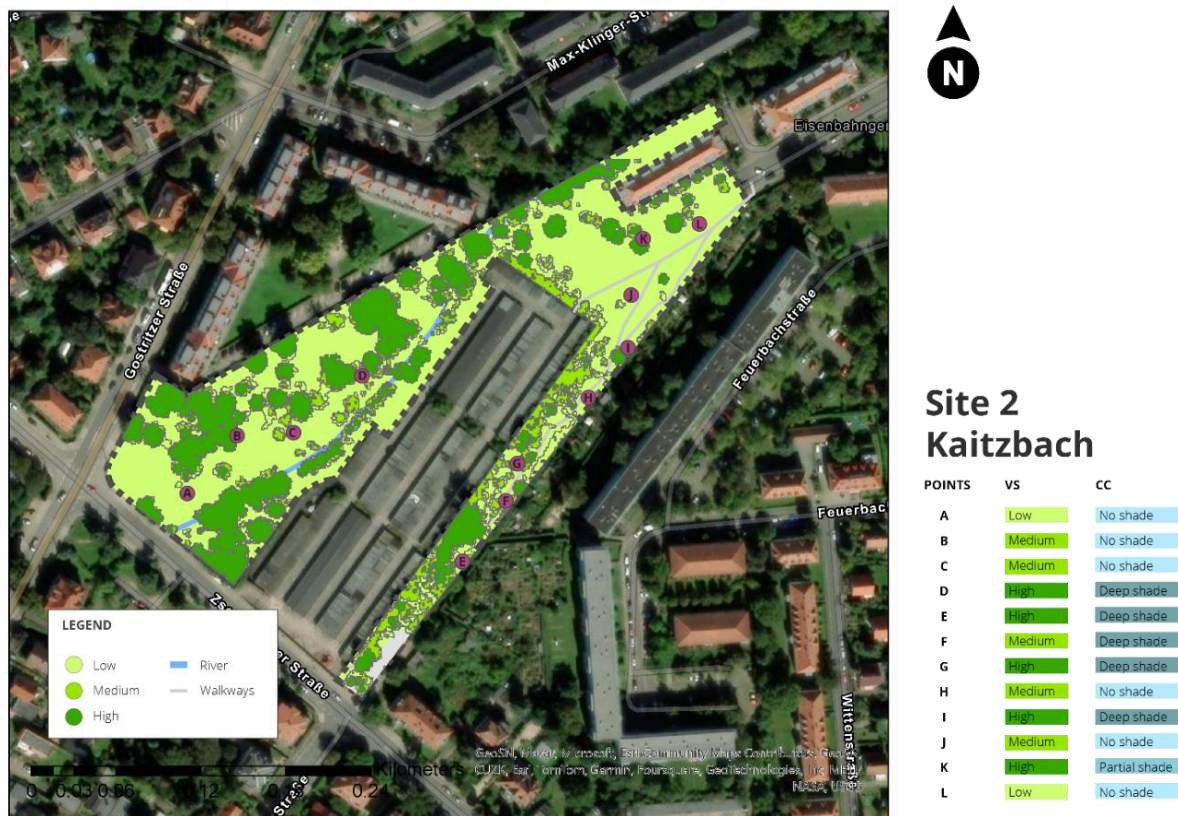


Figure 20 Site 2 Kaitzbach, Traverse Points

Site 2 (Figure 20) was represented by a total of 12 traverse points, of which two were classified as Low VS, five as Medium VS, and five as High VS. Particularly at points E, F, G, H, and I, the vegetation structures were predominantly medium to tall, comprising of hedges and trees, thereby providing partial to deep shade from the canopy cover. Points B and C comprised tall, dense, grassy shrubs, albeit with no direct canopy to provide shade from the afternoon sun. It is noteworthy that at point D, while the canopy cover was observed to be deep from both sides, the vegetation layout from this point towards the northeastern direction became more open, with sparse low trees and shrubs, allowing more airflow from the adjacent part of the parking lot to its east. Due to the arrangement of vegetation at point D and the topography, which was observed to be nearly level with the parking lot, the visibility of the parking lot from this location was notably more pronounced.



Figure 21 Site 3 Kaufpark, Traverse Points

Site 3 was represented by a total of 12 traverse points, of which four were classified as Low VS, four as Medium VS, and five as High VS. Because most trees were located along streets or the perimeter of the site, it has been challenging to obtain recordings in deep shade. Thus, only three out of twelve points were recorded under this condition. The rest of the points had shade on only one side; hence, five out of twelve points were categorized as partially shaded, while the remaining points were not shaded by canopies.

It is noteworthy that the plot between points D, E, and K was fenced and observed to have been converted into a residential area with container trucks built as homes. While it appears to still have tall trees and hedges around its perimeter, it was difficult to determine the level of pavedness, as it was not completely visible from the outside. Moreover, towards the southwest of point I, a large section of the grassland has been cleared, and the operations seemed to be ongoing, with piles of rubble and gravel indicating active construction or development activities.

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Results

This section presents the results obtained from visual assessments and traverse studies conducted at each of the 3 IGS sites. Specifically, it examines air temperature values recorded using the Tinytag logger during the traverse study from May 13 to May 15, 2024. This investigation aims to interpret correlations among these variables and explore implications arising from the configurations of vegetation, canopy cover, paved surfaces, and anthropogenic sources of heat such as transport infrastructure or buildings. The first 10 minutes of the traverse data were discarded to avoid distortions from the previous movements.

4.1.1. Air Temperatures

The following maps depict the urban heat island maps illustrating actual afternoon (Figures 22, 26, 30) and evening (Figures 24, 28, 32) measurements for each site. To derive these maps, average air temperature measurements were recorded at traverse points during both afternoon and evening periods. These measurements were spatially referenced using x and y coordinates and subsequently plotted in ArcGIS Pro to construct spatial datasets. The Inverse Distance Weighting (IDW) geoprocessing tool was utilized to interpolate temperatures across the study areas. IDW operates by estimating values for unknown locations based on nearby known points, assigning greater influence on closer points in the interpolation process (Esri, n.d.). Consequently, this approach facilitated the creation of continuous surface maps depicting the distribution of air temperatures at each site, effectively delineating areas characterized by elevated or reduced temperature concentrations.

4.1.1.1. Actual Air Temperatures: Site 1

The afternoon air temperatures range from 31.5 °C to 34.0 °C, as seen in Figure 22 below. Upon initial inspection, the hottest points are observed in F, succeeded by points E and M (*See Appendix for images and visual assessment of each point*). On the

other hand, the coolest temperature was observed in point A. Between the minimum and maximum temperatures at the site, there was a 2.5 °C difference.

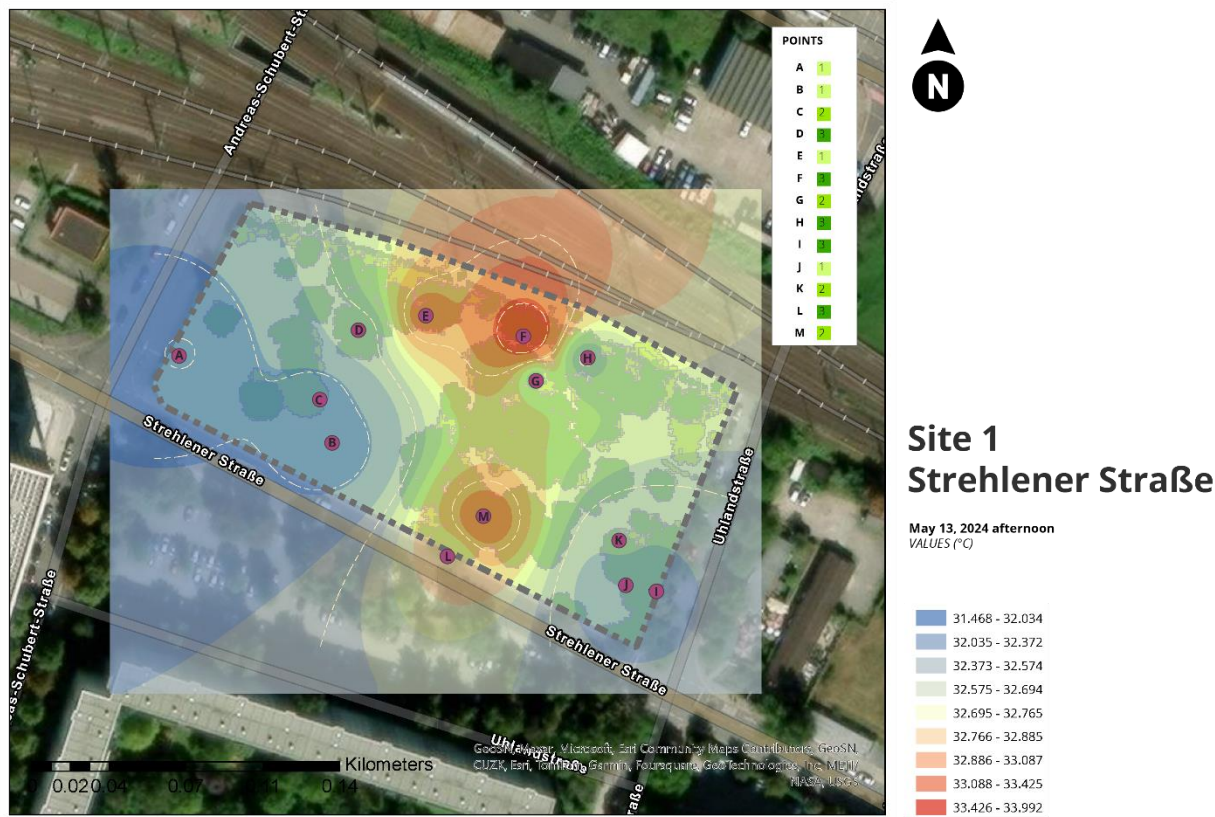


Figure 22 May 13, 2024, Afternoon Air Temperature Distribution, Site 1

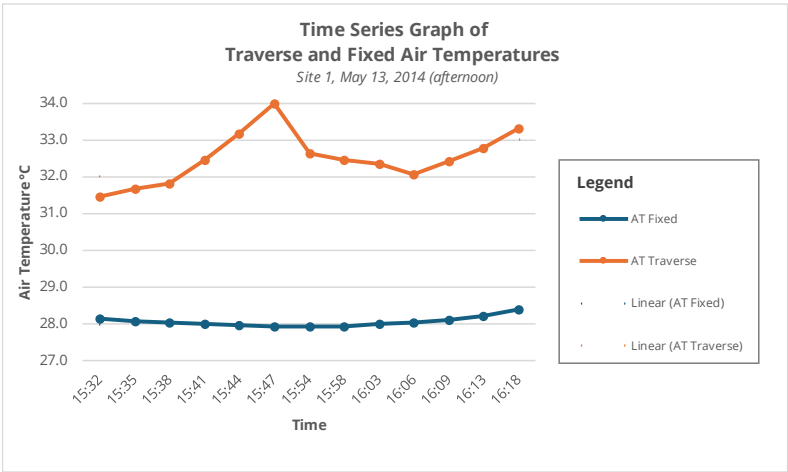


Figure 23 May 13, 2024, Afternoon, Time Series Graph, Site 1¹

Figure 23 shows the time series graph of air temperatures per traverse point, recorded at Site 1, on the afternoon of May 13, 2024. The graph reveals significant

¹ See Chapter 3.6.1. Fixed Station, for site conditions at AT Fixed

fluctuations over the observed period. The temperature initially rises from approximately 31.5°C at 15:32, reaching a peak of about 34.0°C by 15:47. This is followed by a sharp decline to around 32.6°C at 15:54. Subsequently, the temperature stabilizes, alternating between 32.5°C and 32.4°C until 16:06. After this period of relative stability, the temperature exhibits a gradual upward trend, finishing at approximately 33.3°C by the end of the traverse at 16:18. Overall, the trends result to an increase in air temperatures of 0.04°C/minute ^[2] during the entire afternoon traverse at this site.

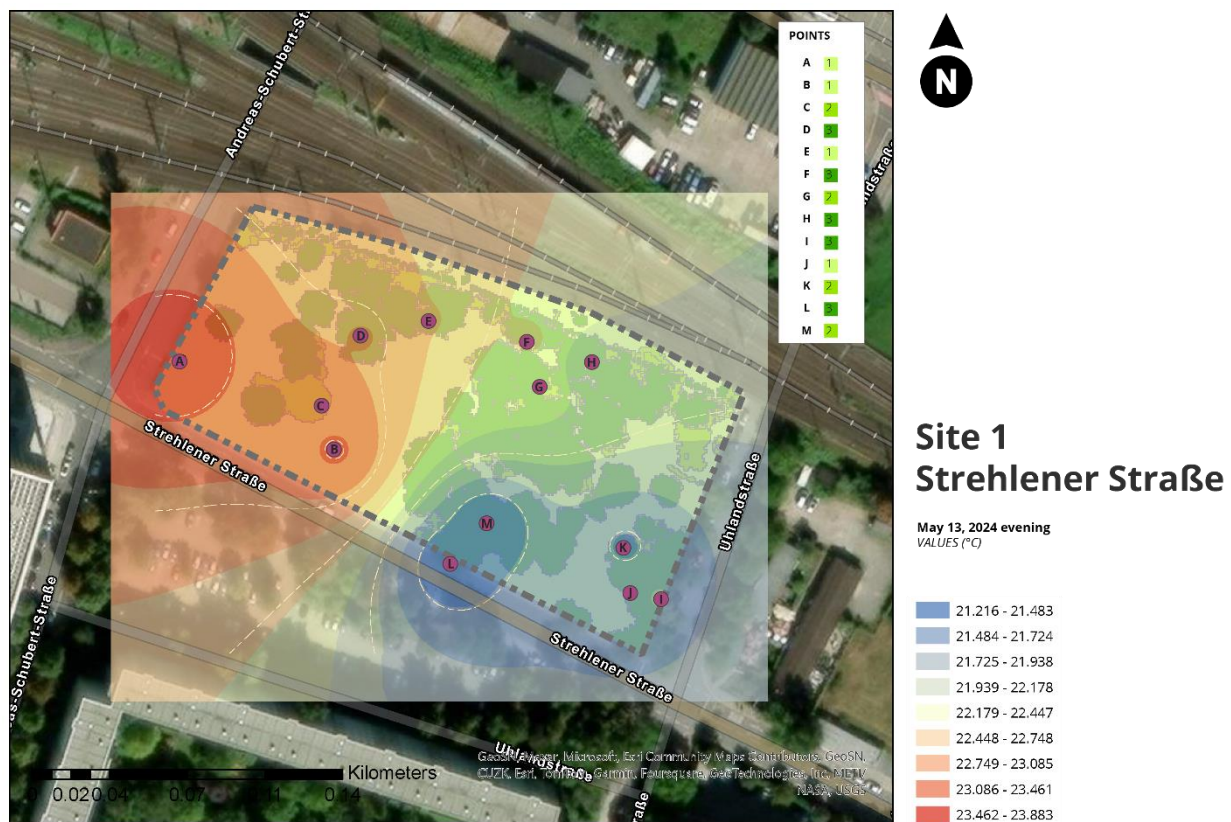


Figure 24 May 13, 2024, Evening, Air Temperature Distribution, Site 1

The air temperature values from the evening traverse of May 13, 2024, at Site 1, as shown in Figure 24 above, highlight areas with higher temperatures concentrated in the southwest (points A, B, and C), while cooler temperatures are predominantly in the southeast (points L and M). The highest and lowest values have a difference of approximately 2.7°C.

² Cooling rate = (final AT – initial AT)/ time elapsed

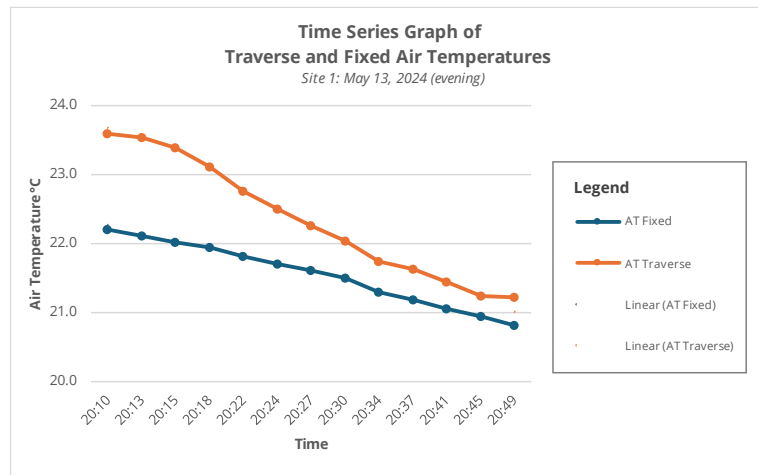


Figure 25 May 13, 2024, Evening, Time Series Graph, Site 1

On the other hand, on the evening of May 13, 2024, the time series graph illustrates a consistent decline in temperature throughout the observed period. Starting at approximately 23.6°C at 20:10, the temperature gradually decreases to around 21.2°C by 20:49. The data points reveal a steady downward trend, with temperatures falling from 23.5°C at 20:13 to 22.8°C by 20:22, and continuing to decline to 21.7°C by 20:34. The trend persists, with the temperature reaching 21.4°C by 20:41, and then stabilizing slightly above 21.0°C towards the end of the period. This results in a cooling rate of 0.06°C per minute for the entire evening traverse.

4.1.1.2. Actual Air Temperatures: Site 2

The afternoon air temperatures range from 29.2 °C to 33.8 °C, showing a difference of 4.6 °C between the recorded minimum and maximum air temperatures, as shown in Figure 26, below. Upon initial inspection, the hottest points are observed in points C to D (See Appendix for images and visual assessment for each point). On the other hand, the coolest points are observed along points E to H.

Due to an initial misjudgment regarding site access, the afternoon traverse commenced from point L and concluded at point D. Subsequently, it was determined that the site was more accessible via Zschernitzerstrasse, which facilitated the evening traverse to start from point A and conclude at point L.

