Nature-Based Urban Acupuncture Strategies for Climate Resilience:

The case study of Curitiba

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Abstract

The increasing urban population, which has become the global majority since 2007, has transformed the scenarios of cities into major contributors to the climate crisis. The intensification of human activity and construction, along with the loss of natural areas, have a direct impact on local microclimates, leading to the emergence of phenomena such as urban heat islands. As a result, growing urban populations face higher exposure to climate-related risks, while cities are becoming more susceptible to extreme weather events.

In response to the urgent need for mitigation and adaptation strategies, this research adopts Curitiba as a case study to assess the feasibility and effectiveness of the urban acupuncture methodology integrated with Nature-Based Solutions (NBS), with an emphasis on reducing the effects of heat waves while also addressing co-benefits related to other urban climate challenges.

Structured in three parts, the thesis begins with a theoretical foundation anchored in the principles of the 2030 Agenda, the Sustainable Development Goals and the central concepts related to urban climate, microclimate and sustainable urban strategies. The second part presents a comparative analysis of three case studies that apply NBS through specific and strategic interventions, often associated with the urban acupuncture approach, highlighting their results and potential for replication in cities with similar climatic conditions.

Finally, the third part focuses on the case study of Curitiba. An analysis of the city's climate and environmental vulnerabilities is conducted, allowing for the recognition of priority areas for intervention. For this purpose, the districts of Centro and Rebouças serve as focus areas. Within these neighborhoods, 24 street segments are identified as potential sites for urban acupuncture implementation.

From this list, four sites are chosen as pilot proposals to assess the effectiveness and feasibility of multi-benefit nature-based solutions previously implemented in European contexts. These strategies aim to enhance thermal comfort, mitigate the effects of heat waves, and promote urban resilience. Their evaluation is carried out through microclimate simulations using ENVI-met software, analyzing variables such as potential air temperature, surface temperature, wind speed, and PET (Physiological Equivalent Temperature) values. The project's goal is to use the pilot interventions as guidelines for other locations, contributing to the development of adaptable and replicable strategies. Additionally, it aims to support urban planning decision-making by recommending policies aligned with global sustainability agendas that effectively address local climate challenges.

Key-words: Urban microclimate; Nature-Based Solutions (NBS); Urban acupuncture; Climate resilience; Thermal comfort; ENVI-met; Curitiba.

0. INTRODUCTION

0.1 Objectives

Since 2007, urban centers have concentrated the majority of the world's population, with projections indicating that this number could reach 68% by 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2019). The increase in human activity, resource consumption, and construction, combined with the expansion of impervious surfaces, such as roads and pavements, has altered environmental factors and weather conditions within cities. Over time, these processes have contributed to the emergence of a characteristic atmospheric condition known as the urban climate (Oke, 1987; Gomez et al., 1998; Hasenack, 1989).

One of the main effects of urbanization is the formation of urban heat islands, characterized by higher temperatures in urbanized areas relative to surrounding regions (Oke, 1987). Although this phenomenon is easily observed when contrasting rural and urban landscapes, its manifestation is not uniform throughout the city and is strongly influenced by local micro-scale characteristics (Oke, 1998). Menon, Leung, and Chunho (2008) identify the phenomenon as one of the most significant urban challenges of the 21st century due to its impacts on public health, increased mortality during heat waves, intensified pollutant production, growing demand for artificial cooling, and the consequent rise in CO^2 emissions—factors that exacerbate the global climate crisis. As a result, cities become even more vulnerable to extreme events, exposing larger populations to significant risks (Chen & Ng, 2012).

In this context, and in alignment with the 2030 Agenda — which seeks to ensure human rights and secure a resilient planet for present and future generations (United Nations, 2015) — it is essential to rethink urban planning and architecture, recognizing their roles as tools both for mitigation, tackling the structural causes of climate impacts (Pollo & Trane, 2021), and for adaptation to evolving conditions (Perez-Lancellotti & Ziede, 2020). A variety of strategies can be employed to promote thermal comfort and contribute sustainably to addressing the climate crisis (Schmitz, 2014). These strategies generally involve managing solar exposure and ventilation, carefully selecting materials for buildings and pavements, and integrating green and blue infrastructure into cities, with particular emphasis on Nature-Based Solutions.

Despite the urgency of interventions, many urban projects require long timelines and significant investments (Balicka et al., 2021). On the other hand, small-scale interventions tend to limit their impact on the immediate surroundings without fully exploring their transformative potential in broader areas (Moussavi et al., 2024). In this context, urban acupuncture, based on multiple targeted interventions that are low-cost and quickly implemented (Perez-Lancellotti & Ziede, 2020), emerges as an approach capable of connecting local actions to a more comprehensive urban transformation.

Thus, this study aims to analyze the application of the urban acupuncture methodology, using the city of Curitiba as a case study — a pioneer in adopting this approach under the leadership of Jaime Lerner (Perez-Lancellotti & Ziede, 2020; Rudy et al., 2022) — assessing its potential when integrated with Nature-Based Solutions strategies to mitigate and adapt to the impacts of urbanization and climate change. The city already exhibits a trend toward increased occurrences of extreme events, such as droughts, heavy rainfall, flooding, and heatwaves (Silveira et al., 2019; Curitiba City Hall, 2020a), with the latter being the primary focus of this research.

0.2 Research question

How can the methodology of urban acupuncture, integrated with Nature-Based Solutions, contribute to the mitigation and adaptation actions in Curitiba, with a specific focus on the impacts of excessive heat?

- What are the main effects of climate change on urban microclimate in Curitiba?

- How can urban acupuncture be used to promote effective interventions that contribute to the mitigation and adaptation to these different climatic impacts?

- In what ways can Nature-Based Solutions be integrated into urban acupuncture interventions to enhance the city's thermal and environmental resilience?

- What are the technical, economic, and social challenges in implementing these strategies in Curitiba?

- How can these interventions generate co-benefits for other urban impacts related to the microclimate and the climate crisis?

- How do the proposed strategies align with the goals of the 2030 Agenda for sustainable cities and climate adaptation?

0.3 Methodology

The structure of this thesis is organized into three main sections, which are outlined below and visually summarized in Figure 01.

Part 01 – Scientific Background: In this initial phase, a literature review was carried out to provide the theoretical foundation for the main topics addressed in this thesis, laying the groundwork for the subsequent chapters. The research process involved the use of academic databases such as Google Scholar and Scopus, as well as the consultation of specialized books related to the subjects under study. Keywords including "urban acupuncture," "microclimate," and "Nature-Based Solutions" were employed to identify relevant literature.

The review began with an overview of the 2030 Agenda, followed by the identification of the most relevant Sustainable Development Goals (SDGs) for this study. These objectives were then connected to the broader themes of urban climate and climate change mitigation and adaptation strategies, progressing from a general framework toward a more specific focus on the climate conditions of the selected case study: the city of Curitiba. Finally, the fundamental concepts of the urban acupuncture methodology and its various applications were examined, with particular attention to its integration with Nature-Based Solutions.

Part 02 – Best practices: The second phase consists of the analysis of three urban projects that exemplify the application of the urban acupuncture methodology combined with the use of Nature-Based Solutions (NBS) and their respective outcomes. The projects located in Germany and Poland are part of the European SALUTE4CE program (2019–2022), which developed guidelines for implementing Urban Environmental Acupuncture integrated with NBS as a strategy to mitigate the impacts of climate change. The project in the city of Eindhoven, in the Netherlands, was part of the UNaLab initiative (2017–2022), employing targeted NBS interventions to strengthen urban climate resilience—particularly in addressing flooding, urban heat islands, and environmental degradation. Among the projects analyzed, the Impulse Region (Germany) and Eindhoven (Netherlands) are located in Cfb climate zones, according to the Köppen-Geiger classification, similar to the climate of Curitiba, which serves as the main case study of this research.