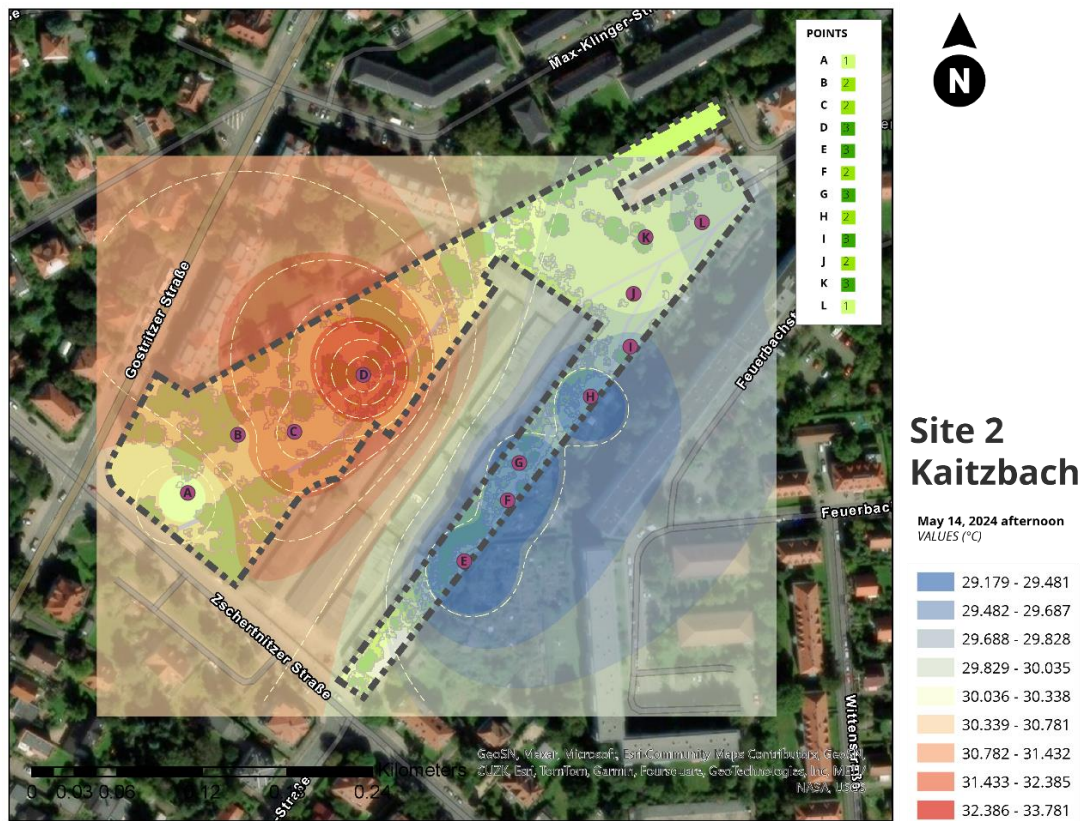


Figure 26 May 14, 2024, Afternoon, Air Temperature Distribution, Site 2

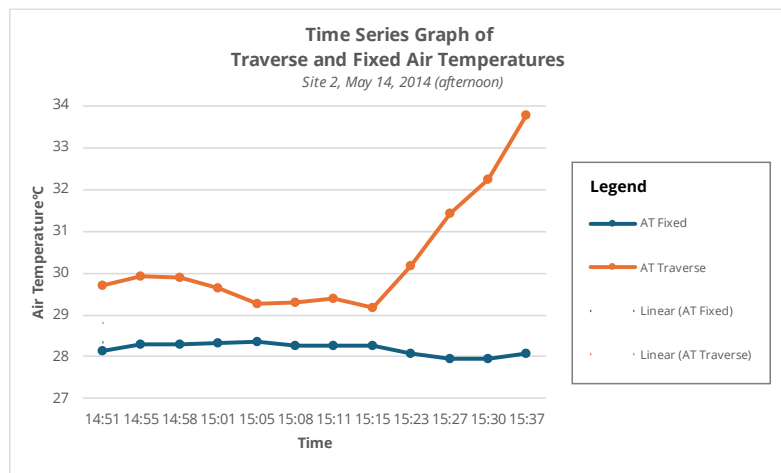


Figure 27 May 14, 2024, Afternoon, Time Series Graph, Site 2

The time series graph of air temperature at Site 2 on the afternoon of May 14, 2024, shown in Figure 27, demonstrates a general upward trend with some fluctuations. Beginning at approximately 29.7°C at 14:51, the temperature exhibits slight variations around this value until 15:11. Following this period of relative stability, the temperature starts to rise more steadily from 30.2°C at 15:23. The upward trend becomes more pronounced towards the end of the observation period, with the temperature increasing

sharply to 33.8°C by 15:37. The observations from this graph indicate an overall warming trend during the afternoon, with a notable acceleration in the rate of temperature increase, at around 0.09°C/minute.

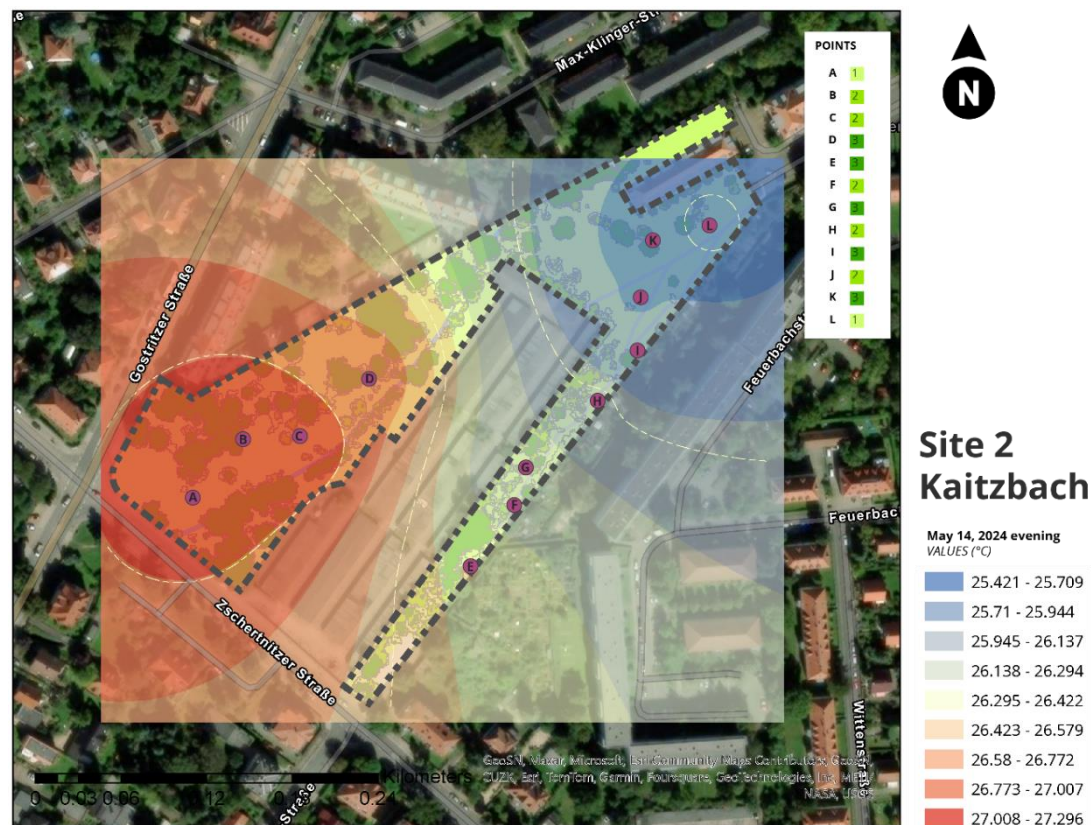


Figure 28 May 14, 2024, Evening, Air Temperature Distribution, Site 2

The evening measurements are depicted in Figure 28. Warmer temperatures are concentrated in the western region near Gostritzer Straße (points A, B, C, and D) while cooler temperatures are predominantly located in the northeastern area along points K, L, and J. Points E, F, G, H, and I show intermediate temperature ranges, which reflects a transition zone between the warmer and cooler regions. Between the maximum and minimum values, there is a difference of about 1.9°C.

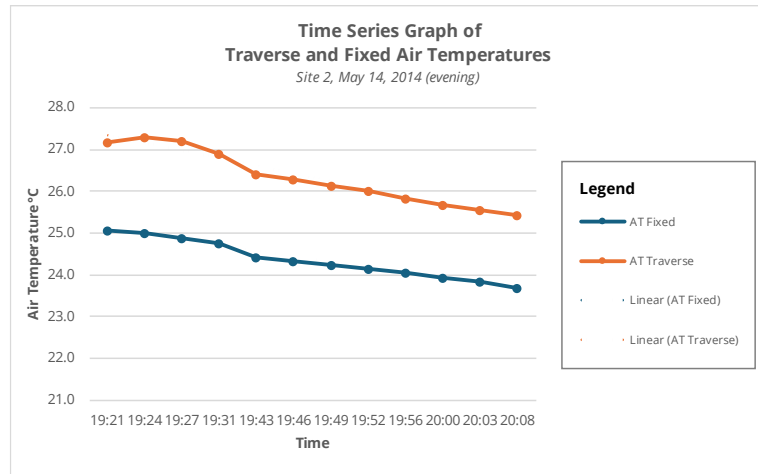
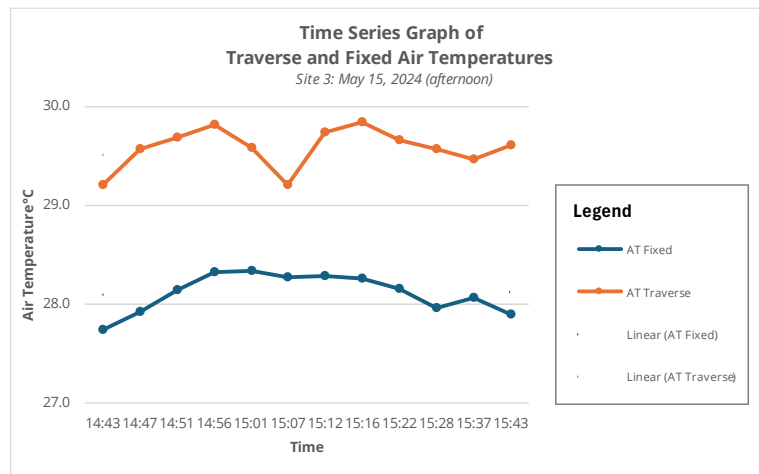
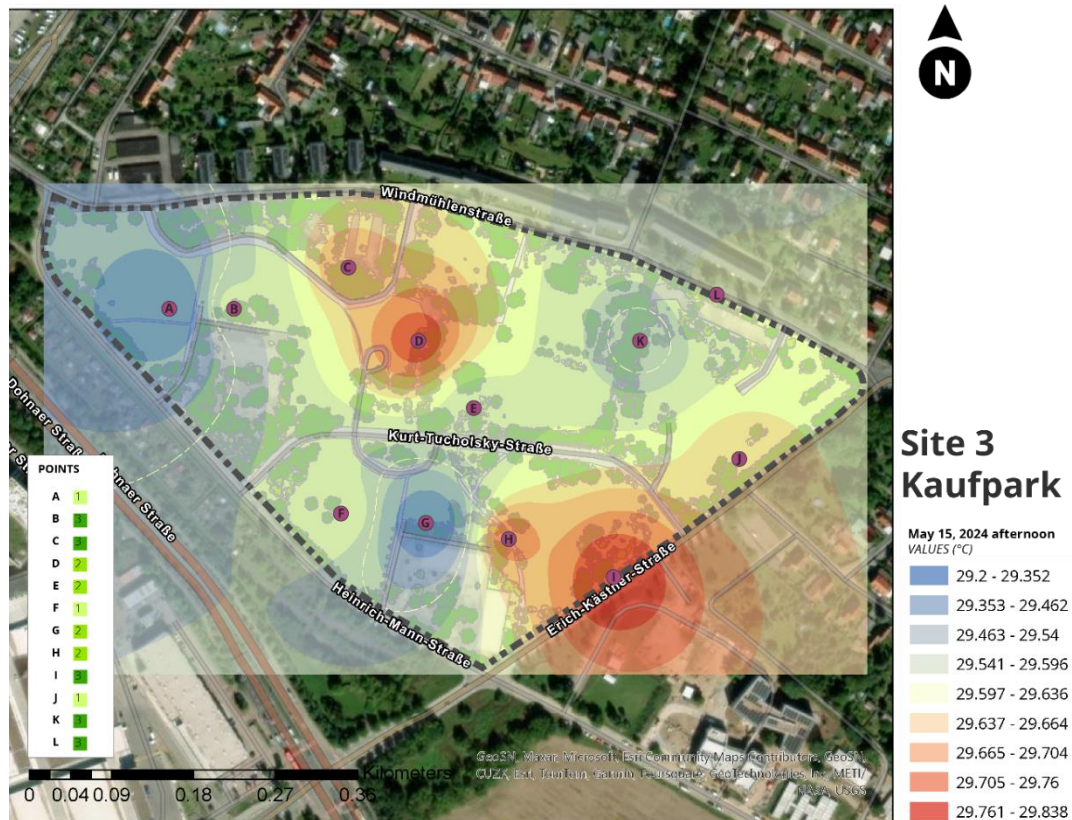


Figure 29 May 14, 2024, Evening, Time Series Graph, Site 2

On the other hand, the evening values demonstrate a general downward trend with some minor fluctuations. Beginning at approximately 27.2°C at 19:21, the temperature exhibits slight variations around this value until point D at 19:31. Following this period of relative stability, the temperature starts to decline more steadily from 26.4°C at point E at 19:43. The downward trend becomes more pronounced from this point towards the end of the observation period, with the temperature decreasing gradually to 25.4°C by 20:08. Overall, the observations from this graph indicate a general cooling trend during the evening, with a consistent decrease in temperature, 0.04°C/minute cooling rate throughout the period.

4.1.1.3. Actual Air Temperatures: Site 3

The afternoon air temperatures at Site 3 range from 29.2°C to 29.8 °C, showing only a difference of 0.6°C between the recorded minimum and maximum air temperatures, as shown in Figure 30. The hottest and coolest points in the site were more distributed instead of being concentrated in one portion. The hottest points are observed in points C to D and H to J (*See Appendix for images and visual assessment for each point*). On the other hand, the coolest points are observed in points A, G and K.



The time series graph depicting air temperature at Site 3 on the afternoon of May 15, 2024, demonstrates notable fluctuations within a relatively narrow temperature range. Starting at approximately 29.2°C at 14:43, the temperature increases steadily, peaking at around 29.8°C by 14:56. Following this peak, a sharp decline is observed, with the temperature dropping to its lowest point of about 29.2°C at 15:07.

Subsequently, the temperature rises again, reaching another peak of approximately 29.8°C by 15:16. The latter part of the observation period is characterized by minor fluctuations, with the temperature oscillating around 29.6°C and ultimately stabilizing at this value by 15:43. Overall, the data indicate only minimal differences, with an increase in the rate of afternoon temperatures of around 0.007°C per minute—further demonstrating the stability of air temperatures at this site.

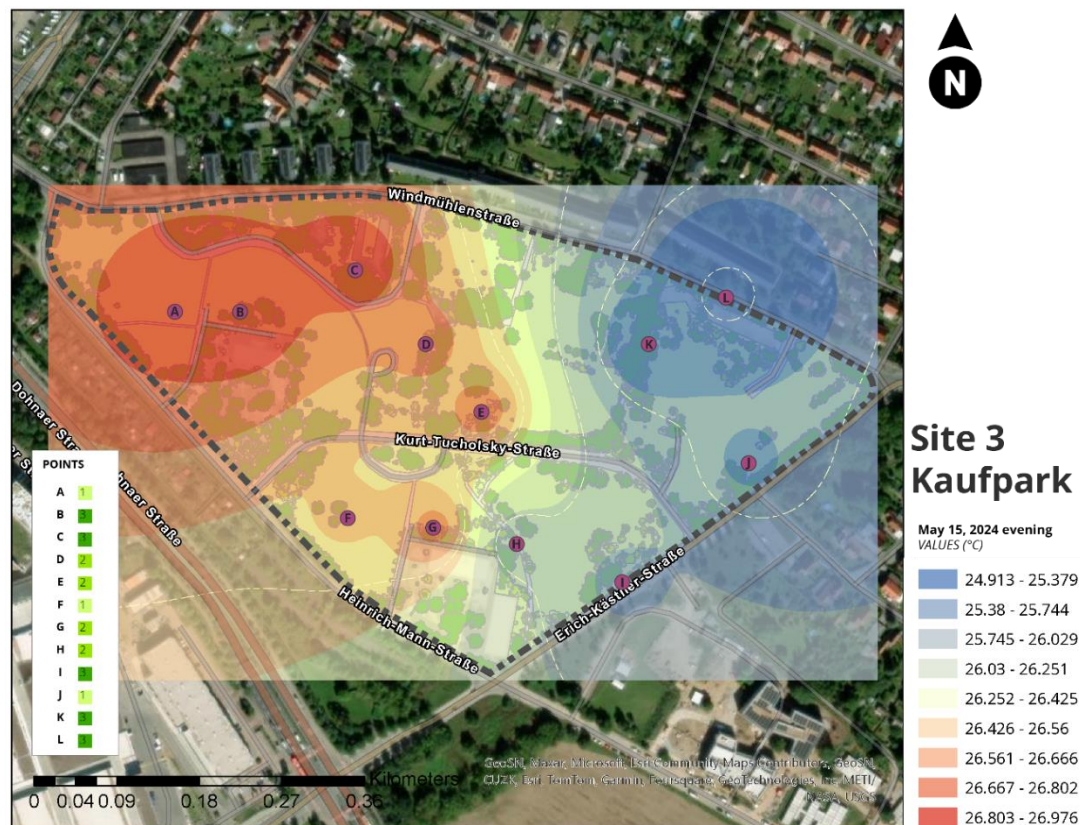


Figure 32 May 15, 2024, Evening, Air Temperature Distribution, Site 3

The air temperature values from the evening traverse on May 15, 2024, at Site 3, highlight a clear pattern across the site, with higher temperatures concentrated in the western region near Dohnaer Straße, along points A, B, and C, while cooler temperatures are predominantly in the eastern and northeastern area near Windmühlenstraße and Erich-Kastner-Straße along points H to L. The temperature range spans from approximately 24.9°C to 27.0°C, having approximately 2.0°C difference between the warmest and coolest points.