Part 03 – Case study: Curitiba, Brazil: The final part of this thesis is dedicated to studying the application of the urban acupuncture (UA) methodology integrated with the use of Nature-based Solutions (NbS) in the city of Curitiba, encompassing scales from city-wide to micro-level. This chapter can also be subdivided into three stages.

Initially, a contextual analysis of the city is conducted, including current and projected climate conditions. This stage also outlines Curitiba's various urban microclimates and highlights its main areas of risk and vulnerability. Data sources include academic platforms such as Google Scholar and Scopus, as well as official municipal and national websites.

In the second stage, two critical neighborhoods — Centro and Rebouças — are selected for further study. Based on a detailed analysis of their characteristics (e.g., vegetation, traffic, zoning, and social dynamics), 24 potential intervention points are identified. From this list, four pilot sites are selected to represent different street typologies in Curitiba. The selection criteria included land use, pedestrian and vehicular flow, urban morphology (height-to-width ratio), vegetation cover, solar exposure, and paving type. This diversity aims to enhance understanding of how UA can be applied in varied urban contexts, supporting future replication. To evaluate current and proposed scenarios at each site, simulations were conducted using ENVI-met software, generating data on potential air temperature, surface temperature, wind speed, and Physiological Equivalent Temperature (PET). Results were compared both within each site and across all selected locations.

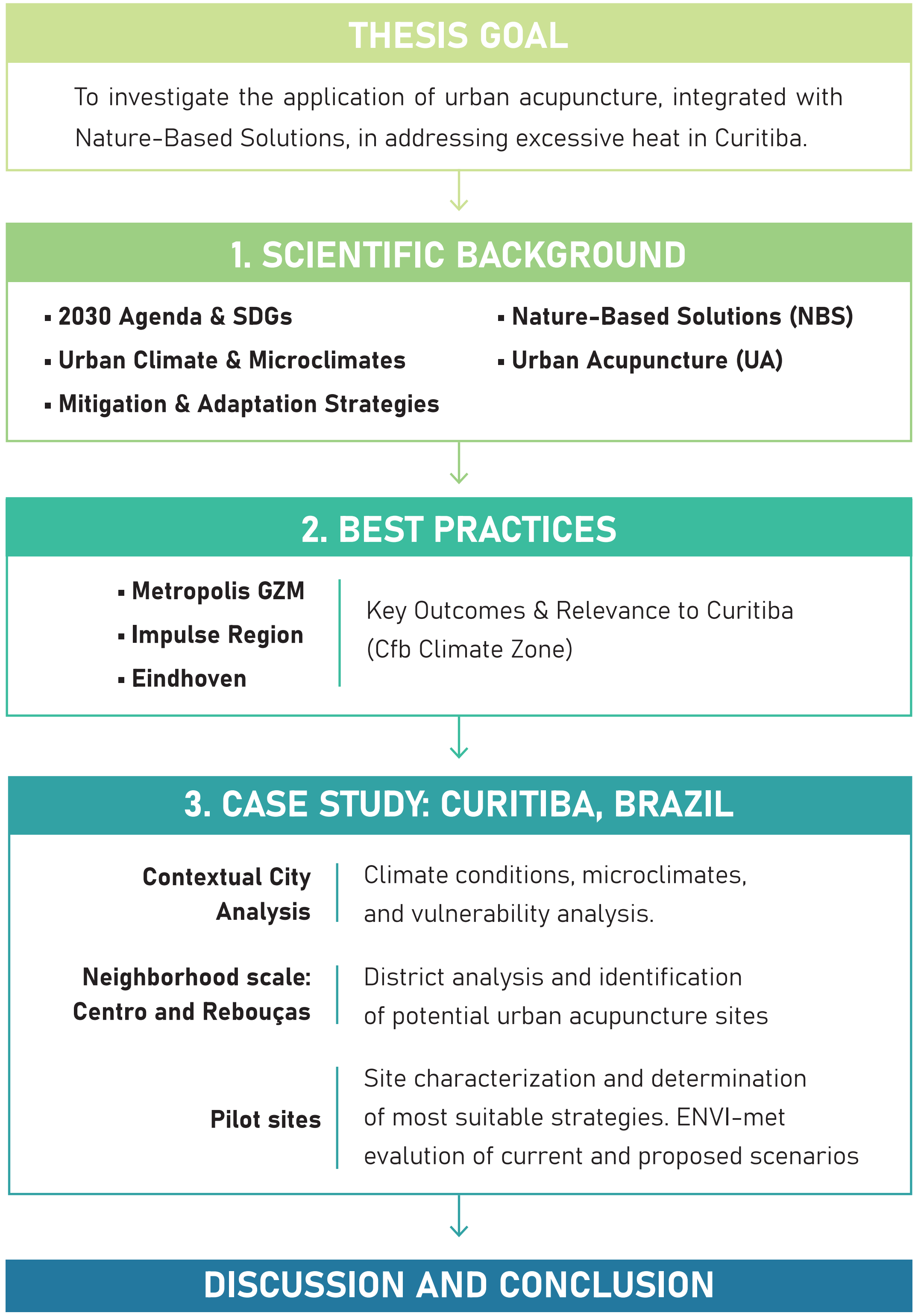


Fig. 01: Methodology diagram.
Source: The author

1. SCIENTIFIC BACKGROUND

1.1 Sustainable development

The increasing research on urban climate is directly linked with global efforts toward sustainable development. The world is experiencing its largest wave of urban growth, with more than half of the global population living in towns and cities since 2007 (United Nations, Department of Economic and Social Affairs, Population Division, 2019). According to the World Cities Report 2022 (United Nations, 2022), the total urban population is projected to grow from 56% in 2021 to 68% by 2050. This trend contributes to rising local air temperatures and greater vulnerability to extreme climate events (Arias et al., 2021).

The risk to public health and well-being makes it essential to consider sustainability in city planning and governance since cities are key factors for addressing environmental and social issues (United Nations, 2022).

Multiple policies have been established in order to foster mitigation and adaptation. The 2030 Agenda is an example of a broad action plan focused on global sustainable development. Its main objectives are to secure human rights and provide a resilient planet for current and future generations.

The project is based on the improvement of the Millennium Development Goals, an initiative introduced in 2015 with the aim of outlining a strategic plan for the next 15 years. It comprises **17 Sustainable Development Goals (SDGs)**, presented in Figure 02, and 169 targets, which aim to balance three key dimensions: economic, social, and environmental sustainability (United Nations, 2015).

For the purpose of this research, three goals can be highlighted as a direct influence to the field of urban planning, and will be

Fig. 02: 17 Sustainable Development Goals. Source: United Nations (2015)

used as reference.

The first one is goal **number 3**: **Ensure healthy lives and promote well-being for all at all ages.** Although its priority is mainly centered on pandemics and major diseases, one of its key targets reports the need for reducing deaths and illnesses influenced by air, water, and soil contamination, as well as emphasizes the urgency of risk mitigation and precautionary actions (United Nations, 2015).

The second reference goal is **number 11: Make cities and human settlements inclusive, safe, resilient and sustainable.** Among its objectives, it encourages sustainable and inclusive urbanization with participatory and integrated planning for human settlements, highlighting the importance of safe, accessible, and affordable transportation systems, with special attention to vulnerable populations such as women, children, people with disabilities and the elderly.

It also highlights the importance of universal access to green public spaces and strengthening connections between urban, peri-urban and rural areas, through national and regional development planning with efforts to protect and preserve cultural and natural heritage.

Finally, the goal also advocates reducing the environmental impacts of cities, with a focus on improving air quality and effective waste management. It promotes the implementation of integrated policies to increase efficiency in the use of resources and, as in the previous goal, adaptation to climate change and resilience to disasters, reducing deaths, economic losses and impacts (United Nations, 2015).

The last goal that should be analyzed is **number 13: Take urgent action to combat climate change and its impacts.** Complementing the above points, it reinforces the importance of policies, strategies, and planning focused on addressing climate change and its effects. It also highlights the importance of education and awareness on mitigation, adaptation and resilience (United Nations, 2015).

All three goals rely heavily on effective management of the urban environment. With the rising densification of these areas, urban centers become especially susceptible to extreme weather conditions resulting from climate change, highlighting the urgency of strategies that integrate resilience and sustainability into urban planning (Chen & Ng, 2012). As consequence, local governments operate as one of the main actors of transformation (Dellas et al., 2018).

Open and public spaces, such as streets, sidewalks, squares, and parks, become then fundamental tools in this process, directly influencing people's quality of life. Such structures can serve to promote sustainable mobility and accessibility, as well as provide spaces for social interaction, leisure, and proximity to natural environments. Also, combined with the expansion and improvement of green areas, provide significant benefits for the physical and mental health of the population. In addition, these efforts act as co-benefits for climate change adaptation and mitigation, helping to reduce the impacts of extreme weather events and build more resilient and sustainable cities (United Nations, 2022).

1.2 Urban climate

Cities are shaped by intense human activity and rapid urbanization, which demand ever-increasing energy and natural resources. These processes significantly transform the Earth's surface, altering vegetation cover and atmospheric conditions. As a result, key climatic factors such as solar radiation, temperature, humidity, precipitation, and wind circulation undergo substantial modifications. This leads to the development of a distinct urban climate, commonly referred to as the "Urban Climate" (Oke, 1987; Gomez et al., 1998).

Hasenack (1989) identifies several major transformations that contribute to this phenomenon. The widespread sealing of natural soil due to street paving and building construction reduces permeability, limits evaporation, and increases heat absorption. Urban morphology—defined by building placement, orientation, and materials—further influences heat retention. Additionally, air circulation patterns shift as wind corridors form along streets and avenues, while urban structures obstruct natural airflow from surrounding areas. Human activities, including industrial production, transportation, and climate control systems, further intensify heat emissions and release particulate matter, which alters condensation processes and increases precipitation.

Monteiro (2003) classifies urban climatic systems into three main categories. The physicochemical category refers to air quality. The hydrometeorological category addresses the effects of urbanization on precipitation patterns. Lastly, the thermodynamic category focuses on thermal comfort and encompasses the formation of urban heat islands (UHIs). Moreover, Oke (2004) proposes classifying the urban climate based on horizontal and vertical scales of interest (Figure 03). The horizontal scale is composed of three levels:

Mesoscale: Typically spanning tens of kilometers. The impact of a city on weather and climate extends across its entire area.

Local scale: This scale typically extends from one to several kilometers. Refers to climatic influences shaped by landscape features such as topography, while excluding microclimatic effects. In urban areas, it describes the climate of neighborhoods with similar development patterns, including land use, building size and spacing, and dominant activities.

Microscale: Range from less than a meter to hundreds of meters. The microclimate is characterized by the dimension of individual elements. It is influenced by buildings, trees, streets, surface materiality and other structures.

Alternatively, the vertical scale defined by Oke (2004) is subdivided into two layers, as shown in Figure 04. The first is called Urban Canopy Layer and refers to the area between the ground and the mean height of the main urban roughness elements - building and trees, where the interaction between the atmosphere and city elements takes place. This layer is typically studied in the microscale, being heavily shaped by its immediate surroundings, particularly the materials and geometry of urban structures and its upper boundary is often imprecise, varying according to the urban and natural morphology.

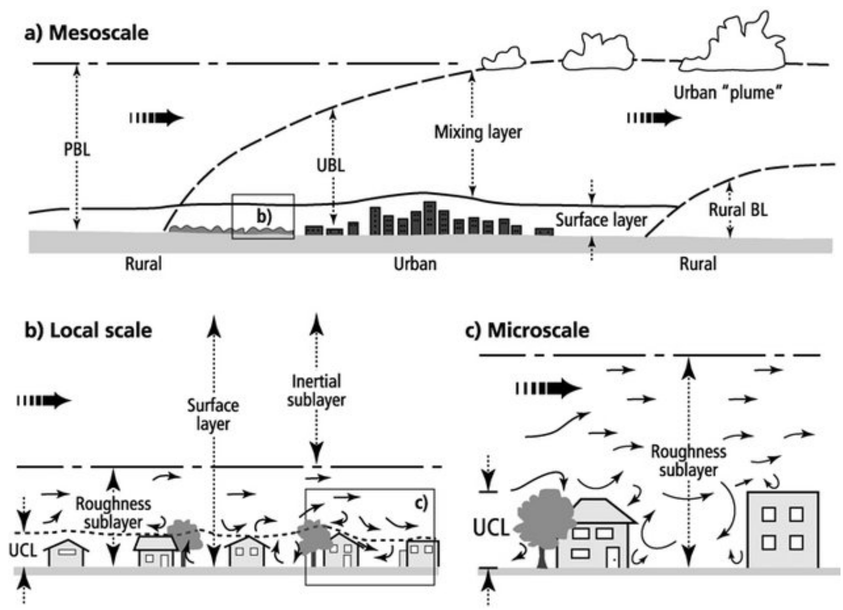


Fig. 03: Schematic of climatic scales and vertical layers found in urban areas.
PBL – planetary boundary layer,
UBL – urban boundary layer,
UCL – urban canopy layer.
Source: Oke (2004)

The second vertical layer, known as the Urban Boundary Layer, lies above the first. It can be studied at both local and mesoscale levels, with its climatic characteristics being influenced by the presence or absence of urban areas.

According to Huang et al. (2008), studying the distinct microclimates within a city plays a crucial role in informing environmental planning and urban development. Similarly, Dumke (2007) highlights that understanding local climatic variations enhances human resilience by improving both indoor and outdoor thermal comfort while promoting the sustainable use of energy resources.

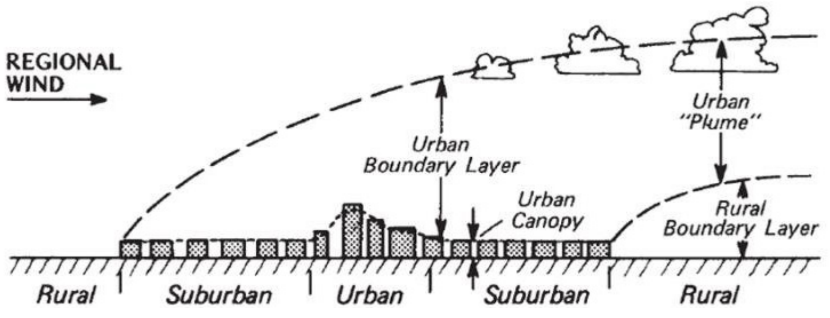


Fig. 04: Classification of urban atmospheric changes.. Source: Oke (1987)

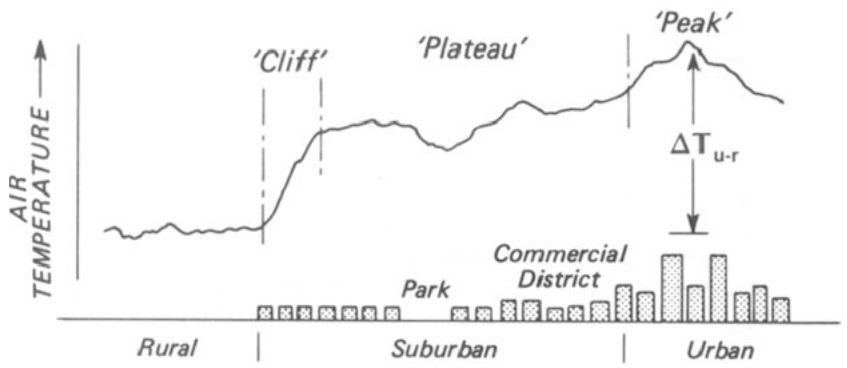
1.2.1 Urban Heat Islands (UHI)

Among microclimatic effects, the most prominent and widely studied is the Urban Heat Island (Schmitz, 2014). This phenomenon is traditionally characterized by the increase in temperature in urban areas compared to their rural surroundings. However, since the rural-urban duality in real cases rarely has a clear distinction and instead forms continuous transitions, an alternative definition would be to compare the temperature of urbanized areas with the temperature of the same location in the hypothetical scenario of non-urbanization (Erell et al., 2010).