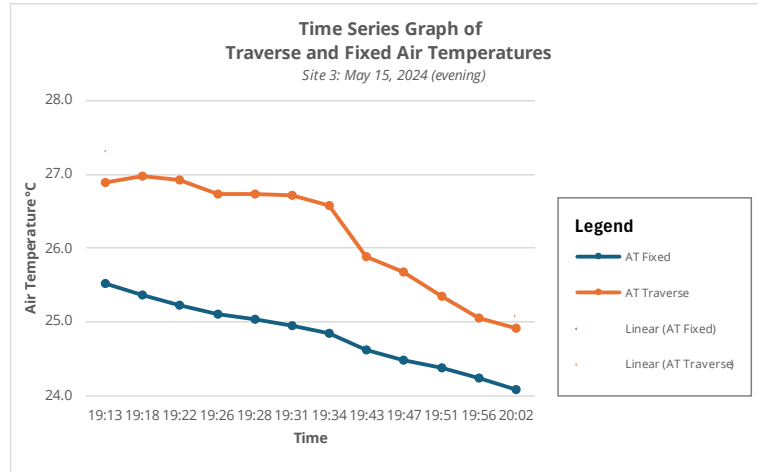


Figure 33 May 15, 2024, Evening, Time Series Graph, Site 3

The time series graph depicting air temperature at Site 3 on the evening of May 15, 2024, reveals a consistent downward trend in temperature over the observed timeframe. Beginning at approximately 26.9°C at 19:13, the temperature shows minor fluctuations but generally declines steadily. The initial period exhibits slight variability, with temperatures oscillating around 26.85°C until 19:28. Subsequently, the temperature drops more markedly, decreasing from 26.7°C at 19:31 to 25.9°C by 19:43. This downward trend becomes more quick from this point, at around 0.05°C/minute cooling rate compared to the 0.02°C/minute cooling rate until 19:34. This downward trend continues, with the temperature reaching around 25.0°C by 20:02. Overall, the data indicate a clear cooling trend throughout the evening, with a steady and pronounced decrease in air temperature during the specified timeframe.

4.1.1.4. Synthesis of Air Distribution Across Selected IGS Sites

To visualize the overall actual results from all three IGS sites from May 13-15, 2024 (Refer to Table 8 in Chapter 3.6.1 for the Fixed Station recordings), the symbology of the heat island maps was modified to accurately reflect the variations in air temperatures across the three locations. The overall minimum recorded temperature was 29.178°C (from Site 2: Kaitszbach), and the maximum was 33.998°C (from Site 1: Strehleener Straße). The range of air temperature difference across the sites was calculated using the following equation:

$$\text{Total Range} = \text{AT Maximum} - \text{AT Minimum}$$

$$= 33.998 - 29.178 = 4.82$$

Next, the Total Range was divided into 9 equal categories to obtain the Standard Interval:

$$\text{Standard Interval} = \frac{\text{Total Range}}{\text{No. of Catagories}}$$

$$= \frac{4.82}{9} = \approx 0.5356$$

Now, 9 categories representing the actual AT differences across the three sites can be defined by adding the Standard Interval incrementally to the minimum temperature, represented by the following colour codes:

Table 9 Standard Afternoon Temperature Symbology

Color Code	Temperature Range (°C)
#7D9ECC	29.2 - 29.7
#A6B9D2	29.7 - 30.2
#C7D1D6	30.2 - 30.8
#E1E9DB	30.8 - 31.3
#F8FBDD	31.3 - 31.9
#F8E1C2	31.9 - 32.4
#F7C1A2	32.4 - 32.9
#F09A7F	32.9 - 33.5
#E4695C	33.5 - 34.0

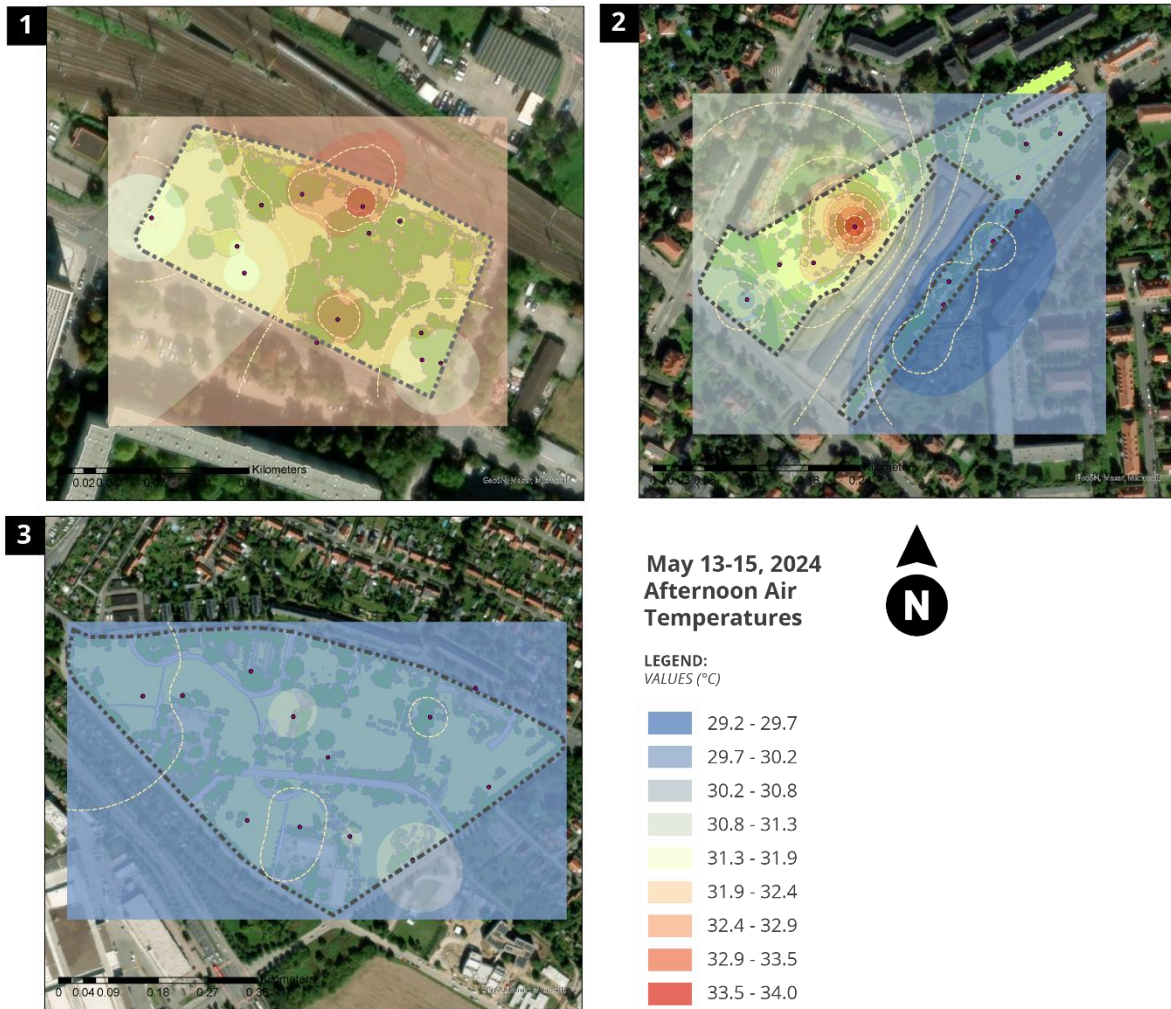


Figure 34 Comparison of Afternoon Air Temperatures Across Study Sites

The analysis of temperature data across the three sites—Sites 1,2 and 3—reveals distinct patterns of variability when compared to using the standardized temperature categories. Among the three sites, Site 2 exhibits the broadest temperature range, spanning from Category 1 (29.2 to 29.7°C) to Category 9 (33.5 to 34.0°C). In contrast, Site 3’s temperature range of 29.2 to 29.8°C is confined primarily to Category 1 and extends only slightly into Category 2, indicating a stable and narrow temperature range with minimal variability.

On the other hand, Site 1’s temperature range, from 31.5 to 34.0°C, encompasses Categories 5 through 9, signifying a higher minimum temperature and a broader range compared to Site 3, yet not as extensive as Site 2. This intermediate range suggests that Site 1 experiences overall warmer temperatures with moderate variability.

The average afternoon air temperature for Site 1 is 32.5°C, 30.3°C for Site 2 and 29.6°C for Site 3, with Sites 2 and 3 being cooler than Site 1 by around 2.3°C and 2.9°C, respectively.

The same process was conducted for the symbology of the evening measurements, having ≈ 0.6756 as the standard interval. The resulting evening symbology and air temperature distribution maps are as follows:

Table 10 Standard Evening Temperature Symbology

Color Code	Temperature Range (°C)
#7D9ECC	21.2 - 21.9
#A6B9D2	21.9 - 22.6
#C7D1D6	22.6 - 23.2
#E1E9DB	23.2 - 23.9
#F8FBDD	23.9 - 24.6
#F8E1C2	24.6 - 25.3
#F7C1A2	25.3 - 25.9
#F09A7F	25.9 - 26.6
#E4695C	26.6 - 27.3

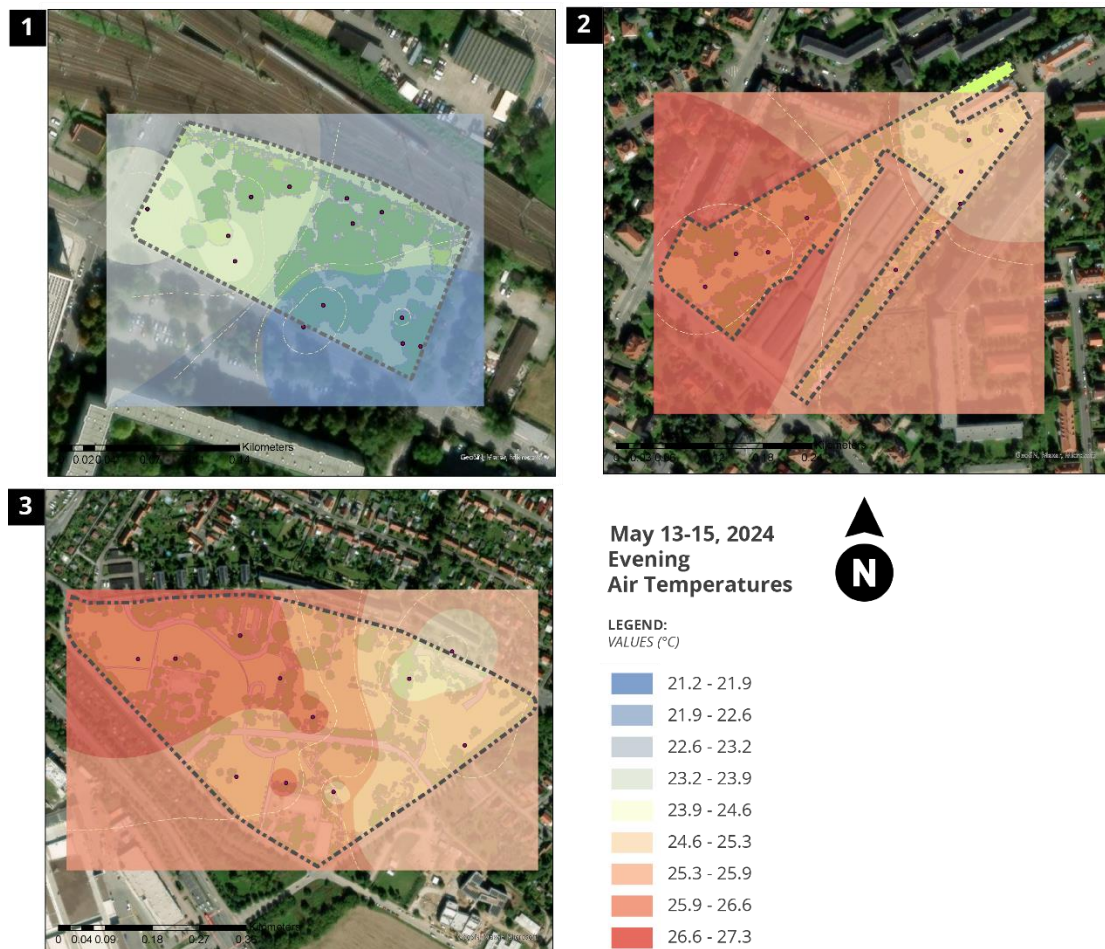


Figure 35 Comparison of Afternoon Evening Temperatures Across Study Sites

Unlike the afternoon recordings, the evening recordings across all sites show relatively consistent air temperatures, each fitting within 4-5 categories of the standard symbology. Specifically, Site 1 spans categories 1 to 4 with temperatures ranging from 21.2 to 23.6°C, while Sites 2 and 3 cover categories 5 to 9, ranging from 25.4 to 27.3°C.

Despite its cooler average temperatures, Site 3 exhibits the greatest variability, with a temperature difference of approximately 2.6°C in the evenings. In comparison, Sites 2 and 1 have smaller variations of about 1.9°C and 2.1°C, respectively.

4.1.2. Interpolation of Air Temperature Values

The actual air temperatures were measured at 13 points for Site 1, and 12 points for Sites 2 and 3. To gain a more comprehensive understanding of the correlations between air temperatures and vegetation structures, as well as the correlations between air temperatures and canopy cover, the interpolation of predicted values based on the actual measurements was conducted using ArcGIS Pro software. The purpose is to increase the number of sample points and to distribute them evenly in each site.

The following geoprocessing tools were employed: 1) **Create Random Points:** 37 to 38 points were plotted randomly within the site boundary, avoiding non-vegetative surfaces, with a minimum distance of 15 meters between each point. 2) **Merge:** The newly created points were merged with the actual points, resulting in a total of 50 points for each site. 3) **Extract Values to Points:** Predicted values were interpolated using the actual values from the traverse points. 4) **Mapping through IDW (Inverse Distance Weighting):** The IDW method was used to create a surface map from the combined values of actual and predicted points values. **Figures 36-38** show the actual and generated points, totalling to 50 points for each site.

Having derived the values of the interpolated points based on the actual air temperature values from the traverse, each point was then categorized and assigned with numerical values based on Vegetation Structure (VS) and Canopy Cover (CC). The assignment of these values, VS: (1) low, (2) medium, (3) high, and CC: (1) no shade, (2) partial shade, and (3) deep shade, was conducted in reference to the Digital Elevation Model of Dresden by the State Office for Geoinformation Saxony, accessed

in June 2024, as well as the visual assessment of vegetation structures from the traverse studies to ensure precision. The raw values can be found in the *Appendix*.



Figure 36 Merged Actual and Interpolated Points, Site 1



Figure 37 Merged Actual and Interpolated Points, Site 2



Figure 38 Merged Actual and Interpolated Points, Site 3

4.1.3. Boxplots of Air Temperature Distributions

Following the interpolation of predicted points, new points are assigned their corresponding values relative to VS and CC based on the biotope maps, visual assessment of individual VS and LiDAR data. The datasets are then cleaned by removing extreme values, allowing for the visualization of a more general trend between the air temperature data and the two variables.

The boxplots of the data for each site are presented to visualize the median and distribution of the datasets. These are as follows:

4.1.3.1. Site 1 Strehleener Straße

- **Site 1, May 13, 2024, Afternoon**

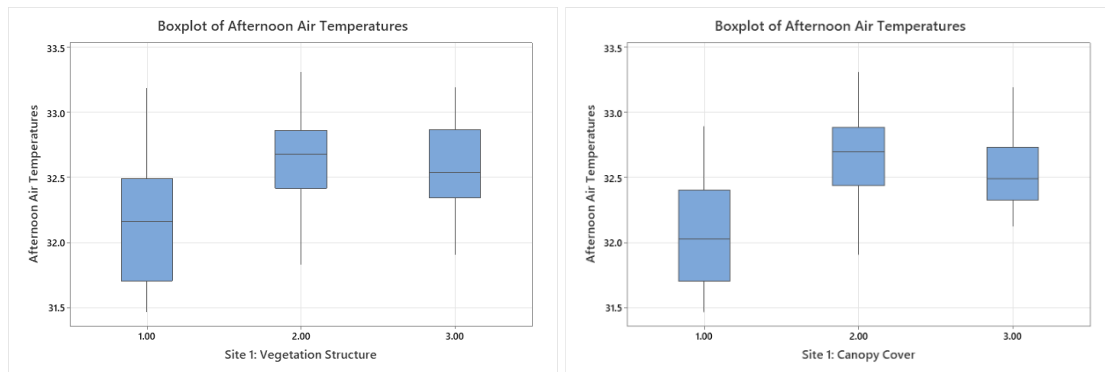


Figure 39 Site 1, May 13, Boxplots of Afternoon (a) AT and VS and (b) CC

The first boxplot in Figure 39, as seen above shows the distribution of afternoon air temperatures at Site 1 across three vegetation structures: low (1), medium (2), and high (3). The median temperatures are around 32.2°C for low vegetation structure, approximately 32.7°C for medium vegetation structure, and about 32.5°C for high vegetation structure. The variability in temperatures is largest for the low vegetation structure and smallest for the medium vegetation structure. Overall, there is a slight increase in median temperatures with higher vegetation structures, but the differences are minimal, indicating that the change in vegetation structure has a relatively small impact on afternoon temperatures at this site.