Although it is more easily identified between urban and rural areas, understanding the effect as a city-wide occurrence can be misleading (Erell et al., 2010). The heat island is not evenly distributed throughout the city. As Oke (1998) highlighted, the urban microclimate is influenced by the immediate surroundings, rather than by distance from the edge or the center. Its effects can be observed at various scales, from the surroundings of individual buildings to large urban areas, with distinct characteristics in open and vegetated spaces compared to densely built-up areas (Oke, 1998; Coltri, 2006).

The classical Urban Heat Island (UHI) profile (Figure 05), as described by Oke (1987), features heat "peaks" in areas with higher anthropogenic activity, typically the city center, compared to residential and peripheral zones. As the distance from these hotspots increases, temperatures gradually decline, forming the "plateau". The "cliff" refers to the limits between urban and rural areas, where temperature differences are most pronounced.

Fig. 05: Generic cross-section of a typical urban heat island. Source: Oke (1987)



This phenomenon is considered by Menon, Leung, and Chunho (2008) to be one of the most critical urbanization-related issues of the 21st century, with an estimated 3 million people living in affected cities. Elevated temperatures increase ozone production in urban atmospheres and drive higher demand for artificial cooling, leading to greater CO_2 emissions and contributing to global warming (US EPA, 2008). Additionally, they directly impact the population's quality of life by posing adverse health effects and increasing mortality rates during heat waves. However, in some climates, temperature rises may also provide benefits in winter, highlighting the need for a localized analysis and a balance between winter advantages and summer drawbacks (Erell et al., 2010; Heisler, 2010; Brazel, 2010).

Urban heat islands can be subdivided in two categories, the surface and the atmospheric level. Surface urban heat island (SUHI), are more intense than the second, being influenced by urban design and the various urban surfaces such as streets and building roofs (US EPA, 2008; Kong et al., 2021).

Several factors contribute to rising temperatures in urban areas. First, the anthropogenic factor plays a significant role, referring to the heat and pollution generated by human activities, such as building climate control, industrial processes, transportation, and other activities typical of highly dense cities (Gartland, 2010). Another important factor to consider is urban morphology — including building geometry, street orientation, and aspect ratio — which affects wind speed and, in the case of streets and urban canyons, reduces the amount of incident radiation due to the decreased Sky View Factor (SVF) caused by buildings (Oke, 1981; Gartland, 2010). The SVF represents the angle of visible sky from a given point (Rossi, 2012).

Moreover, surface materials also have a major influence on this scenario. In cities, the removal of vegetated and liquid surfaces, combined with an increase in impermeable surfaces such as concrete, asphalt, and construction materials, reduces evapotranspiration and air humidity, making heat dissipation more difficult (Oke, 1981; Gartland, 2010). Additionally, albedo (reflectance) and emissivity (thermal performance) of materials must be considered. Lower albedo and emissivity cause greater absorption and retention of heat during the day, as well as the emission of radiation at night, directly affecting the energy balance and local climate (Oke, 1987). These characteristics are summarized in Table 01.

Table 01: Important urban characteristics for the formation of Heat Islands. Source: Gartland (2010) - adapted by the author

Characteristics that contribute to the formation of a heat island	Effects on the energy balance
Lack of vegetation	Reduces evaporation
Widespread use of impermeable surfaces	Reduces evaporation
Higher thermal diffusivity of urban materials	Increases heat storage
Low solar reflectance of urban materials	Increases radiation balance
Urban geometries that trap heat	Increases radiation balance
Urban geometries that reduce wind speeds	Reduces convection
Increased pollution levels	Increases radiation balance
Increased energy consumption	Increases anthropogenic heat

1.2.2 Thermal Comfort

Human thermal comfort is defined by ASHRAE (2005) as the state of satisfaction with the thermal environment. It is both a physiological and perceptual experience, varying from person to person. However, at its core, it relates to the balance between heat retention and dissipation in a given environment (Erell et al., 2010).

Rossi (2012) identifies key environmental variables influencing the comfort zone and thermal sensation. Air temperature (Ta) affects heat exchange through convection and respiration, with convective exchange increasing as the temperature difference between the body and environment grows. During evaporation, its effect depends on relative humidity and air velocity. Relative humidity (RH) refers to the proportion of water vapor present in the air, also being influenced by temperature, often dropping in hotter conditions. This plays a role in how the body releases heat, as it can either support or limit the evaporation of moisture from the skin. Air velocity (Va) interacts with temperature and humidity; in unsaturated environments, where air temperature is lower than skin temperature, wind accelerates evaporation, aiding cooling. Lastly, mean radiant temperature (MRT) refers to the average temperature of surrounding surfaces involved in thermal radiation exchange with the body, which can be higher or lower than air temperature.

As these factors vary significantly depending on the location and the adaptability of the inhabitants—even within the same population—Erell et al. (2010) argue that thermal discomfort is essentially caused by rapid heat exchanges between the body and the environment. Thus, to better understand the effects of design on human experience, the author emphasizes the importance of an in-depth study of energy exchange processes.

There are several ways to analyze and quantify these effects, with thermal indices being based on the relationships between environmental climatic variables and the physiological and sensory responses of the body, considering daily activities and clothing (Schmitz, 2014).

Standard Effective Temperature (SET): It can be defined as the dry bulb temperature in an ideal environment where the air has a constant temperature and 50% relative humidity (RH), in which a person, wearing standardized clothing for a specific activity, would experience the same skin wittedness and heat exchange at the skin surface as they would in the actual test environment (Gagge et al., 1986).

Resultant Temperature (RT): Developed by Missenard (1948), it is based on the Effective Temperature (ET) and considers the following ranges for each variable: dry bulb temperature, from 20 to 45°C; wet bulb temperature, from 18 to 40°C; and air velocity, from 0 to over 3 m/s. According to Szokolay (1985), it is ideal for moderate climates; however, in tropical climates, it tends to overestimate the cooling effect of air at temperatures above 35°C and humidity levels above 80%.

Heat Stress Index (HSI): It consists of the ratio between the total heat loss through evaporation required for thermal balance and the total heat loss through the maximum evaporation that can be achieved in the environment (Belding & Hatch, 1955).

Wet Bulb Globe Temperature (WBGT): Developed by Yaglou and Minard (1957) it is one of the most commonly used indices for heat stress (Mahgoub et al., 2020). It considers three environmental parameters: air temperature (dry bulb), natural wet bulb temperature (ventilated environment), and globe temperature.

Olgyay bioclimatic chart: Olgyay (1976) presents the comfort zone based on relative humidity and air temperature. The chart, originally developed for hotter regions (Olgyay, 1968), was later adapted to incorporate data that allowed its use in temperate, hot, and humid climates.

Index of Thermal Stress (ITS): Proposed by Givoni (1976) and adapted for outdoor spaces by Pearlmutter et al. (2007), it measures the overall thermal exchange between the body and its environment in warm conditions, with a detailed focus on evaporation. It also links physiological heat exchange to perceived thermal sensation, based on empirical observations of subjective comfort. The ITS is considered the most comprehensive index for evaluating environmental heat stress (Erell et al. 2010).

Universal Thermal Climate Index (UTCI): The UTCI (Universal Thermal Climate Index) follows the concept of equivalent temperature, which compares the human body's response to heat in a real environment with that in a reference environment. It was created to be applicable to all types of weather independently of the person. The UTCI indicates the temperature of a reference environment that would cause the same level of thermal stress as the real environment, taking into account factors like wind, radiation, humidity, and air temperature (Bröde et al., 2010; ISB, 2001; ISB, 2003).

Actual Sensation Vote (ASV): evaluated through multiple regression, this index is based on over 10,000 environmental and personal data collected by the RUROS project - Rediscovering the Urban Realm and Open Spaces (Niklopoulou, 2004) in seven cities across five European countries.

Predicted Mean Vote (PMV): Developed by Fanger (1970), this index aims to assess the degree of thermal discomfort by correlating thermal sensation with metabolic activity, clothing, and environmental variables (temperature, humidity, air velocity, and mean radiant temperature), highlighting the importance of the combined effect of these factors (Dumke, 2007).

Physiological Equivalent Temperature (PET): Defined by Höppe (1999), it represents the air temperature (°C) that would maintain the energy balance of the human body, characterizing the thermal bioclimate of a region. PET takes into account variables such as air temperature, relative humidity, wind speed, and mean radiant temperature (Nakata, 2010), and interprets them from a physiological perspective, considering how these factors affect the body's internal temperature regulation processes (Höppe, 1999). Based on these parameters, Matzarakis and Mayer (1996) enabled the adaptation of thermal perception values and levels of physiological stress — originally assessed through the Predicted Mean Vote (PMV) index — to the PET scale.

1.2.3 Climate crisis

Rapid and intense urbanization impacts not only the microclimate of cities but also the global environment. Urban areas, which continue to expand, are estimated to account for 70% of global carbon dioxide emissions (Seto et al., 2014). Combined with other drivers of global warming, this growth is expected to further exacerbate the extreme effects of the climate crisis (Pollo & Trane, 2021).

Climate change is driving an increasing frequency of extreme events that surpass the historical range of variability (Ryan, 2013). Notable examples include a projected temperature rise of 1.8 to 4.0°C between the periods 1980–1999 and 2090–2099, exacerbating urban heat islands and intensifying heat waves. Additionally, storms and strong winds accompanied by heavy rainfall are becoming more frequent, heightening the risk of flooding and water body overflows. Finally, prolonged droughts are expected to become more prevalent (Endlicher, 2012; Schmitz, 2014; Starzewska-Sikorska et al., 2022).

Cities are among the most affected areas, becoming increasingly vulnerable and less resilient for their inhabitants (Ryan, 2013). According to Stern (2007) and Garnaut (2008), the longer the response to the climate crisis is delayed, the higher the costs and the more irreversible its effects become. This underscores the urgent need for adaptation and mitigation measures, which are closely tied to the morphology, materiality, and metabolism of urban environments (Ryan, 2013).

Table 02 outlines the key effects of climate change and their impacts on urban areas.

CLIMATE CHANGE	EFFECT ON CITIES
CHANGES IN AVERAGE CLIMATIC CONDITIONS	
Increase in temperature and intensification of the Urban Heat Island effect	Increased energy consumption for air conditioning
	Worsened air quality
Increase or decrease in precipitation	Increased flood risk
	Higher risk of landslides
	Growing rural-to-urban migration
	Risk to food supply in cities
Sea level rise	Flooding in coastal areas
	Reduction in economic revenue and tourism
INCREASE IN EXTREME EVENTS	
Extreme storms and tropical cyclones	Severe floods
	Higher landslide risks
	Economic and livelihood losses for the population
	Damage to homes, infrastructure, and businesses
Drought	Water scarcity
	Increase in food prices
	Losses in hydroelectric energy production
	Growing rural exodus from affected areas
Heat waves / Cold waves	Energy demand spikes for air conditioning, e.g., heating indoor spaces
	Health risks to the population
Abrupt climate changes	Severe impacts from sudden and significant sea level rise
	Severe impacts from sudden and significant temperature increases
EXPOSURE CHANGE	
Population movements	From affected rural areas
Biological changes	Spread of pathogenic diseases

Table 02: Climate change effects on cities. Source: Endlicher (2012), adapted by Wilbanks et al. (2007).

1.3 Mitigation and adaptation

Two main strategies can be applied to address the effects of urbanization on climate: mitigation and adaptation, each playing a crucial role in managing environmental impacts and fostering sustainable development.

Mitigation policies have a preventive nature, addressing the root causes of climate effects (Pollo & Trane, 2021) and are characterized by requiring short- and long-term investments across multiple scales (Goklany, 2007; Klein et al., 2007). According to Perez-Lancellotti and Ziede (2020), mitigation can be subdivided into two categories of actions: the first focuses on reducing greenhouse gas emissions, while the second addresses anthropogenic activities that lead to the deterioration of natural systems. When applied to the urban context, these actions focus on energy resources and demand, building efficiency, urban densification, and the protection and implementation of greenery (Pollo & Trane, 2021).

On the other hand, adaptation strategies aim to develop structures that help reduce the damage caused by climate change, building resilient cities against extreme events, and improving the quality of life for citizens in these areas (Perez-Lancellotti & Ziede, 2020). These actions are characterized by their immediate effects, requiring short-term investments, mostly at the micro-urban scale (Pollo & Trane, 2021).

Although each approach has distinct goals and scales of action, Tunji-Olayeni et al. (2019) argue that combining both offers the most effective strategy for addressing the climate crisis, with the micro-scale being the optimal level to achieve meaningful results in both mitigation and adaptation (Grafakos et al., 2018).

1.3.1 Urban planning and design strategies

Urban planning and design serve as fundamental tools for reducing the effects of excessive urbanization on the environment, as well as for improving the energy efficiency of cities. They contribute not only to enhancing thermal comfort in both outdoor and indoor spaces but also to achieving long-term effects in combating the climate crisis (Schmitz, 2014).

When addressing microclimate dynamics, it is essential to consider the unique characteristics of each location. Therefore, mitigation and adaptation strategies cannot be regarded as universal (Pejović, 2022). Higueras (2006), building on the studies of Olgyay (1976), defines general guidelines for the four existing climatic regions: cold, temperate, hot-dry, and hot-humid, as presented in Table 03.

Although each location has its own specific characteristics, it is still possible to outline some of the most extensively researched strategies and analyze how they shape the urban climate.

Table 03: Bioclimatic Strategies for Climatic Regions. Source: Olgyay (1976), adapted by Higueras (2006)

Climatic Region	Bioclimatic Strategies
Cold	• Maximize heat production
	• Increase radiation absorption, reducing heat loss through conduction and evaporation.
Temperate	• Establish seasonal balance, as both cold and heat play a significant role throughout the year
	• Implement measures that allow both heat production and reduction through radiation and convection
Hot-Dry	• Reduce heat production and facilitate heat loss through radiation
	• Minimize heat gains through conduction and promote evaporation
Hot-Humid	• Reduce heat production
	• Reduce heat buildup through radiation
	• Enhance heat loss through evaporation

Control of solar access and air flux

Solar exposure plays a fundamental role in thermal comfort in outdoor environments, passive heating of buildings and alternative energy sources. Ventilation, like the previous, affects thermal sensation and is also an important tool for improving air quality by aiding in the dispersion of pollutants (Erell et al., 2010). Besides shaping the urban microclimate, these factors are crucial in addressing the climate crisis, as proper ventilation and sun exposure control can help mitigate the effects of heat waves (Endlicher, 2012).

The morphology and layout of the urban fabric are key factors in regulating solar exposure and ventilation within cities (Schmitz, 2014). Specifically, building density influences wind patterns, radiation balance, and air temperature (Givoni, 1998), which are all crucial elements of the urban microclimate. Additionally, the relationships between building heights and street dimensions—expressed through ratios such as height-to-width (H/W), length-to-width (L/W), and the orientation of the urban section—play an important role in shaping these environmental conditions (Shashua-Bar & Hoffman, 2003).