On the other hand, in relation to CC, as shown in the second boxplot in Figure 39, it can be observed that the median temperatures increase slightly from 32.0°C in no shade to about 32.7°C in partial shade and 32.5°C in deep shade, with less variability in shaded conditions. While the presence of canopy cover appears to result in slightly higher and more consistent afternoon temperatures, the overall differences among the three levels are minimal.

- **Site 1, May 13, 2024, Evening**

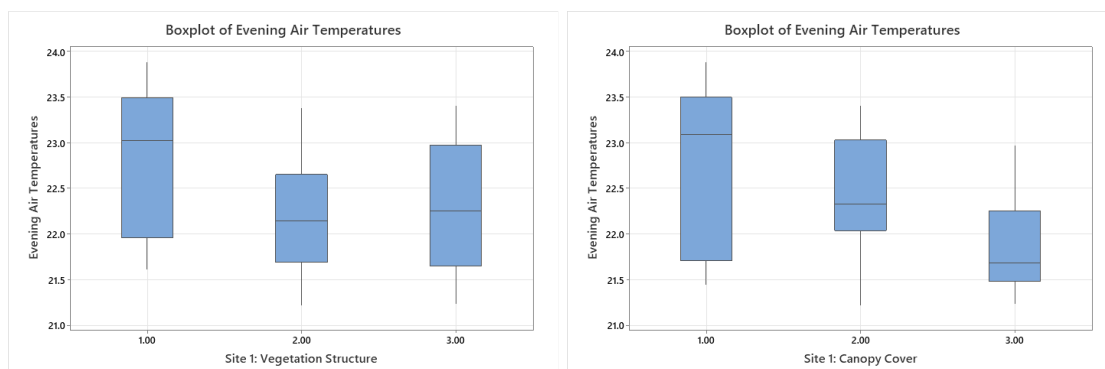


Figure 40 Site 1, May 13, Boxplots of Evening (a) AT and VS and (b) CC

The median temperatures are highest for low VS (1) and lowest for medium (2) and high (3) VS, indicating a cooling effect in the evening air temperature with increased vegetation, with a temperature reduction of almost 1.0°C. In the second boxplot, it can be observed that the median temperature is highest for no shade (1), slightly lower for partial shade (2), and lowest for deep shade (3), by up to a reduction of ~1.3°C. Furthermore, temperature variability is greatest for low VS and least for medium VS, suggesting that while there are variations, the overall impact of VS on evening temperatures is modest. Similarly, increased CC, particularly deep shade, is associated with cooler and more consistent evening temperatures, though the differences among the three levels remain relatively small.

4.1.3.2. Site 2 Kaitzbach

- **Site 2, May 14, 2024, Afternoon**

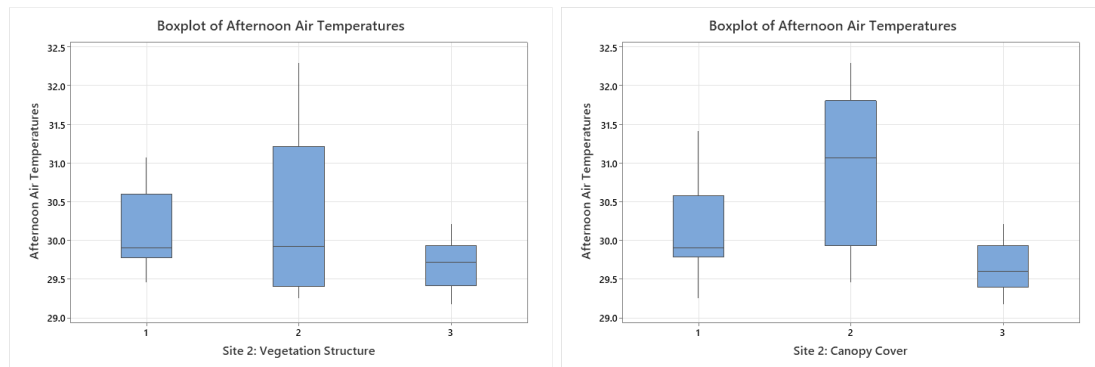


Figure 41 Site 2, May 14, Boxplots of Afternoon (a) AT and VS and (b) CC

Based on the first boxplot in Figure 41, median afternoon air temperatures are similar across low and medium vegetation at Site 2, approximately 30.0°C, while the high VS has a median of about 29.7°C. It can also be observed that the temperature variability is slightly larger for low and medium vegetation structures compared to high vegetation structure.

Meanwhile, the median temperatures are highest for partial shade at 31.1°C, followed by no shade at 30.0 °C, and lowest for deep shade at 29.6°C. Temperature variability is greatest for no shade and smallest for deep shade, indicating more consistent temperatures under deeply shaded conditions. The median values in deep

shade indicate slightly lower temperatures with a minimum difference of $\sim 0.30^{\circ}\text{C}$ compared to non-shaded points.

- **Site 2, May 14, 2024, Evening**

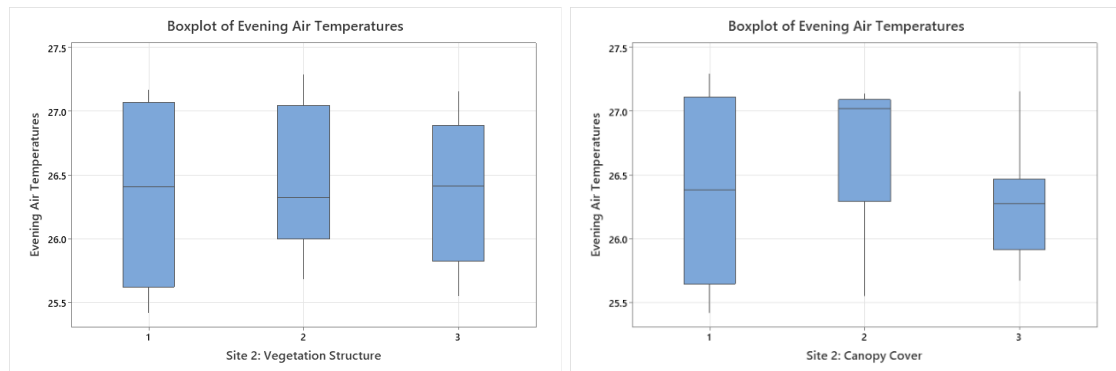


Figure 42 Site 2, May 14, Boxplots of Evening (a) AT and VS and (b) CC

For the evening air temperature measurements at Site 2, temperature variability is highest for low VS and least for high VS, suggesting that increased VS results in more stable evening temperatures. The second boxplot presents the distribution of evening air temperatures across three levels of canopy cover (CC). The median temperature is highest for partial shade (2), and lowest for deep shade (3)—indicating a reduction of up to 1.0°C with increased canopy cover. Temperature variability is greatest for no shade and least for deep shade, suggesting that increased canopy cover, particularly deep shade, is associated with cooler and more consistent evening temperatures. Although there is a notable difference in median temperatures and variability across the three levels, the overall impact remains relatively small.

4.1.3.3. Site 3 Kaufpark

- **Site 3, May 15, 2024, Afternoon**

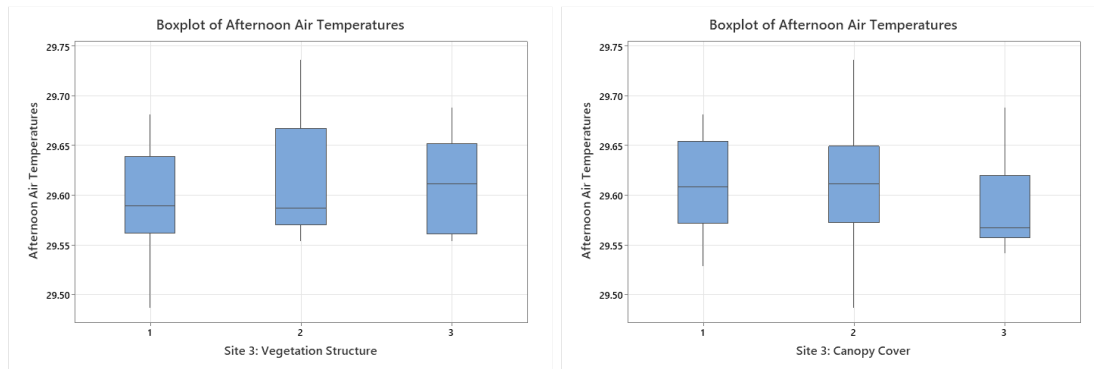


Figure 43 Site 3, May 15, Boxplots of Afternoon (a) AT and VS and (b) CC

The first boxplot in Figure 43 shows that the median temperatures are approximately 29.6°C for all levels of VS. The temperature variability, on the other hand, is the highest for medium VS and the lowest for low VS. Overall, the impact of vegetation structure on afternoon temperatures at this site is relatively small, as the variations show only up to ~0.03°C of difference.

The second boxplot presents the distribution of afternoon air temperatures at Site 3 across three levels of CC. The median temperatures of no shade (1) and partial shade (2) are similar at around 29.6°C. In deep shade, the median temperature slightly decreases by ~0.04°C, also showing the least variability. These observations suggest that increased canopy cover, particularly deep shade, is associated with marginally lower and more consistent afternoon temperatures.

- **Site 3, May 15, 2024, Evening**

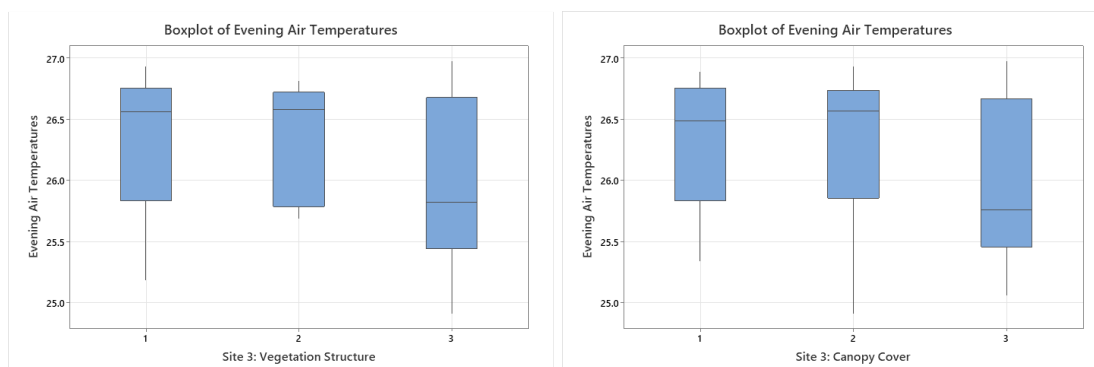


Figure 44 Site 3, May 15, Boxplots of Evening (a) AT and VS and (b) CC

The first boxplot in Figure 44 shows the distribution of evening AT at Site 3 across different levels of VS. The median temperatures are slightly higher for low (1) and medium VS (2) compared to high VS (3), indicating a cooling effect of approximately 0.5°C with increased vegetation structure.

Meanwhile, the second boxplot presents the distribution of evening AT across three levels of CC. The median temperature is highest for no shade (1) and partial shade (2), and lowest for deep shade (3), indicating a reduction of up to 0.7°C with increased canopy cover. Temperature variability is greatest for deep shade and least for partial shade. Overall, the impact of both VS and CC on evening temperatures is relatively modest, despite variations in median temperatures and variability.

4.1.3.4. Summary of Boxplots Across 3 IGS Sites

- **Afternoon Air Temperatures**

The impact of VS and CC on afternoon temperatures can be summarized as follows:

Vegetation Structure (VS):

- **Site 1:** Median temperatures are 32.2°C (low), 32.7°C (medium), and 32.5°C (high), with the greatest variability in low vegetation.
- **Site 2:** Median temperatures are around 30.0°C (low and medium) and 29.7°C (high), with larger variability in low and medium vegetation.
- **Site 3:** Median temperatures in all three VS are ~ 29.6°C, with highest variability in medium vegetation.

Overall, higher vegetation structures show slightly higher median temperatures, but the differences are minimal, while the temperature variability is generally higher in lower vegetation structures.

Canopy Cover (CC):

- **Site 1:** Median temperatures are 32.0°C (no shade), 32.7°C (partial shade), and 32.5°C (deep shade), with reduced variability in shaded conditions.

- **Site 2:** Median temperatures are 29.9°C (no shade), 31.1°C (partial shade), and 29.6°C (deep shade), with the smallest variability in deep shade.
- **Site 3:** Median temperatures are 29.6°C across all shade levels, with a minuscule difference and the least variability in deep shade.

Increased canopy cover is generally associated with slightly lower and more consistent afternoon temperatures. However, the overall differences in temperatures among the levels of canopy cover are also small. The presence of shade results in slightly higher temperatures in some cases, such as in Site 1, but a trend towards lower temperatures in deeper shade was also observed, particularly in Sites 2 and 3. Having a more consistent set of afternoon temperatures in deeper shaded areas may imply that vegetation with greater canopy cover acts as a microclimate regulator in all three sites.

- **Evening Air Temperatures**

Vegetation Structures (VS)

- **Site 1:** Median temperatures are highest for low vegetation structure (VS) and lowest for medium and high VS, resulting in a temperature reduction of approximately 1.0°C in the evening air temperature. Temperature variability is greatest for low VS.
- **Site 2:** Temperature variability is highest for low VS and least for high VS, suggesting increased VS contributes to more stable evening temperatures.
- **Site 3:** Median temperatures are slightly higher for low and medium VS, and lower for high VS, indicating a cooling effect of approximately 0.5°C with increased vegetation structure.

Canopy Cover (CC)

- **Site 1:** Median temperatures are highest for no shade, slightly lower for partial shade, and lowest for deep shade, resulting in a temperature reduction of approximately 1.3°C. Increased canopy cover (CC), particularly deep shade, is associated with cooler and more consistent evening temperatures.

- **Site 2:** Median temperatures are highest for partial shade and lowest for deep shade, with a reduction of up to 1.0°C. Temperature variability is greatest for no shade and least for deep shade, indicating that increased CC, particularly deep shade, is associated with cooler and more consistent evening temperatures.
- **Site 3:** Median temperatures are highest for no shade and partial shade, and lowest for deep shade, resulting in a reduction of up to 0.7°C. Temperature variability is greatest for deep shade and least for partial shade.

Overall, the boxplots for the evening AT indicate that increased vegetation structure and canopy cover generally lead to cooler and more stable temperatures, with deep shade demonstrating the most significant cooling effect.

4.1.4. Scatterplots of Air Temperature Distributions

The following scatterplots are presented to visualize the potential correlations and trends between the variables AT, VS and CC.

4.1.4.1. Site 1 Strehleener Straße

- **Site 1, May 13, 2024, Afternoon**

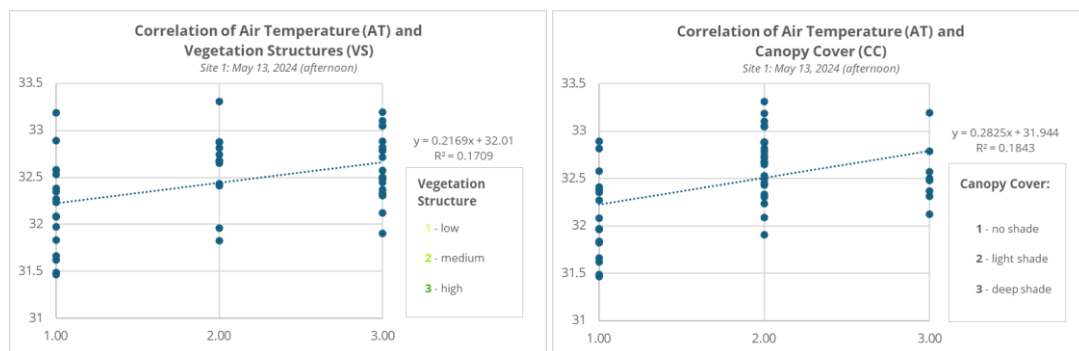


Figure 45 Site 1, May 13, Scatterplots of Afternoon (a) AT and VS and (b) CC

The scatterplots above depict the correlations between air temperature (AT) and two variables: vegetation structures (VS) and canopy cover (CC) at Site 1 on May 13, 2024, in the afternoon. Both scatterplots show weak positive correlations, as indicated by the positive slopes of the regression lines (0.2169 for VS and 0.2825 for CC). The R^2 values are 0.1709 for VS and 0.1843 for CC, meaning that approximately 17.09%

and 18.43% of the variance in air temperature can be explained by vegetation structure and canopy cover, respectively.

The modest R^2 values in both plots imply that less than 20% of the variability in air temperature can be explained by these factors. The interpretation suggests that at this site, both higher VS and deeper CC are associated with slightly higher temperatures. To better understand these trends, further studies could explore other factors, such as reduced air circulation or increased heat retention in vegetated and shaded areas, as well as additional environmental variables.

- **Site 1, May 13, 2024, Evening**

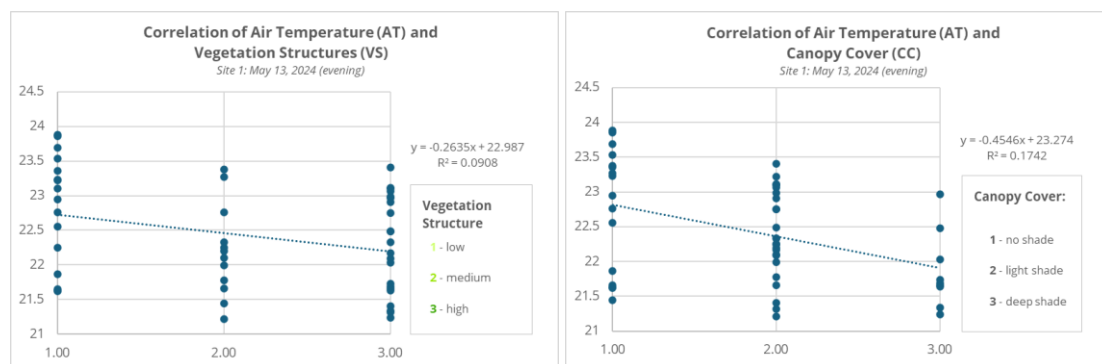


Figure 46 Site 1, May 13, Scatterplots of Evening (a) AT and VS and (b) CC

Figure 46 reveals a negative correlation between evening AT and both VS and CC at Site 1 on May 13, 2024. The trendline equations show that air temperature decreases as vegetation structure and canopy cover increase. However, the R^2 values are relatively low—0.0908 for VS and 0.1742 for CC—indicating that only 9.08% and 17.42% of the variance in air temperature, respectively, are explained by these factors. The trends show the reversal of the results from the afternoon recordings. However, while higher VS and deeper are associated with lower air temperatures, other factors also significantly influence evening air temperatures. Furthermore, the slightly stronger relationship between AT and CC suggests that CC might have a more substantial cooling effect than VS. Nevertheless, the weak overall correlations indicate the need for further studies to examine additional variables.

4.1.4.2. Site 2 Kaitsbach

- **Site 2, May 14, 2024, Afternoon**

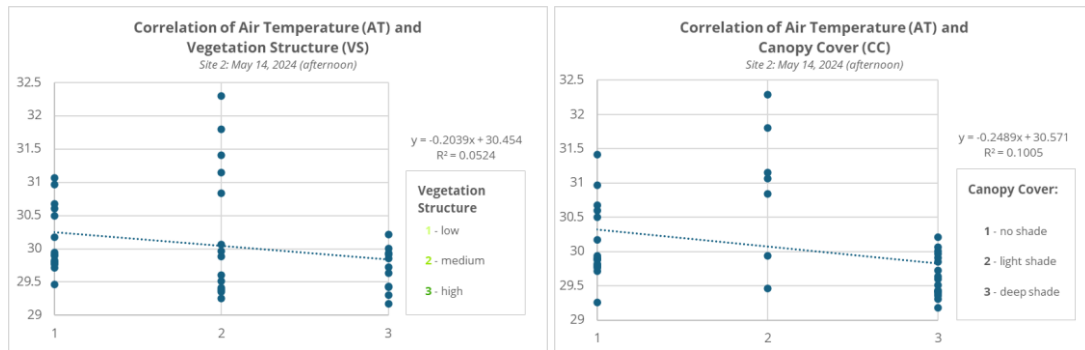


Figure 47 Site 2, May 14, Scatterplots of Afternoon (a) AT and VS and (b) CC

The scatterplots for Site 2 in the afternoon of May 14, 2024 (Figure 47), show weak negative correlations between AT and the variables VS and CC. The regression lines for VS and CC have slopes of -0.2039 and -0.2489, respectively, indicating a slight decrease in air temperature as VS goes higher and canopy cover increases (moving towards deeper shade). The R^2 values are 0.0524 for VS and 0.1005 for CC, suggesting that only 5.24% and 10.05% of the variance in air temperature can be explained by these variables.

These results imply that, although the correlations are weak, there is a slight trend of lower afternoon air temperatures being associated with higher VS and deeper shade at Site 2. Therefore, suggesting that increasing vegetation and shade could contribute to afternoon cooling effects, albeit marginal, in this environment. Additionally, other environmental or climatic factors not measured in the study might have had more influence on the air temperatures on the day of the recording.

- **Site 2, May 14, 2024, Evening**

Figure 48 reveals minimal correlations between evening AT and both VS and CC at Site 2 on May 14, 2024. The trendline equations show a very slight positive relationship with VS and a slight negative relationship with CC, suggesting that higher air temperatures are associated with higher VS, while lower air temperatures are associated with deeper shade. However, with the extremely low R^2 values,—0.0008 for VS and 0.0026 for CC—this suggests that while VS and CC show some association

with air temperatures, other factors play a much more significant role in influencing evening air temperatures.

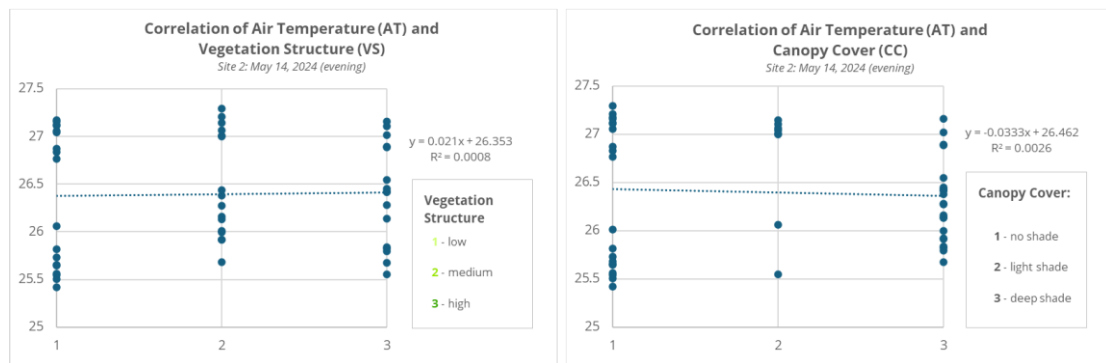


Figure 48 Site 2, May 14, Scatterplots of Evening (a) AT and VS and (b) CC

4.1.4.3. Site 3 Kaufpark

- Site 3, May 15, 2024, Afternoon

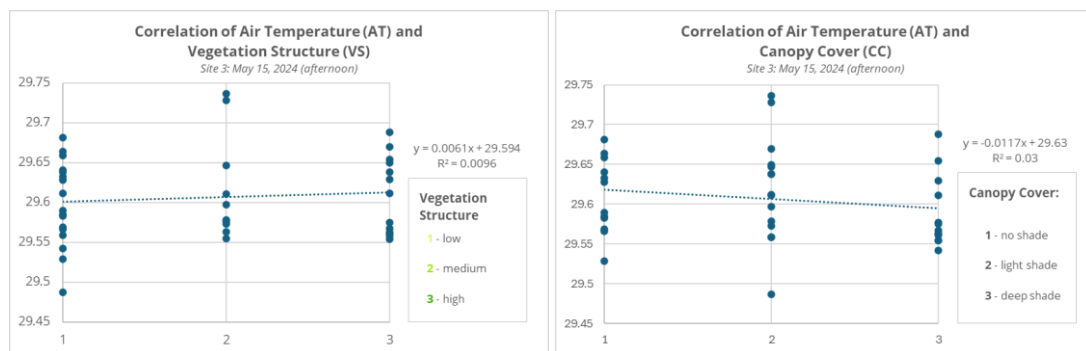


Figure 49 Site 3, May 15, Scatterplots of Afternoon (a) AT and VS and (b) CC

Shown above are the scatterplots of AT VS and CC, respectively, for Site 3 on the afternoon of May 15, 2024. The regression line for VS has a slope of 0.0061 and an R² value of 0.0096, indicating a negligible positive correlation and that only about 0.96% of the variance in air temperature is explained by vegetation structure. The data points show no clear trend. Meanwhile, the regression line for CC has a slope of -0.0117 and an R² value of 0.03, suggesting a very weak negative correlation, with only 3% of the variance in air temperature explained by canopy cover. The data points indicate that air temperatures were slightly lower as the canopy cover increased.

Similar to Site 1 and 2, the results from Site 3 imply that other environmental or climatic factors not accounted for in this study may have been more influential in determining the afternoon air temperature variations. For instance, it is possible that the time of day or specific site characteristics could be affecting these results. Therefore, further studies could explore additional variables or different times of the day to better understand the drivers of air temperature changes.

- **Site 3, May 15, 2024, Evening**

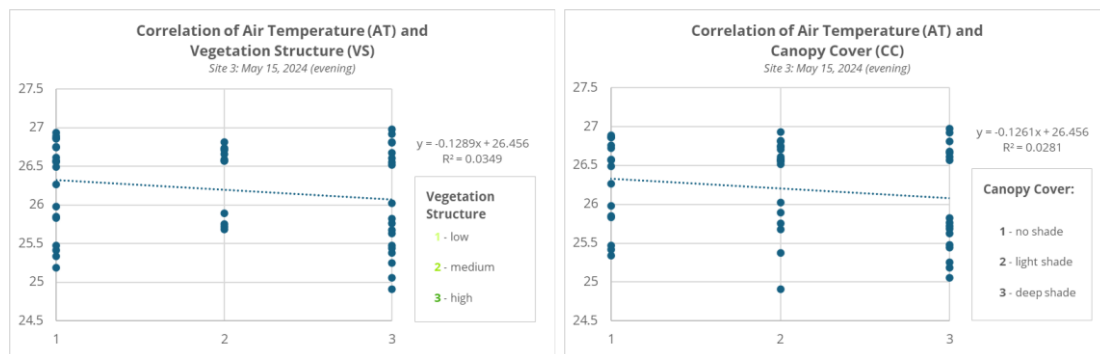


Figure 50 Site 3, May 15, Scatterplots of Evening (a) AT and VS and (b) CC

Figure 50, on the other hand, reveals weak negative correlations between evening AT and both VS and CC at Site 3 on the same day. The trendline equations indicate that air temperatures are slightly lower in areas with higher vegetation structure and deeper canopy cover. However, the R^2 values are low—0.0349 for VS and 0.0281 for CC—indicating that only 3.49% and 2.81% of the variance in air temperature, respectively, are explained by these factors. Therefore, suggesting that while higher VS and greater CC are associated with marginally lower air temperatures, other factors also play a more significant role in influencing evening air temperatures.

4.1.4.4. Summary of Scatterplots Across 3 IGS Sites

- **Afternoon Air Temperatures**

Vegetation Structure (VS):

- **Site 1:** Weak positive correlations with a regression slope of 0.2169 and an R^2 value of 0.1709, indicating that 17.09% of the variance in air temperature (AT) can be explained by VS. Higher VS is associated with slightly higher temperatures.
- **Site 2:** Weak negative correlations with a regression slope of -0.2039 and an R^2 value of 0.0524, suggesting that only 5.24% of the variance in AT can be attributed to VS. Higher VS is associated with slightly lower temperatures.
- **Site 3:** Negligible positive correlations with a regression slope of 0.0061 and an R^2 value of 0.0096, explaining only 0.96% of the variance in AT. There is no clear trend in temperature changes with VS on this site.

Overall, the impact of VS on AT is minimal across all sites, with only small portions of the temperature variability being explained by changes in vegetation structure.

Canopy Cover (CC):

- **Site 1:** Weak positive correlations with a regression slope of 0.2825 and an R^2 value of 0.1843, indicating that 18.43% of the variance in AT can be explained by CC. Higher CC is associated with slightly higher temperatures.
- **Site 2:** Weak negative correlations with a regression slope of -0.2489 and an R^2 value of 0.1005, suggesting that 10.05% of the variance in AT can be attributed to CC. Higher CC is associated with slightly lower temperatures.
- **Site 3:** Weak negative correlations with a regression slope of -0.0117 and an R^2 value of 0.03, explaining only 3% of the variance in AT. Higher CC is associated with slightly lower temperatures.

- **Evening Air Temperatures**

Vegetation Structure (VS):

- **Site 1:** Negative correlation between evening air temperature (AT) and VS, with an R^2 value of 0.0908.
- **Site 2:** Minimal positive correlation between evening AT and VS, with an R^2 value of 0.0008.
- **Site 3:** Weak negative correlation between evening AT and VS, with an R^2 value of 0.0349.

Canopy Cover (CC):

- **Site 1:** Negative correlation between evening AT and CC, with an R^2 value of 0.1742.
- **Site 2:** Slight negative correlation between evening AT and CC, with an R^2 value of 0.0026.
- **Site 3:** Weak negative correlation between evening AT and CC, with an R^2 value of 0.0281.

The scatter plots reveal that increased canopy cover (CC) is generally associated with slightly lower and more consistent afternoon temperatures across all sites. Similarly, higher vegetation structure (VS) and increased CC are associated with slightly lower evening air temperatures. However, the effects in both afternoon and evening are minimal, indicating that other environmental or climatic factors likely play a more significant role in determining temperature variations. Therefore, further studies are recommended to explore additional variables or different times of the day to better understand these trends.

4.2. Limitations

This study encompasses several noteworthy limitations that should be acknowledged when interpreting the research findings. Firstly, the selection of sites based on Informal Green Space (IGS) typologies is confined to specific case studies in Dresden, Germany, thus limiting the generalizability of the findings to other cities in

Germany or Europe. Due to the lack of available data on Informal Green Spaces in Dresden, the selection of initial sites was facilitated through the recommendations of the proponent's advisers. Therefore, the selected locations may not fully capture the full range of IGS diversity across the city and in other cities.

Furthermore, the data-gathering process considers temporal variabilities, particularly in the case of remotely sensed data such as LiDAR data and satellite images, which may be constrained by the availability of datasets within a specific time frame, potentially leading to disparities with the current environmental conditions.

Additionally, the study did not delve into the specific plant species at each site; instead, it took a more general approach by considering the types of plants (i.e., shrubs, bushes, hedges, grass, meadows, trees) and the horizontal and vertical structure of plants by providing descriptions of vegetation heights, arrangement, leaf structures, and shapes. Moreover, the effectiveness of the vegetation structures is limited solely to the specified sites, as various factors such as plant age and site-specific growth conditions vary depending on the location and time of year, which may influence the results.

Despite these limitations, this study shall serve as a significant initial exploration of the microclimatic performance of Informal Green Spaces (IGS) in relation to their surrounding urban environments. It shall provide a foundation for future research endeavours to address these constraints, improve data accessibility, and expand the knowledge in this field of study.

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

5.1. Discussion

The results from the three IGS sites exhibit diverse outcomes. Given that the sites are situated in different LCZs and vary in size, layout and predominant vegetation structures, the findings align with Feyisa et al. (2014) and Shah et al. (2021), who assert that 'the cooling benefits of vegetation vary based on spatial and temporal factors, as well as the unique characteristics of each plant species', and that 'the cooling impact of

green spaces in urban environments is determined by a combination of factors pertaining to both the design of the green spaces and the attributes of the surrounding area', respectively. Additionally, Salmond et al. (2016) support this by stating that 'the impact of trees on the microclimate is contingent upon the regional climatic conditions, geographical location, and urban structure'.

5.1.1. Site 1 *Strehleener Straße*

The afternoon results at Site 1 reveal that higher temperatures were associated with higher VS and CC; however, the scatterplots show low R^2 values, suggesting that other factors may have been impacting the afternoon air temperature distribution rather than the structure of vegetation at the site.

One of the possible factors that might have affected the air temperatures is the health of the trees. According to the visual assessment of the site (See Appendix), most canopies were found to be dry and shedding, indicating that the trees likely had low Leaf Area Index (LAI) values during the campaign. This condition may have affected the trees' evapotranspiration capabilities. As noted by Xu et al. (2011), LAI is essential for the development of tree canopies and significantly influences processes such as photosynthesis and evapotranspiration. Therefore, because the trees were in poor condition during the traverse campaign, the cooling benefits were not fully realized, particularly in the afternoon when temperatures were highest. This observation highlights the crucial role that plant health plays in providing shade, which is supported by Salmond et al. (2016), who assert that the age and health of trees significantly impact their cooling effects.

Furthermore, the highest temperature was observed along the road and near the railway, specifically at point F. It is likely that a passing train, coupled with the lack of screening from the railway to the north and the relatively dense vegetation, in the form of broad-leaved shrubs to the south of point F, contributed to heat retention effects due to increased surface roughness. This observation is consistent with the findings of Gunawardena et al. (2017), who note that dense forests obstruct wind flow, thereby trapping warmer air beneath the canopy. This phenomenon can be attributed to the

influence of vegetation on the drag coefficient³. As demonstrated by multiple studies, the drag coefficient rises with the increase in both the height and density of vegetation (Zhang et al., 2022). In this specific scenario, although the trees were not in optimal condition at the time of the traverse, the presence of tall, dense, leafy shrubs to the right of point F may have contributed to the entrapment of heat from the railway.

Meanwhile, the heat radiated by the road itself further elevates temperatures at points L and M. This interplay of factors highlights how infrastructure and vegetation density can significantly influence localized temperature variations in urban settings.

Interestingly, during the afternoon traverse, the lowest temperatures have been observed along the grasslands and meadows, from points A to D. This is affirmed by Marshall et al., (2023) who suggest that ‘meadow planting offers supplementary advantages for climate change adaptation by enhancing albedo through increased reflectivity and mitigating the urban heat island effect’. Moreover, the low-level, tensile structure of the VS in this area facilitated improved wind flow on the day of the traverse, with the wind direction originating from the northwest and moving southeast, thereby producing a cooling effect on the air temperature.

The afternoon air temperature recordings at Site 1 reveal several key findings: (1) Vigorous trees are crucial for providing shade and enhancing evapotranspiration capabilities; (2) The height, density, and composition of vegetation can contribute to warming effects by affecting surface roughness and airflow, especially in the presence of anthropogenic heat sources; and (3) Grasslands and meadows offer cooling benefits through the albedo effect and by promoting improved wind flow.

In the evening measurements, the cooling effect of both vegetation structure and canopy cover became more apparent. The results show that temperatures are highest with low vegetation and no shade, decreasing with more vegetation and shade, resulting in cooler evening air temperatures by up to 1.3°C. These results are supported by Lin and Lin (2010), whose study observed that trees significantly reduce air temperatures in the evenings— ‘cooler ground temperatures in the afternoon, facilitated by trees,

³ The drag coefficient represents the resistance to windflow caused by roughness elements (Arya, 2001 in Zhang et al., 2022).

allow less heat to be dissipated into the air at nighttime, thereby producing a cooling effect'. However, these results contrast with the findings of Wujeska-Klaus & Pfautsch (2020), Zhao et al. (2023), and Puliafito et al. (2013), which suggest that medium to tall trees tend to retain warm air during nighttime under the canopies, slowing down the release of heat.