One common urban feature where these variables are particularly relevant is the street canyon, defined by two parallel rows of buildings and the space between them (Syrios & Hunt, 2008). A street canyon is considered uniform when its height-to-width ratio is approximately 1 and the building facades have minimal openings. In contrast, a ratio below 0.5 characterizes a shallow canyon, while a ratio of 2 indicates a deep canyon (Ahmad et al., 2005). The distance between two major intersections defines the canyon's length (L), which, in relation to height (H), allows it to be classified as short (L/H = 3), medium (L/H = 5), or long (L/H = 7) (Ahmad et al., 2005).

According to Erell et al. (2010), to achieve adequate insolation for both buildings and pedestrians, especially during the winter months, attention must be given to solar orientation and the limitation of building density and height, although such characteristics are challenging to control in large urban centers.

As noted by the authors, controlling exposure is also extremely important since pedestrian thermal comfort depends not only on air temperature but also on limiting exposure to radiant load. Strategies to block sunlight may include, in addition to the morphological aspects of buildings, the use of canopies, arcades, and shading devices, as well as the addition of trees and vegetation.

Regarding airflow, pedestrians are affected in two ways. First, it causes a mixing of energy and moisture, eliminating small climatic variations between nearby areas. Second, it facilitates the exchange of energy on human skin, increasing sweat evaporation in hot climates and causing the wind-chill effect in cold climates (Erell et al., 2010). The roughness and porosity of the urban fabric are determining factors in this aspect. Roughness refers to the variations and irregularities in the heights of obstacles and buildings, which are high in urban centers, tending to reduce wind speed in these areas. Porosity, on the other hand, is related to the permeability of airflow due to the distance between buildings and the width of streets (Schmitz, 2014).

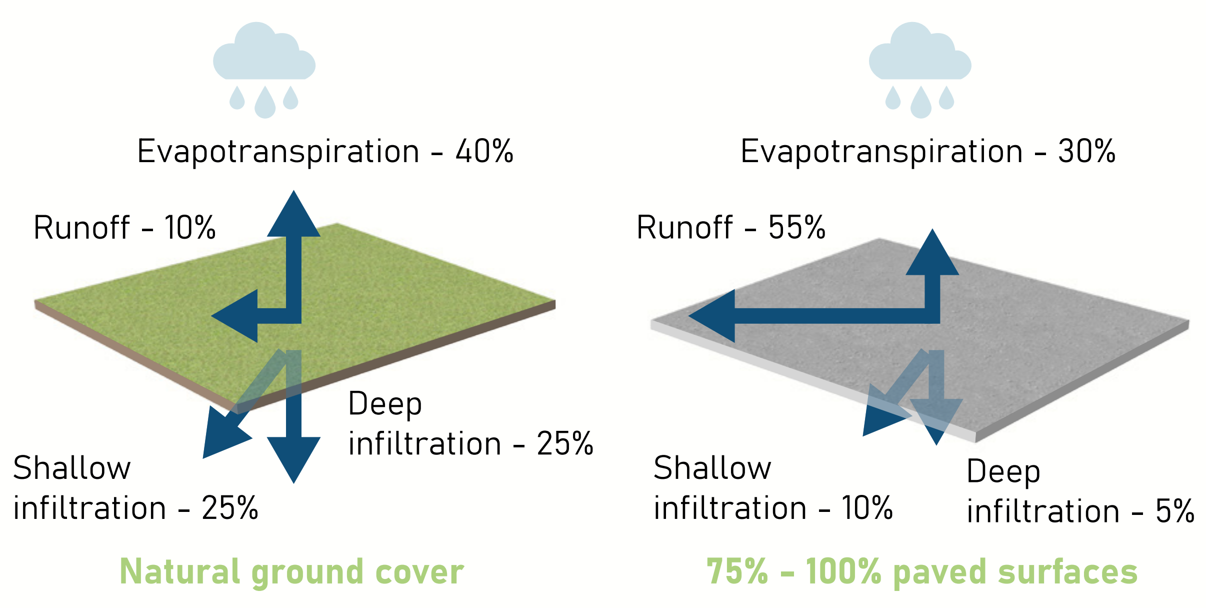
Different combinations of building height and distance can contribute to either the acceleration (creating wind tunnels) or blockage of air circulation (Romero, 1988; Givoni, 1998). Studies show that areas with higher porosity, by allowing some level of airflow, help prevent the formation of wind tunnels (Erell et al., 2010). Moreover, the circulation, speed, and turbulence of winds significantly contribute to improving air quality by influencing the dispersion of pollutants, whether gaseous or particulate. Urban design strategies can support this process by diversifying building heights, incorporating sloped roofs, and creating wider street canyons with shorter, continuous city blocks (Erell et al., 2010).

Building and paving materials

The thermal and hydrological balances of a location are directly influenced by the material properties of its urban surfaces (Erell et al., 2010). According to Nuruzzaman (2015), increasing the reflectivity of urban surfaces and promoting greater evaporation and transpiration are beneficial to mitigate the impacts of surface urban heat islands (SUHIs). Reflectance (albedo) and emissivity are the primary factors governing heat absorption and transmission (Schmitz, 2014). These variables impact surface temperature and, consequently, the surrounding air temperature, exposing pedestrians to long-wave radiant heat and causing discomfort, especially during the daytime (Erell et al., 2010).

The surface's permeability, in turn, affects the urban microclimate by regulating relative humidity and evapotranspiration (Schmitz, 2014). Incorporating materials with higher water absorption capacity, such as vegetated areas, permeable pavements, and green roofs, helps mitigate urban heat islands while also lessening the impact of heavy rainfall, including flooding and inundation (Endlicher, 2012; Gartland, 2010). Figure 06 presents the difference of infiltration and evapotranspiration between natural and paved grounds.

Fig. 06: Hydrogram of change due to an increase of impermeable surfaces.
Source: Starzewska-Sikorska et al. (2022) - adapted by the author



Cool materials are those that exhibit high reflectance to solar radiation,i.e. high albedo, and a high emissivity factor (Santamouris et al., 2011). They can be applied in various ways, including pavements, facades, roofs, vegetation, and other urban structures. The key characteristics of these surfaces are related to substrate composition, material properties, color variation, and porosity (Erell et al., 2010; Gartland, 2010). White materials have high reflectivity and emissivity, while colored materials vary in their reflection of infrared radiation (Santamouris et al., 2012).

According to Santamouris et al. (2012), reflective materials can reduce surface temperatures by several degrees and lower peak urban temperatures by up to 2°C, also contributing to the fight against global warming. In addition, these materials help reduce the thermal load on buildings, resulting in significant energy savings. Despite the benefits, it is important to consider that highly reflective surfaces can also cause undesirable effects, such as visual discomfort due to excessive glare or an increase in the radiant load on pedestrians (Erell et al., 2010).

Applying cool materials on rooftops has a smaller impact on the microclimate compared to altering materials at ground level, as it affects heat transfer beyond the urban canopy layer. However, this measure remains important because it improves building thermal comfort, reduces cooling energy demand, lowers air pollution levels, and mitigates urban heat island effects. Additionally, when implemented extensively, it can create a cumulative effect, influencing the city's climate as a whole (Erell et al., 2010; Gartland, 2010).

The Table 04 presents the value of albedo and emissivity for some of the most common natural and urban materials.