5.1.2. Site 2 Kaitzbach

In contrast to the results of Site 1, the afternoon air temperatures at Site 2 showed a marginal decrease associated with the increase in the level of VS and CC. However, due to the low R^2 values, it is necessary to consider other factors outside the examined variables.

Site 2 demonstrated distinct thermal effects in its western and eastern sections, with the western portion exhibiting heating and the eastern portion experiencing cooling. The pronounced difference in the composition of Vegetation Structure (VS) between the two sections supports the conclusions of Lehman et al. (2014), who state that “the composition of green cover, including lawns, meadows, shrubs, hedges, and trees, as well as the height classification of the vegetation layer, significantly influences the climatic effects observed in urban open spaces”.

For instance, along the eastern side, from points E to I, a cooling effect was observed. The lower temperatures in this portion can be explained by:

- 1) The vegetation in this area, characterized by dense, well-maintained cover along very narrow pathways, provided substantial shading.
- 2) Moreover, the orientation of the parking lot and the dense row of hedges, shrubs, and trees at its eastern boundary likely mitigated the warming effects generated by the parking lot itself.

Meanwhile, the recordings from points A to D along the western portion demonstrated warming effects. This phenomenon can be explained by several factors:

- 1) Although the western portion includes a section of the Kaitzbach River, no cooling effect was observed at the mentioned points due to the river's width being less than

1 meter, insufficient to produce significant cooling effects. Peng et al. (2012) found that “the critical width of an urban river necessary to noticeably reduce temperature and increase humidity was at least 44 meters”. Previous studies have stated that the greater the width of the river, the more significant its cooling effects on microclimates (Yue et al., 2013, Syafii et al., 2016, cited in Jiang et al., 2021).

- 2) The absence of shade to block direct sunlight from the south to southwest of the site during the recording period (*See Appendix for the Shadows and Sun Paths*), combined with increased surface roughness due to the orientation of buildings and tall vegetation in the western portion of the site, may have impeded wind flow originating from the northwest, contributing to the heating effects along points A to C. Additionally, the tall, dense grass in this section could act as a heat source. He et al. (2022) suggest that the leaf density of shrubs or grass can lead to higher air temperatures above the plant canopy during the daytime due to increased solar radiation intercepted by the top layer of the canopy.
- 3) Heat emanating from the central large parking lot extended into the surrounding areas, exacerbated by the parking lot’s orientation and the lack of vegetative screening between the parking lot and point D, which was described as low, open, and sparse. Using point D as a reference, the area to the east of point D (where the parking lot was located) had low surface roughness, while the area to the west was characterized by tall, dense trees. This disparity in surface roughness contributed to heat-trapping effects.

The results of the afternoon air temperature recordings at Site 2 can therefore be summarized as follows:

- Dense canopy cover and high vegetation play a crucial role in mitigating heating effects by providing shading and screening from direct afternoon sunlight, contributing to cooling.
- Heating effects in urban environments can arise from a combination of solar radiation, the thermal contribution of paved surfaces, and the heating capabilities of tall dense grass during daytime.

- The structure of vegetation—characterized by factors such as plant height, density, spacing, and arrangement—along with building orientations that are perpendicular to prevailing wind flow, can influence localized heating effects.

Meanwhile, the evening measurements indicate that higher vegetation and increased canopy cover, especially deep shade, lead to more stable and consistently cooler evening temperatures, reducing them by up to 1.0°C. There is also a minimal positive correlation between evening temperatures and vegetation structure, and a slight negative correlation with canopy cover, suggesting that more vegetation and shade contribute to less temperature variability. However, due to the significantly low R^2 values, it is difficult to conclude these correlations definitively. Instead, it appears that the variations in evening temperatures at this site are more likely associated with the times of recordings at each traverse point (see Figure 29 in Chapter 4.1.1.2).

5.1.3. Site 3 Kaufpark

Site 3 exhibited the lowest and most consistent afternoon air temperatures among the three IGS sites examined, with all levels of VS and CC having approximately the same average afternoon air temperatures. The warmest points were identified as C, D, and H, I, J. Based on the detailed vegetation structure (VS) visual assessment and field notes from the day of the recordings, it is possible that the elevated temperatures at point C, despite its location among trees, were influenced by the heat-trapping effects of the adjacent parking lot to the north. Conversely, point D was expected to record higher temperatures due to direct solar radiation from the west. Meanwhile, the concentration of warmer temperatures at points H, I, and J may have been influenced by the heat emanating from the adjacent road, Erich-Kästner-Straße.

The observed cooling trend from the northwestern part of the site towards the southeast could be attributed to the prevailing winds at the time of the recordings, which may have been facilitated by the grasslands, low building heights, and the parallel orientation of the buildings located to the northwest of the site (see Figure 8 in Chapter 3.4.3). Although the impacts of vegetation structure (VS) on temperature could not be precisely determined due to low R^2 values, the relatively low and regulated air

temperatures at Site 3 represent a significant finding that could be important for future development plans concerning brownfield sites.

Higher vegetation with canopy coverage also performed slightly better in comparison to trees beside the main road and parking lots, such as points C and I. This observation is supported by the findings of Souch and Souch (1993), which state that “street trees are found to be less effective at cooling than both individual trees and clumps planted over grass”.

The evening temperatures are slightly higher with low to medium vegetation structure (VS) and decrease with more vegetation, indicating a cooling effect of up to 0.5°C. Similarly, temperatures are highest without shade and decrease with deeper shade, reducing by up to 0.7°C. Weak negative correlations between evening temperatures and both VS and CC are noted. However, similar to Site 2, it was difficult to draw definitive conclusions due to the low R^2 values. Additionally, the air temperatures at Site 3 also began to decrease significantly around the same time that the air temperatures at Site 2 started to decrease more steadily, approximately at 19:43.

5.1.4. Comparisons between 3 IGS Sites

As seen in Figure 34 in Chapter 4.1.1.4, the variations in afternoon air temperatures across the three sites can be attributed to factors considered in the site selection process, primarily the Local Climate Zone (LCZ) and the size of the IGS. This is supported by Manoli et al. (2019), cited in Egerer et al. (2024), stating that ‘the extent of the urban heat island phenomenon is contingent upon both macroscopic climatic factors and microscale urban morphology,’ as well as the findings of Aram et al. (2019) that emphasize that the size of the green space directly influences the cooling intensity it provides.

When compared using standard symbology, the following observations were made: (1) the highest afternoon temperatures were recorded at Site 1 (Strehlener Straße), (2) the widest range of temperature variations was depicted at Site 2 (Kaitzbach), and (3) the lowest and most consistent temperatures were found at Site 3 (Kaufpark).

It should be noted that Site 1 is considerably smaller, covering approximately 11,733.75 m², in contrast to Sites 2 and 3, which encompass approximately 30,989.50 m² and 106,050.62 m², respectively. Additionally, Site 1 is in a predominantly concrete area classified as LCZ 8 (large low-rise) due to the railway to its north; to the immediate south of the site are high-rise buildings above 9 meters in height. This observation can also be attributed to the “park-breeze” phenomenon, which occurs when cooler air from greenspaces is drawn into urban areas, and warmer urban air circulates back into the greenspaces, making greenspaces in urban settings less comparable to those in rural areas (Jansson et al., 2006; Oke et al., 1989, cited in Gunawardena et al., 2017).

In contrast, Site 2 exhibits a more complex vegetation structure, particularly in its western and eastern portions. The influence of the large central parking lot, combined with the surrounding building layout, may contribute to the observed variations in afternoon air temperatures. Site 3, although exhibiting some localized higher temperatures, did not show significant changes in the site’s microclimate throughout the afternoon traverse. This stability can be attributed to Site 3’s larger size and its classification as LCZ 2 (open low-rise). The results suggest that Site 3 plays a role in stabilizing the microclimatic conditions of the area, supporting the case for regulating any potential conversion of the greenspace into paved and built surfaces.

The evening air temperature distributions (Figure 35) show that temperatures across all sites are relatively stable, fitting within 4-5 standard categories. Site 1 had the coolest air temperatures, with an average of 22.3°C, while Sites 2 and 3 had overall evening air temperatures of 26.2-26.3°C. Due to the discrepancy in the timings of the evening traverse, it is difficult to compare the results of Site 1 to those of Sites 2 and 3, as the evening temperatures decreased at a more rapid rate after 19:43, while Site 1 measurements were taken starting from 20:10. It is therefore recommended to ensure consistency in the starting and ending times of the traverses when comparing multiple sites.

5.1.5. Methodological Review and Strategies for Improvement

Besides the findings related to vegetation structures and air temperature variations within the selected IGS sites, the following aspects of the methodology have been identified for improvement:

- **Advantages of a Longer Observation Period**

A longer observation period could have enriched the analyses further, enabling comparisons of the warmest and coolest points at each site. Additionally, an extended observation timeframe would allow for a more robust assessment of temporal variations and anomalies in temperature patterns, as well as changes in plant growth. This would provide a deeper understanding of the microclimatic dynamics relative to vegetation structures and canopy cover and contribute to more accurate and generalizable conclusions. Due to the limited amount of time allotted for data gathering of in-situ measurements, as well as the unfavourable weather conditions in Dresden during May, the analyses only elaborated on one day per site.

- **Significance of Even Distribution in Vegetation Structure Among Traverse Points**

It has been apparent in the analyses that in the evening measurements, significant temperature reduction was observed within short periods. Therefore, it would have been ideal to take equal recordings of different vegetation structures (VS) - low, medium, and high - in a more evenly distributed manner throughout the campaign. For instance, the initial measurements were predominantly taken in areas with low VS, whereas the latter part of the campaign focused more on areas with high VS. This uneven distribution may have affected the overall results as the temperatures at night go down in a matter of minutes. Therefore, a more balanced approach could provide a more comprehensive understanding of the relationship between vegetation structure and evening air temperatures.

- **Importance of Consistent Start and End Times for Evening Traverse**

The results of the study also highlight the need to maintain consistency in the start and end times for the traverse, especially during the evenings when the temperatures significantly go down in a more rapid manner than in the afternoon. For instance, it was difficult to make conclusions for the evening measurements as the Site 1 evening traverse was conducted from around 20:10, while Sites 2 and 3 were conducted around the same time, around 19:10. Consistency in traverse timing is crucial to ensuring the reliability and comparability of temperature data across different sites.

- **Necessity of Consistent Stabilization Time for Traverse Measurements**

It is also to be reiterated that when conducting traverse measurements using the Tinytag, to allow more than 10 minutes of stabilization time at the first point of traverse and maintain consistency in doing so across all sites of interest. This is important to avoid any potential distortions from the previous movements.

- **Fixed Station in a Relatively Built-up Zone**

Due to concerns regarding theft and vandalism, the fixed station was installed within a private weather station characterized by abundant vegetation and shade. Consequently, it would have been advantageous to establish a fixed or control station in a relatively urbanized area to enhance the understanding of the general cooling effect of the IGS compared to an environment lacking vegetation.

5.2. Conclusions

The following conclusions are drawn from the literature review and the study results, aligned with the main objectives of this dissertation:

- 1) Informal Green Spaces (IGS) play a crucial role in providing various ecosystem services, such as cooling effects, flora and fauna support, and informal recreational opportunities. These areas, characterized by spontaneous vegetation, high species diversity and low maintenance levels, are capable of mitigating the UHI effect similar to formal green spaces. Despite their ecological and social values, IGS are frequently underrepresented in green infrastructure discussions, which typically

focus on managed parks and gardens. To fully leverage the potential of IGS, it is imperative to integrate them into greenspace planning frameworks and raise awareness of the many advantages they provide through further studies.

- 2) The three different IGS sites exhibited different results; correlations indicated that lower and more stable afternoon temperatures were more associated with CC than with the height of the vegetation. However, the low R^2 values suggest that other factors also play a significant role in the temperature variations across the sites examined.
- 3) The health and structural characteristics of vegetation significantly impact air temperature regulation. Sites with healthier trees and deep canopies generally exhibit more effective afternoon cooling through processes such as evapotranspiration and shading. The effectiveness, however, is contingent upon specific site conditions and the composition of the surrounding morphology. Additionally, different types of vegetation and their spatial arrangement can provide both cooling and warming effects. For example, grasslands and meadows, through the albedo effect and enhanced wind flow, can significantly reduce temperatures, while tall dense leafy shrubs and tall grasses can trap heat, particularly when adjacent to anthropogenic heat sources.
- 4) The cooling impact of green spaces is influenced by their size, layout, and the Local Climate Zones (LCZ) in which they are situated. Larger green spaces and those located in less built-up areas tend to provide more consistent and effective cooling, as demonstrated by the more stable temperatures at Site 3 compared to Sites 1 and 2. Furthermore, the presence of infrastructure, such as roads, railways, and parking lots, contributes to localized heating effects. Areas adjacent to such built structures often record higher temperatures due to the heat radiated from these surfaces and the influence of surrounding vegetation in trapping heat.
- 5) Vegetation's cooling effects vary throughout the day, with significant benefits observed during the evening. Areas with higher vegetation cover and deeper shade show more stable and cooler temperatures in the evening.

- 6) For a more accurate and comprehensive analysis, future studies should consider longer observation periods, and employ consistent timing for measurements, and an even distribution of vegetation structure recordings. Furthermore, allowing adequate stabilization time for instruments at the start of measurements is important to ensure the reliability of the data collected. Additionally, having a reference station in a relatively built-up area would have further enriched the study.

5.3. Recommendations

The following recommendations, based on the study's findings, provide strategies for urban planners, policymakers, and stakeholders to integrate and protect Informal Green Spaces (IGS) in Dresden. Moreover, they also aim to guide researchers and students in further studying vegetation's impact on microclimates and the role of IGS.

5.3.1. Recommendations for Urban Planners, Policymakers and other Relevant Stakeholders

- **Incorporate Informal Green Spaces into Dresden's Green Space Inventory:**

IGS should be formally recognized within Dresden's green space inventory due to their significant contributions to surface cooling benefits, akin to those of formally designed parks and gardens. Recognizing and categorizing these spaces based on size, typology, accessibility, and other relevant factors such as social usage and ecological features ensures that their benefits are fully acknowledged and leveraged. Furthermore, including these green spaces in Dresden's publicly accessible data repository through open data mapping encourages researchers to pursue studies on the subject and allows planners to make informed decisions that enhance urban resilience, promote public health, ensure equitable green space distribution, and protect species diversity supported by these green spaces.

- **Integrate IGS in the Greenspace Planning Instruments of Dresden**

The incorporation of IGS into the Dresden Model and the Landscape Plan of Dresden is imperative for achieving comprehensive greenspace planning for the city. By including IGS in the plans and decision-making, it ensures that all types of green spaces, including those unplanned or not formally recognized, are systematically accounted for. This acknowledges the significant ecological and social functions these spaces provide, such as biodiversity support and microclimate benefits. Consequently, this integration facilitates more informed management and protection of these greenspaces.

- **Stakeholder Engagement and Community Involvement**

Engaging stakeholders and involving the community in the planning and management of green spaces is essential for the development of sustainable urban environments. Participatory approaches enable residents to contribute their local knowledge and preferences, thereby enhancing the relevance and acceptance of initiatives related to informal green spaces (IGS). Additionally, the implementation of educational programs and awareness campaigns can significantly boost community involvement. These initiatives encourage residents to actively participate in improving perceptions of IGS, transforming users' experiences and promoting environmental stewardship.

- **Monitoring and Evaluation**

Implementing a robust monitoring and evaluation system is crucial for assessing the effectiveness of green space initiatives. Regular monitoring gathers data on usage, condition, and ecological health, providing insights for the long-term management of these green spaces. Evaluation identifies successful strategies and necessary adjustments to ensure efficient resource use and protection. This step fosters transparency and accountability, ultimately supporting the long-term sustainability and adaptability of IGS by ensuring they continue to meet environmental, and user needs effectively.

5.3.2. Recommendations for Future Studies

- **Conduct Case-Based Studies:**

Case-based studies are essential for addressing the unique characteristics of each site, including surrounding urban morphology, size, vegetation, and the extent of paved areas. These studies facilitate a tailored understanding of specific environmental and urban contexts, enabling more effective, site-specific urban planning and green space management strategies. Additionally, case-based studies provide a more precise understanding of the complex, actual conditions that often limit simulation methods, thereby offering more accurate and reliable insights for urban planning and management.

- **Investigate Leaf Area Index (LAI):**

Researching the Leaf Area Index (LAI) yields valuable insights into plant health, growth patterns, and overall vegetation density. LAI provides specific information on the evapotranspiration rates, shading capacity, and carbon sequestration potential of various plant species. Furthermore, accurate LAI measurements are crucial for informed decisions on plant selection and maintenance, thereby enhancing urban green spaces' ability to mitigate heat, improve air quality, and support biodiversity. When measuring LAI, it is essential to consider factors such as time of day, cloud cover, and weather conditions, as these variables can affect the accuracy of readings.

- **Analyze Urban Morphology around Green Spaces:**

Detailed studies of surrounding urban morphology are essential for understanding the spatial structure and organization of urban areas, including the orientation and interaction of buildings, streets, open spaces, and vegetation. Elements such as street layout, building materials, heights, and land uses significantly influence the cooling benefits of green spaces. Analyzing these dynamics can reveal patterns and trends in factors such as wind flow and solar radiation that affect the cooling performance of green spaces. Thus, by examining the physical form of urban environments, planners can better integrate natural and built elements, thereby optimizing the cooling effects and other ecosystem services provided by green spaces.

- **Perform Microclimate Simulations to Compare with In-situ Measurements:**

Microclimate simulations are instrumental in comparing on-site measurements with model predictions. These simulations help understand the impact of various vegetation layers and urban features on local climate conditions, such as temperature, humidity, and wind patterns. By comparing real-time data with simulation models, discrepancies can be identified, and models refined for better accuracy.