Surface			Albedo	Emissivity
Natural materials	Soils	Dark, wet	0.05 to 0.40	0.98 to 0.90
		Light, dry		
	Grass	Long 1.0 m	0.16 to 0.26	0.90 to 0.95
		Short 0.02 m		
	Agricultural crops, tundra		0.18 to 0.25	0.90 to 0.99
	Orchards		0.15 to 0.20	0.90 to 0.99
	Forest	Deciduous, Bare	0.15 to 0.20	0.97 to 0.98
		Deciduous, Leaved		
		Coniferous	0.05 to 0.15	0.97 to 0.99
	Water	Small zenith angle	0.03 to 0.10	0.92 to 0.97
		Large zenith angle	0.10 to 1.00	0.92 to 0.97
Urban materials	Roads (Asphalt)		0.05 to 0.20	0.95
	Walls	Concrete	0.10 to 0.35	0.71 to 0.90
		Brick	0.20 to 0.40	0.90 to 0.92
		Stone	0.20 to 0.35	0.85 to 0.95
		Wood	0.90	0.90
	Roofs	Tar and gravel	0.08 to 0.18	0.92
		Tile	0.10 to 0.35	0.90
		Slate	0.10	0.90
		Thatch	0.15 to 0.20	0.90
		Corrugated iron	0.10 to 0.16	0.13 to 0.28
	Windows	Clear glass, zenith angle < 40°	0.08	0.87 to 0.94
		Clear glass, zenith angle 40-80°	0.09 to 0.52	0.87 to 0.92
	Paints	White, whitewash	0.50 to 0.90	0.85 to 0.95
		Red, brown, green	0.20 to 0.35	0.85 to 0.95
		Black	0.02 to 0.15	0.90 to 0.98

Table 04: Radiative properties of common natural and urban materials. Source: Oke (1987)

Green and blue infrastructure

The addition of blue and green infrastructure in urban environments was, until recently, seen merely as a tool for creating recreational spaces for the community. However, more recent studies highlight its influence on the microclimate and its role in mitigating the climate crisis by affecting humidity and air quality, water retention, and reducing heat islands, while also bringing benefits to biodiversity, functionality, and the attractiveness of a place (Stangel, M., 2023). The analysis and integration of these structures into urban development projects assist policymakers in creating more climate-resilient cities, enhancing the health and well-being of inhabitants on multiple scales, and enabling projects with citywide effects on urban heat island mitigation (Gunawardena et al., 2017).

The presence of vegetation and water bodies in green spaces contributes to thermal and humidity regulation, reducing extreme climate variations (Grey & Deneke, 1986; Tyrväinen et al., 2005; Dimoudi & Nikolopoulou, 2003). Increased air humidity supports the formation of moisture islands, while the absence of these elements favors the emergence of dry islands, which are common in highly urbanized areas (Alves, 2011). During periods of intense heat, vegetated areas have a more pronounced cooling effect, whereas water bodies can increase nighttime and late-summer temperatures. However, the combination of both provides complementary environmental benefits (Gunawardena et al., 2017).

Lombardo (1985), in studying São Paulo's climate, observed a significant temperature reduction in open areas with greater vegetation cover and near water reservoirs. The author estimated that a vegetation index of 30% would be ideal for maintaining urban thermal balance, while regions with less than 5% tree cover would exhibit characteristics similar to those of a desert.

The implementation of such structures constitutes the so-called Nature-based Solutions (NBS), defined by the European Commission as "solutions inspired and supported by nature that are cost-effective, provide environmental, social and economic benefits and help build urban climate resilience" (Eggermont et al., 2015). This concept is further discussed in the next chapter of this thesis.

These solutions promote resilience by incorporating natural elements into cities, landscapes, and coastal areas through locally adapted and resource-efficient interventions (Starzewska-Sikorska et al., 2022). Additionally, NBS offer an affordable approach to addressing societal challenges, providing benefits for both human well-being and biodiversity by involving actions related to the protection, restoration, and management of natural and semi-natural ecosystems (Mccormick, 2020;

Starzewska-Sikorska et al., 2022).

Urban blue spaces and urban water bodies can be defined as all surface water bodies, both static and dynamic, located in urban areas (Gunawardena et al., 2017). The implementation of these elements impacts microclimatic conditions in cities through evaporation, helping to reduce surface temperature (Robitu et al., 2004), air temperature (Nakayama & Fujita, 2010), and mean radiant temperature (Robitu et al., 2006).

Although small water bodies, in isolation, do not have significant thermal effects on their surroundings and may be considered of lesser relevance in urban climate design (Jacobs et al., 2020), these structures, especially when combined with vegetation and shading, can contribute to cooling the urban environment, affecting air temperature and relative humidity within a 1 to 2-meter radius (Albdour & Baranyai, 2019). Moreover, when distributed on a large scale, these water bodies can cause noticeable thermal changes in neighborhoods, cities, or regions, helping to reduce sensible heat in the atmosphere (Gunawardena et al., 2017; Jacobs et al., 2020). Natural or artificial water elements can also generate the "oasis effect," where the water surface, typically cooler than the surrounding environment, increases humidity and facilitates the circulation of cooler air layers within cities (Kuttler, 1998, apud Starzewska-Sikorska et al., 2022).

Green infrastructure can take many forms, including urban forests, parks, street trees and verges, private gardens, transportation corridor edges, as well as green roofs and vegetated façades (Gunawardena et al., 2017), Figure 07 presents some of these examples, categorizing them into Natural Assets, Enhanced Assets, and Engineered Assets. These urban green spaces provide essential ecosystem services, such as increasing soil porosity to reduce surface runoff, mitigating floods, enabling sustainable drainage, protecting biodiversity, improving air quality and circulation, and regulating local microclimates. As a result, they play a crucial role in addressing climate change and extreme weather events (CCC, 2014; Gill et al., 2007; Starzewska-Sikorska et al., 2022).

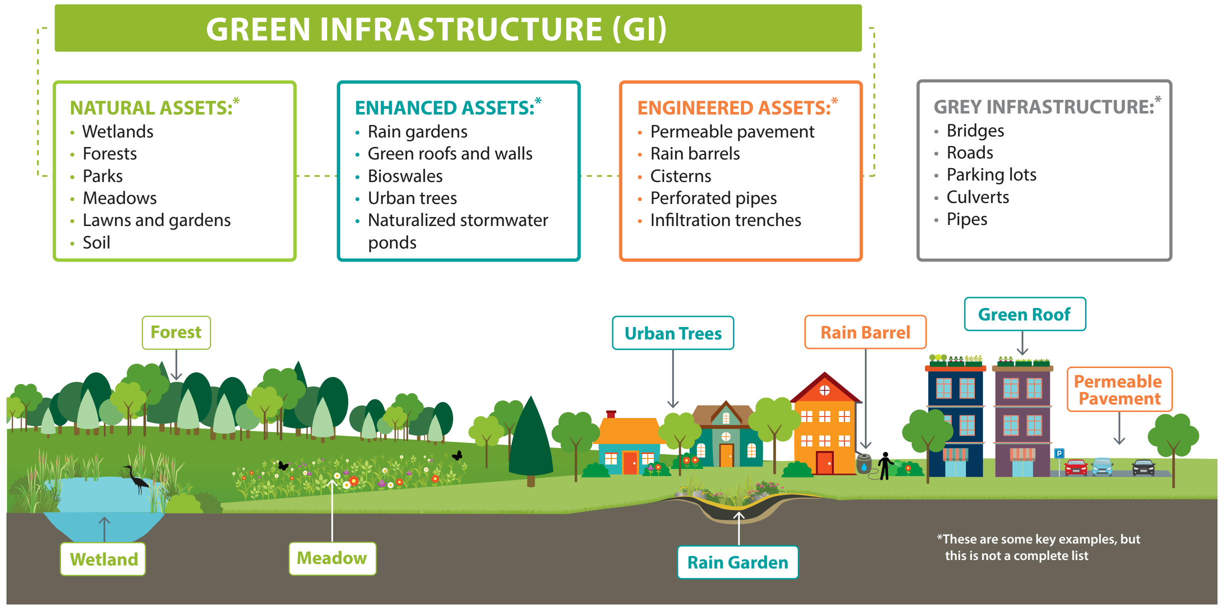


Fig. 07: Examples of Green Infrastructures. Source: Green Infrastructure Ontario Coalition. (n.d.)