- **Evaluate Other Ecosystem Services in Future Studies:**

Future research should broaden its scope to include a comprehensive evaluation of the diverse ecosystem services provided by IGS beyond their climatic benefits. This involves implementing an assessment framework that captures various ecosystem services, such as biodiversity support, water regulation, soil health, air quality improvement, cultural services like recreation and aesthetic enjoyment, provisioning services like food and medicinal plants, and supporting services such as habitat provision and nutrient cycling. A diversified methodological approach, incorporating field surveys, remote sensing, and community-based participatory methods, will be essential to thoroughly understand the multifaceted benefits of informal green spaces.

- **Thermal Comfort Benefits of Informal Green Spaces (IGS)**

Research should also investigate the influence of informal green spaces (IGS) on local microclimates, particularly in terms of the associated thermal comfort benefits for users. Additionally, examining human perceptions and usage patterns can provide insights into how specific vegetation types and configurations contribute to user thermal comfort. Comparative studies between IGS and formal green spaces (FGS) can identify the unique thermal advantages of IGS, if any. Understanding these dynamics is crucial for informing urban planning strategies that leverage IGS to mitigate heat stress, enhance public health, and adapt to climate change.

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APPENDIX

Appendix A: Site 1, Raw Data *(merged actual and interpolated values)*

Site 1: Vegetation Structure (VS)	Site 1: Canopy Cover (CC)	Afternoon Air Temperature (AT) °C	Evening Air Temperature (AT) °C
3	2	32.8	22.1
1	1	31.6	23.7
2	2	32.7	22.3
1	1	32.3	21.7
3	2	33.1	21.4
3	2	32.3	23.1
3	2	33.0	21.3
3	2	32.5	23.0
3	2	33.1	22.8
3	3	34.0	22.5
1	2	32.2	23.1
1	1	31.8	23.4
1	1	32.4	21.6
3	2	32.3	23.1
1	1	32.0	23.2
3	3	32.3	21.7
1	1	32.4	22.9
2	1	32.0	23.3
1	2	32.1	23.2
1	1	32.6	21.9
3	3	32.6	21.7
3	3	32.1	21.6
2	1	32.8	22.8
1	1	31.5	23.9
2	2	32.9	22.2
3	3	32.5	23.0
3	2	32.8	22.2
1	1	32.9	22.6
2	2	32.7	22.0
2	2	32.9	21.8
3	3	33.2	21.3
1	2	32.5	22.2
2	2	32.4	21.7
3	2	32.9	22.3
2	2	32.7	22.1
3	2	32.7	22.9
3	2	31.9	23.4
1	1	31.5	23.9
1	1	31.7	23.5
2	1	31.8	23.4
3	2	32.5	23.1
1	2	33.2	22.8
3	2	34.0	22.5
2	2	32.7	22.3
3	3	32.5	22.0
3	3	32.4	21.7
1	1	32.1	21.6
2	1	32.4	21.4
3	3	32.8	21.2
2	2	33.3	21.2

Appendix B: Site 2, Raw Data *(merged actual and interpolated values)*

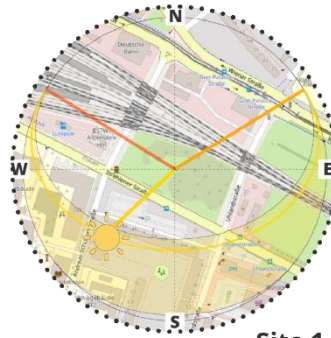
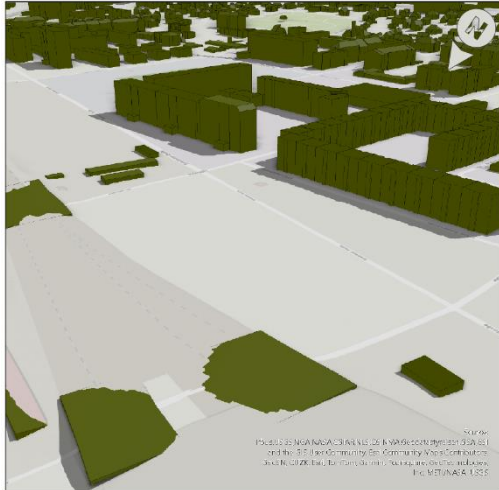
Site 2: Vegetation Structure (VS)	Site 2: Canopy Cover (CC)	Afternoon Air Temperature (AT) °C	Evening Air Temperature (AT) °C
1	1	29.8	25.5
3	3	29.9	25.7
3	3	30.2	26.5
1	1	31.0	27.1
1	1	30.6	27.2
2	3	29.4	26.2
3	3	29.7	26.4
3	3	29.4	26.4
1	1	33.5	26.9
2	2	31.8	27.0
2	3	29.6	26.4
1	1	29.9	25.8
1	1	29.8	25.6
2	3	30.0	25.9
1	2	29.5	26.1
1	1	30.5	27.1
2	2	30.8	27.1
1	1	30.7	27.1
1	1	32.2	26.8
2	2	32.3	27.0
1	1	29.9	25.7
2	3	31.0	26.4
3	3	33.3	26.9
1	1	29.9	25.6
1	1	29.8	25.7
3	3	31.5	27.2
1	1	29.8	25.5
3	2	31.2	27.1
3	3	32.0	27.0
1	1	33.1	26.8
3	3	29.9	25.8
2	2	31.2	27.1
2	3	29.5	26.1
3	3	29.4	26.3
1	2	31.1	27.0
2	3	29.4	26.0
3	3	30.0	25.8
2	3	30.1	25.9
1	1	30.2	27.2
2	1	31.4	27.3
2	1	32.2	27.2
3	3	33.8	26.9
3	3	29.2	26.4
2	3	29.4	26.3
3	3	29.3	26.1
2	1	29.3	26.0
3	3	29.6	25.8
2	1	29.9	25.7
3	2	29.9	25.6
1	1	29.7	25.4

Appendix C: Site 3, Raw Data *(merged actual and interpolated values)*

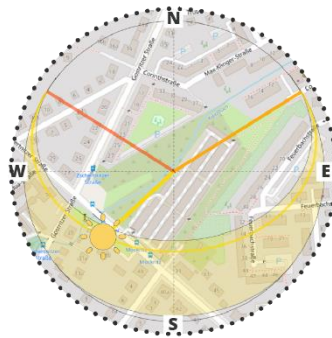
Site 3: Vegetation Structure (VS)	Site 3: Canopy Cover (CC)	Afternoon Air Temperature (AT) °C	Evening Air Temperature (AT) °C
1	1	29.3	26.9
3	2	29.6	26.5
3	2	29.4	26.8
2	3	29.6	26.7
3	3	29.6	25.6
1	1	29.6	26.0
3	3	29.4	26.8
1	1	29.6	26.3
3	3	29.6	25.5
1	1	29.5	26.9
1	1	29.6	26.5
3	2	29.6	26.6
2	3	29.6	25.7
1	1	29.7	26.8
1	1	29.6	25.4
1	1	29.6	25.5
2	2	29.6	26.6
3	2	29.7	26.0
2	2	29.7	25.8
1	1	29.6	26.6
1	2	29.6	26.7
1	1	29.6	25.8
2	3	29.6	26.6
2	2	29.6	26.8
3	3	29.6	25.3
1	3	29.5	25.2
3	3	29.8	25.8
1	2	29.6	26.6
3	3	29.2	26.7
3	3	29.6	26.6
1	2	29.6	26.6
2	3	29.6	25.7
1	2	29.5	26.9
3	2	29.6	25.4
3	3	29.6	25.8
2	2	29.6	26.6
1	1	29.7	25.8
3	3	29.7	25.4
1	1	29.2	26.9
3	3	29.6	27.0
3	3	29.7	26.9
2	1	29.8	26.7
2	2	29.6	26.7
1	1	29.6	26.6
2	2	29.2	26.7
2	2	29.7	25.9
3	2	29.8	25.7
1	1	29.7	25.3
3	3	29.5	25.1
3	2	29.6	24.9

Appendix D: Shadows and Sun Paths (Afternoon)

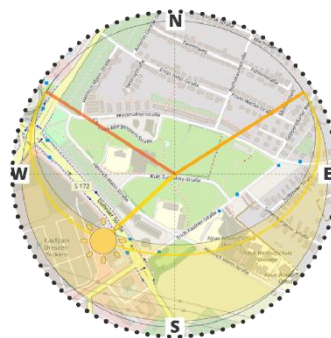
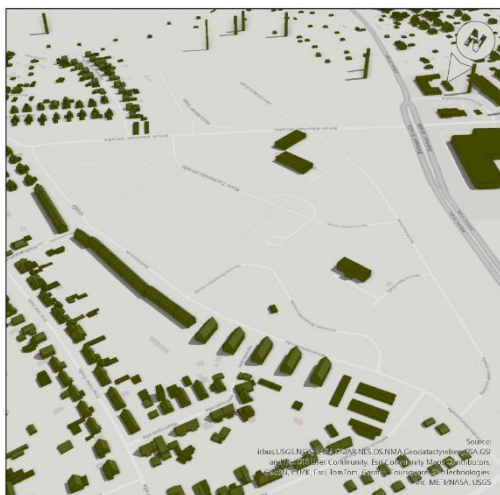
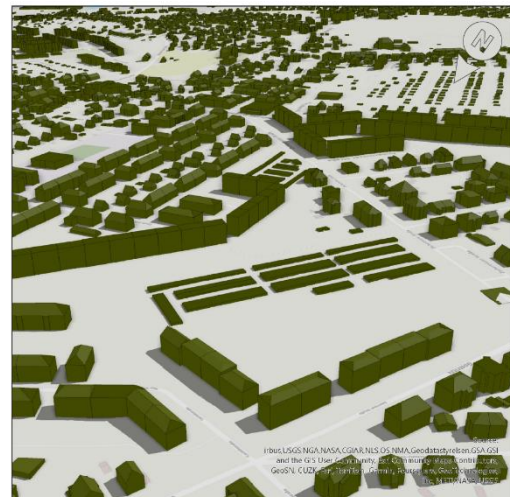
Shadows derived from the 3D Building of Dresden (Geoinformation and Surveying Saxony, 2023), and sun paths adapted from Suncalc.org (Hoffman, 2024a-c).



Site 1, May 13, 2024
15:00 Shadows and Sun Path



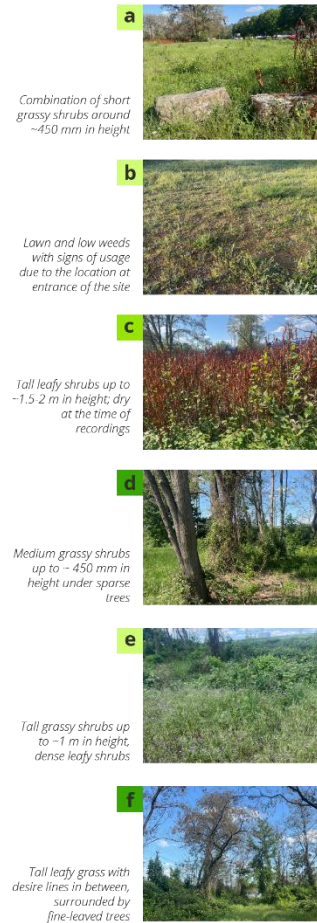
Site 2, May 14, 2024
15:00 Shadows and Sun Path



Site 3, May 15, 2024
15:00 Shadows and Sun Path

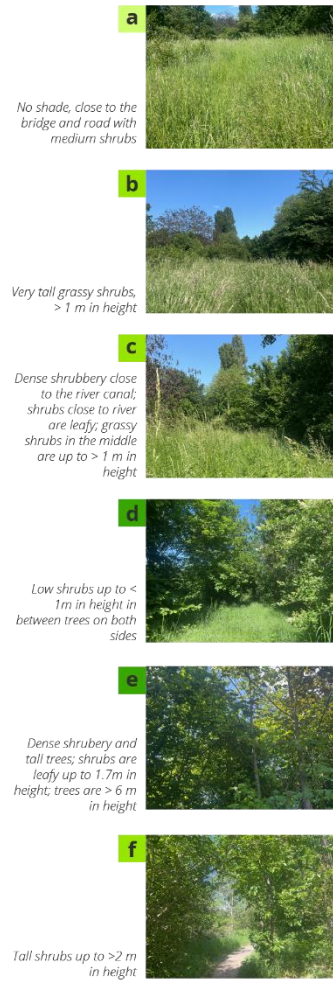
Appendix E: Site 1, VS (images)

Site 1 Strehleener Straße



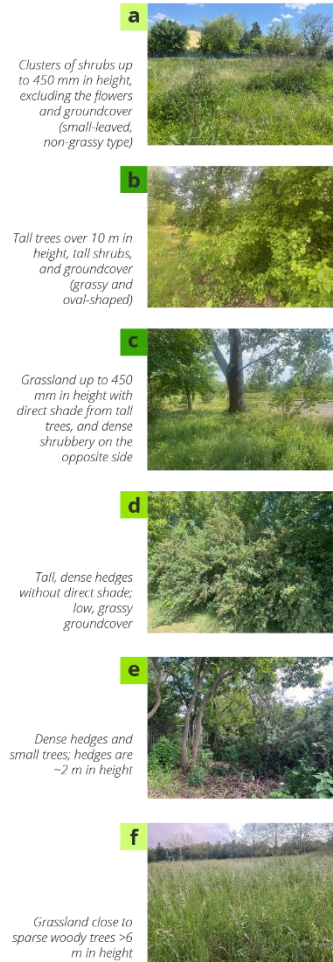
Appendix F: Site 2, VS (images)

Site 2 Kaitzbach

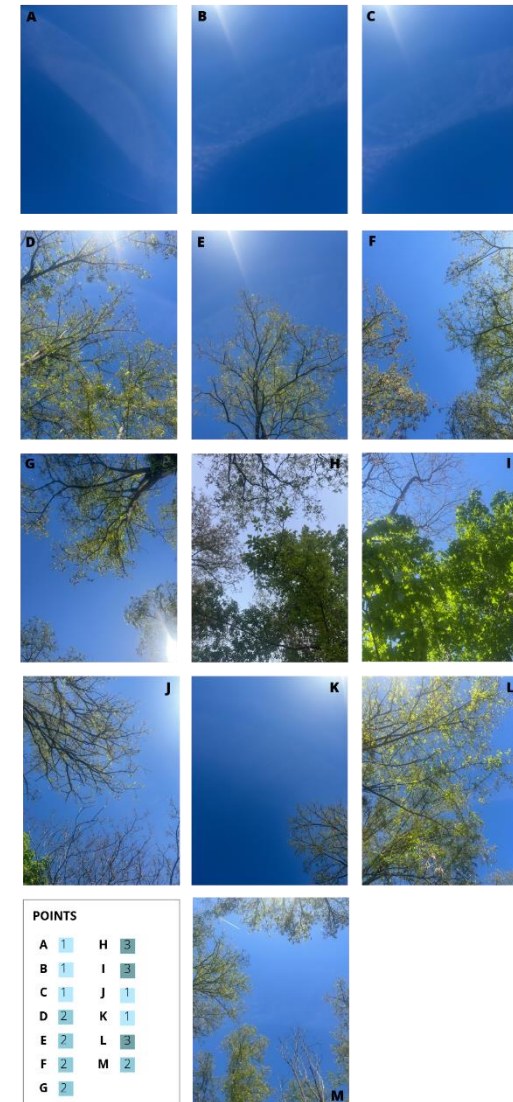


Site 3 Kaufpark

Appendix G: Site 3, VS (images)



Site 1 Strehleener Straße



Site 2 Kaitzbach

Canopy Cover (CC)
per traverse point

Appendix I: Site 2, CC (images)



POINTS			
A	1	H	1
B	1	I	3
C	1	J	1
D	3	K	2
E	3	L	1
F	3		
G	3		

Appendix J: Site 3, CC (images)

Site 3 Kaufpark

Canopy Cover (CC)
per traverse point



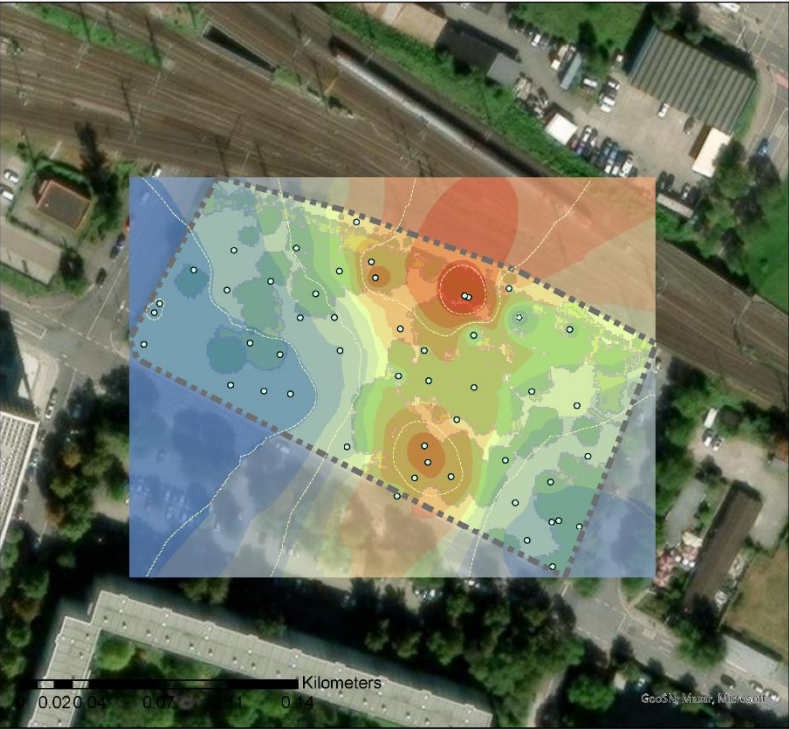
POINTS			
A	1	H	2
B	3	I	2
C	3	J	1
D	1	K	3
E	2	L	2
F	1		
G	2		

Appendix K: Site 1, Afternoon and Evening Air Distribution (actual and interpolated)

Site 1
Strehleener Straße

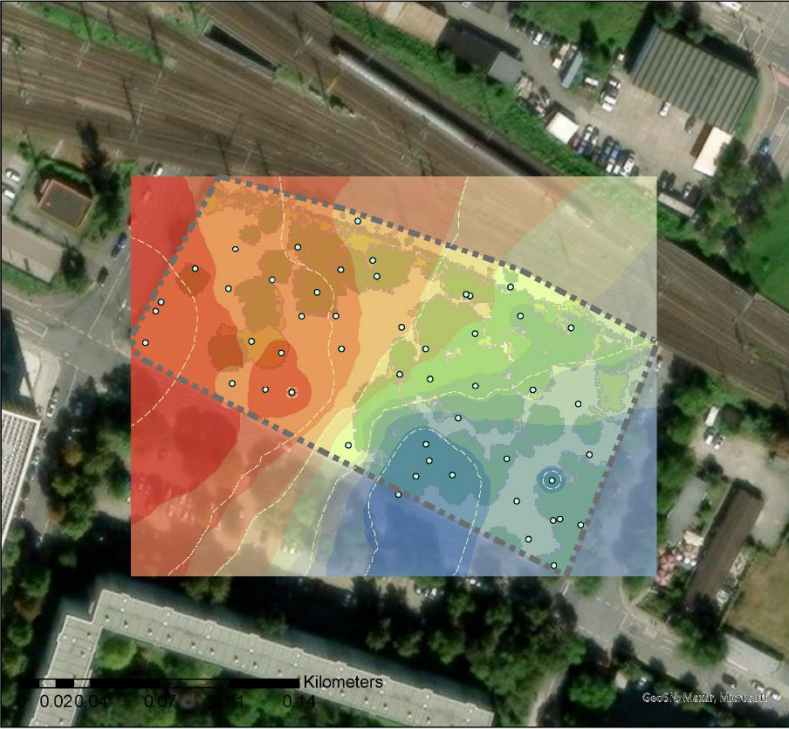


May 13, 2024, Afternoon and Evening Air Distribution,
Merged Actual and Interpolated Points



May 13, 2024 afternoon
VALUES (°C)

31.468 - 32.034	32.766 - 32.885
32.035 - 32.372	32.886 - 33.087
32.373 - 32.574	33.088 - 33.425
32.575 - 32.694	33.426 - 33.992
32.695 - 32.765	



May 13, 2024 evening
VALUES (°C)

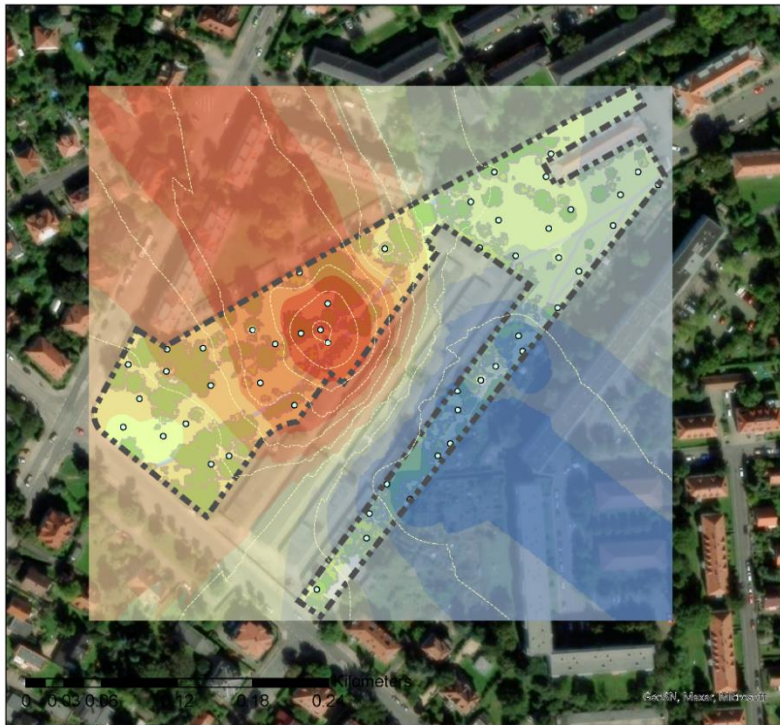
21.216 - 21.483	22.448 - 22.748
21.484 - 21.724	22.749 - 23.085
21.725 - 21.938	23.086 - 23.461
21.939 - 22.178	23.462 - 23.883
22.179 - 22.447	

Appendix L: Site 2, Afternoon and Evening Air Distribution (*actual and interpolated*)

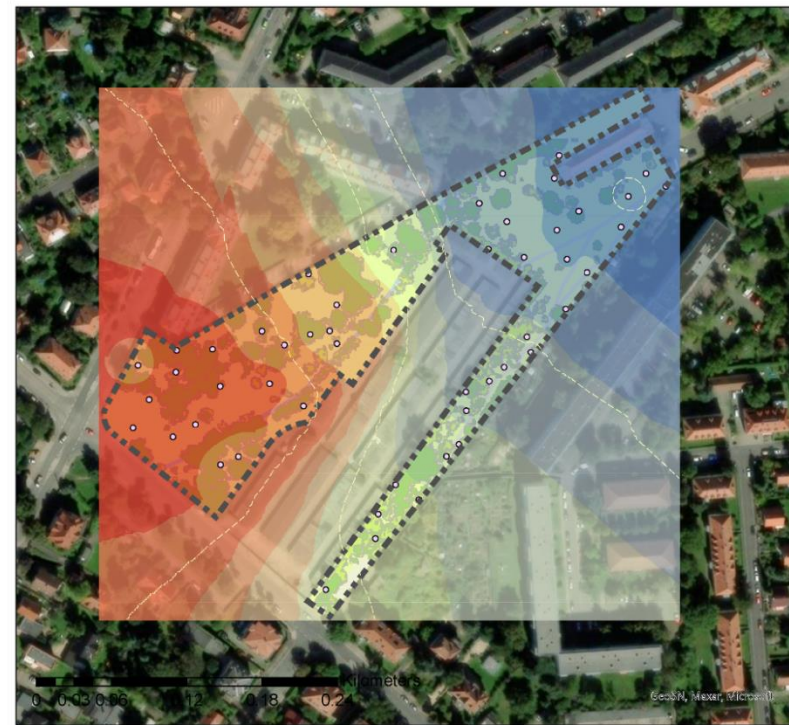
Site 2 Kaitzbach



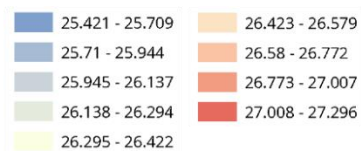
May 14, 2024, Afternoon and Evening Air Distribution,
Merged Actual and Interpolated Points



May 14, 2024 afternoon
VALUES (°C)



May 14, 2024 evening
VALUES (°C)

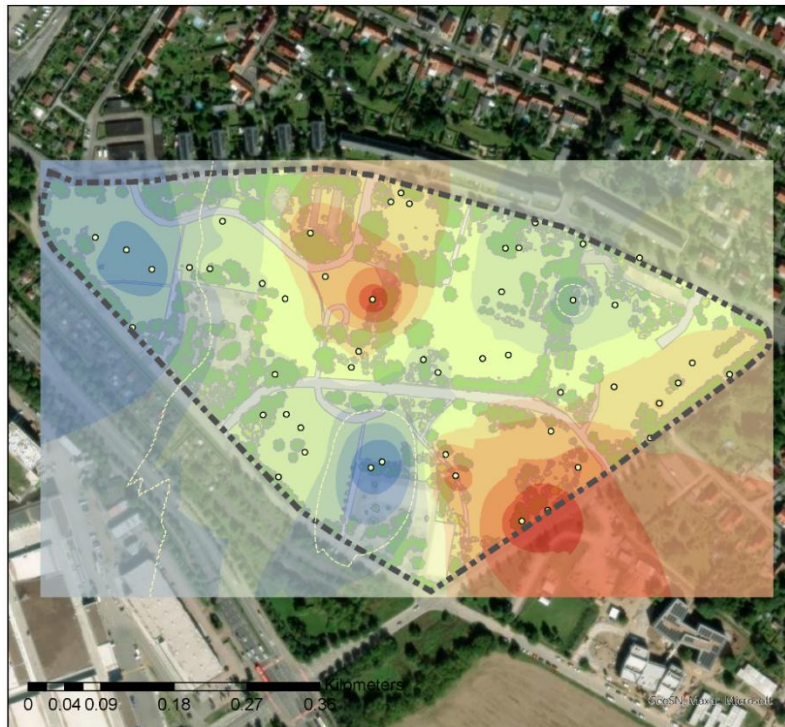


Appendix M: Site 3, Afternoon and Evening Air Distribution (actual and interpolated)

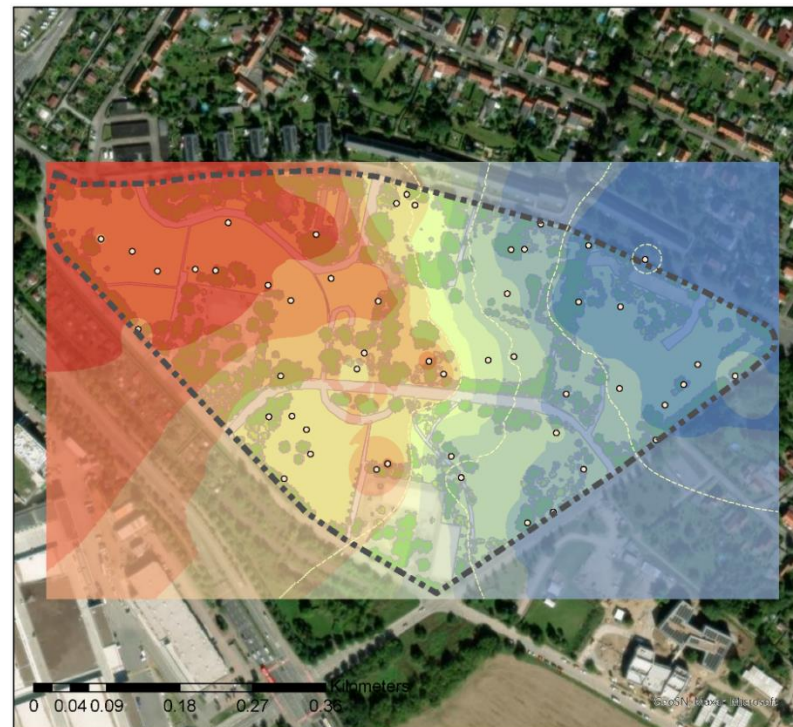
Site 3 Kaufpark



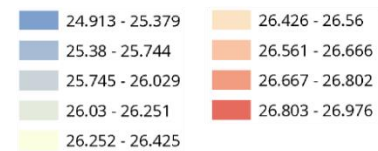
May 15, 2024, Afternoon and Evening Air Distribution,
Merged Actual and Interpolated Points



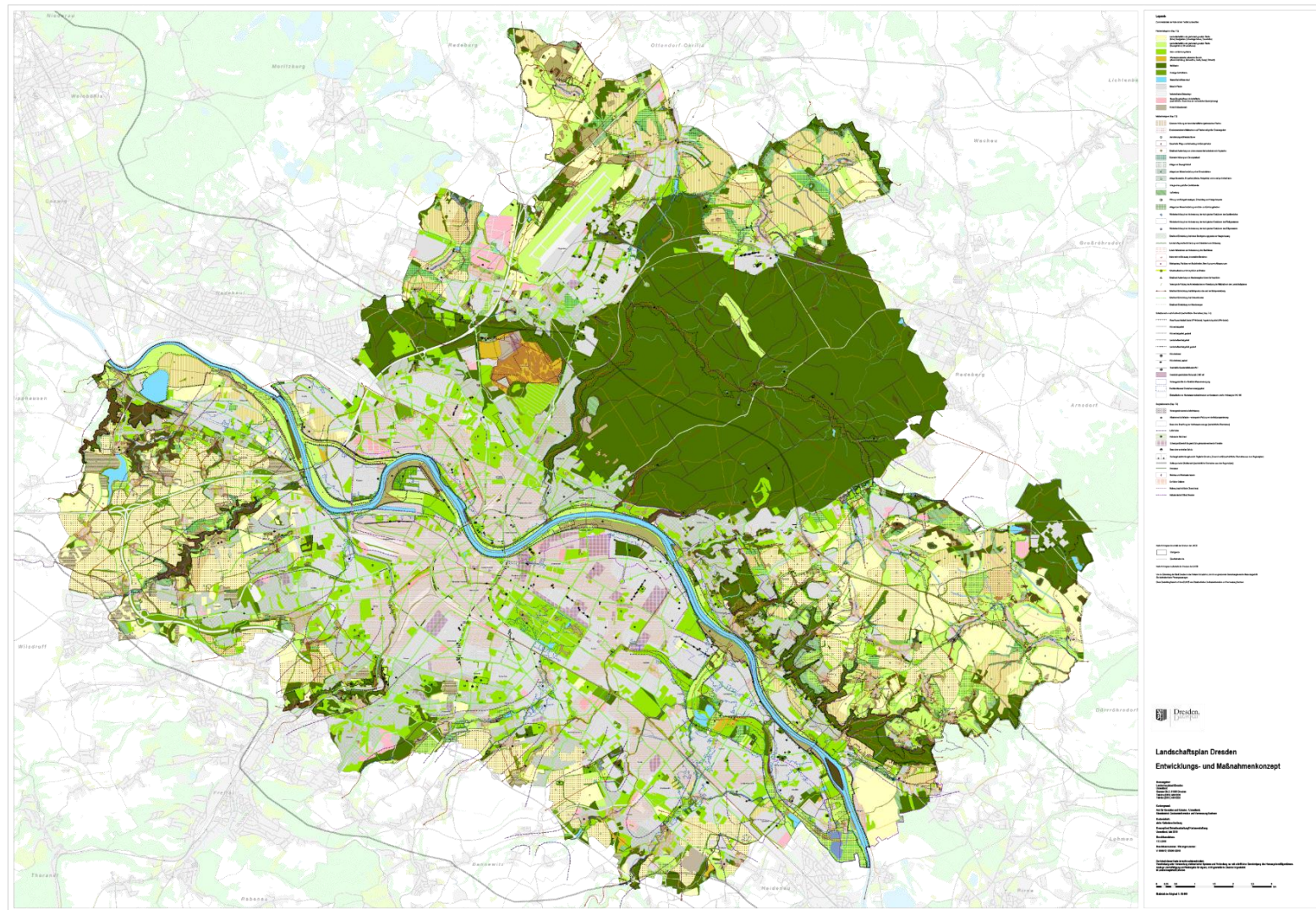
May 15, 2024 afternoon
VALUES (°C)



May 15, 2024 evening
VALUES (°C)



Appendix N: Landscape Plan, Dresden



Appendix O: Historical Satellite Images, Site 1 and 2

Images captured from Google Earth Pro (2024a & 2024b)

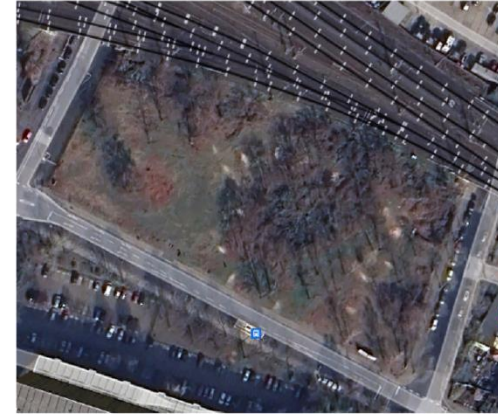
Site 1 2.2003



Site 1 6.2011



Site 1 3.2024



Site 2 2.2003



Site 2 6.2011



Site 2 7.2022



Appendix P: Historical Satellite Images, Site 3

Images captured from Google Earth Pro (2024c)

Site 3 2.2003



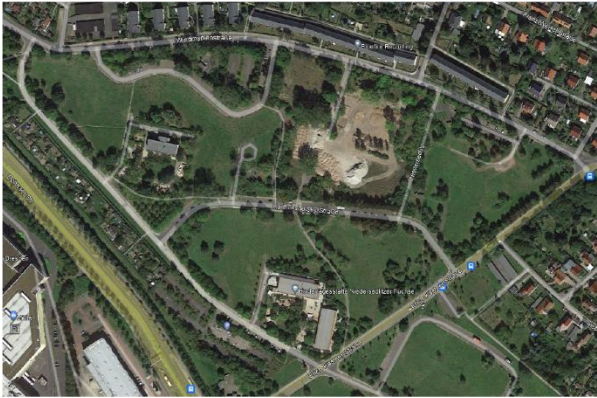
Site 3 12.2008



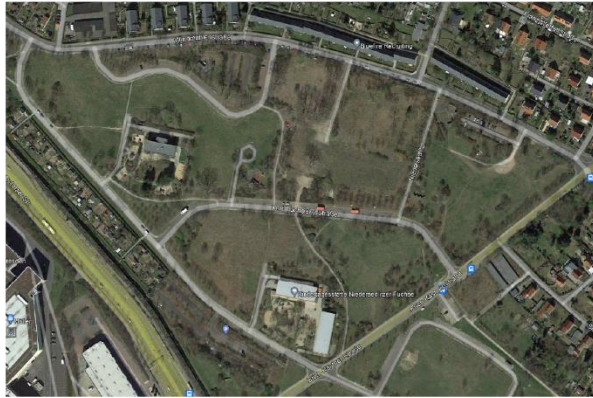
Site 3 6.2011



Site 3 8.2016



Site 3 4.2020



Site 3 7.2023