Additionally, integrating vegetation into urban areas enhances aesthetic appeal, improves thermal comfort, reduces noise pollution, and creates shaded spaces (Starzewska-Sikorska et al., 2022). It also supports physical and mental well-being by promoting physical activity, alleviating stress, depression, and anxiety, and lowering mortality rates linked to heatwaves and respiratory or circulatory diseases (Plesník and Plesníková, 2018; Starzewska-Sikorska et al., 2022).

The positive influence of green spaces on the microclimate is due to plants' high absorption and radiation rate, as well as their lower heat capacity and thermal conductivity compared to buildings and open spaces. Vegetation also helps reduce air temperature through evapotranspiration, decreases infrared radiation, and lowers wind speed near the surface. Additionally, it contributes to retaining dust and air pollutants, improving air quality (Gianna, 2001).

Expanding vegetation cover is a key strategy for mitigating urban heat islands (Solecki et al., 2005). Evapotranspiration from urban greenery—such as tree-lined streets, parks, and gardens—reduces temperatures of surrounding areas, forming "Urban Cool Islands" (Shashua-Bar et al., 2009) and acting as a natural air conditioner during summer months (Heisler, 1974). This process helps lower temperatures in both the air and vegetation.

Additionally, urban trees provide shade, reducing direct sun exposure, minimizing heat accumulation, and keeping surfaces cooler (Gartland, 2010). Tree planting in cities creates an "oasis effect," mitigating heat on both macro and micro scales by expanding evaporative surfaces and dissipating latent heat, ultimately balancing urban energy dynamics (Yu & Hien, 2006).

Amid the climate crisis, vegetation plays a crucial role by temporarily retaining CO2 and reducing energy consumption in buildings through the use of shade trees, green walls, and vegetated roofs (Gill et al., 2007). Furthermore, the implementation of green infrastructure can increase the distance between pollution sources and people, acting as a semi-permeable barrier to airflow and thereby reducing population exposure to pollutants (Starzewska-Sikorska et al., 2022).

Although vegetation positively influences the urban microclimate, its impact depends on plant type, weather conditions, and time of day, making it a complex and variable phenomenon (Erell et al., 2010). Urban trees can also have some negative effects, such as blocking wind and reducing its speed by approximately 30–40% in the case of deciduous species (Ali-Toudert & Mayer, 2007; Spangenberg et al., 2008). Additionally, large-canopy trees may hinder nighttime cooling by partially blocking longwave radiation (Spangenberg et al., 2008).While this effect can be unfavorable in hot climates, it is beneficial in colder regions, as it reduces thermal discomfort caused by wind (Schmitz, 2014).

Moreover, not all vegetation is effective in air purification. The ability of plants to reduce air pollution depends on three main factors: vegetation density, species height, and the natural properties of their leaves (Starzewska-Sikorska et al., 2022). Figure 08 compares the effectiveness of various structures in pollutant absorption.

Regarding distribution and quantity, Streiling and Matzarakis (2003) demonstrated that both a single tree and a small group of trees can positively impact the urban climate. However, their effect is more significant when planted in clusters, a strategy the authors recommend to maximize thermal benefits. Studies indicate that even small green spaces (60 × 40 m) can lower local temperatures by up to 3°C, significantly improving urban thermal conditions (Saito et al., 1990). While a single tree influences only the immediate microclimate, large urban parks can extend their positive effects to the surrounding built environment (Yu & Hien, 2006).

The connectivity between green areas also affects their climatic impact. Interconnected small green spaces can create a more efficient cooling effect than large, isolated parks by enhancing thermal exchange and increasing the overall green volume in the city (Starzewska-Sikorska et al., 2022). Thus, the higher the green area index, the greater the thermal exchange between these areas and the lower the air temperature in urban spaces (Mathey et al., 2011; Oliveira, 1988).

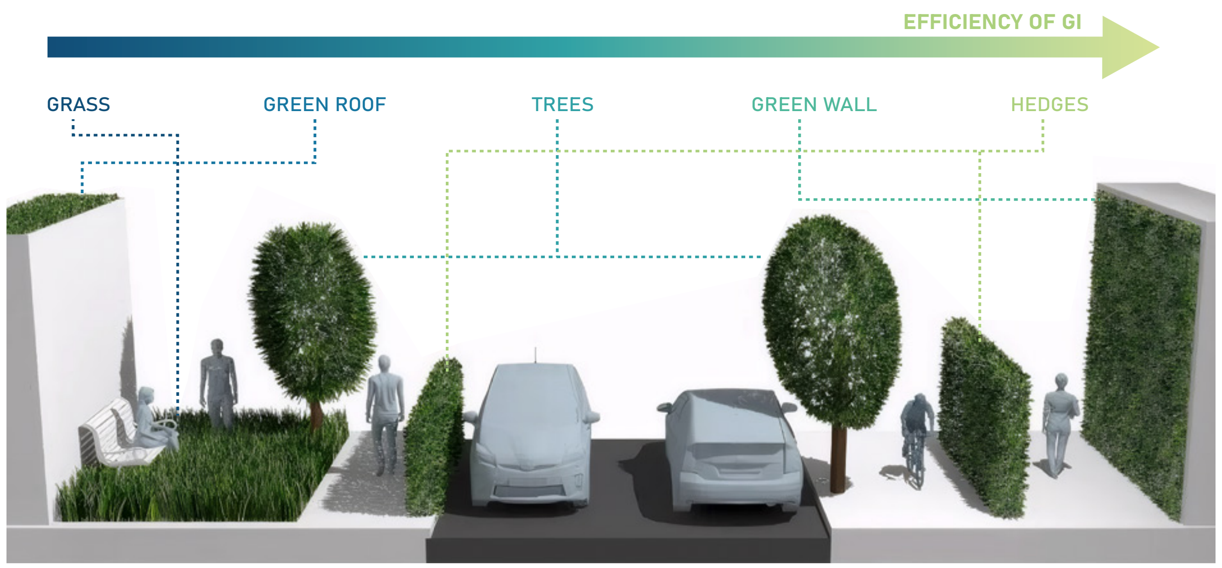


Fig. 08: Efficiency of Green Infrastructures in absorption of pollutants.
Source: Starzewska-Sikorska et al.(2022)

1.3.2 Strategies for the temperate oceanic climate (Cfb)

As will be further discussed in Chapter 3, Curitiba serves as the primary case study for this research. According to the Köppen climate classification, the city has a Cfb climate — temperate, without a dry season, and with a warm summer (Mendonça & Dubreuil, 2005). This categorization provides a foundation for designing more effective climate mitigation and adaptation strategies tailored to the city's specific environmental conditions. According to Olgyay (1963), in temperate climates, bioclimatic strategies should prioritize thermal balance throughout the seasons, as both cold and heat occur significantly over the course of the year. The author also emphasizes the importance of adopting measures that enable both the generation and dissipation of heat through radiation and convection.

In Curitiba, areas of discomfort due to cold are noticeable. However, the adverse effects of Urban Heat Islands during the summer—such as increased thermal stress indoors and diminished outdoor thermal comfort—significantly surpass any potential advantages of these events in the winter (Schmitz, 2014; Kruger, 2015).

Schmitz (2014), in studying thermal comfort of the city, concluded that short- and medium-term interventions in consolidated areas—such as intensive use of vegetation and materials with better thermodynamic properties—can significantly improve the urban microclimate. These measures, which do not require legislative changes, hold concrete potential to mitigate the effects of global warming and contribute to climate adaptation in the coming decades.

In a comprehensive literature review examining the impact of blue and green infrastructure on mitigating urban heat islands, Kumar et al. (2024) concluded that, in general, the most effective cooling and evapotranspiration measures in temperate climates are the implementation of wetlands at the meso-scale and parks at the micro-scale. Moreover, taking as an example the projected climate changes for the temperate European climate, where most studies on Cfb climate zones are conducted, the authors reaffirm the importance of implementing adaptive strategies such as green roofs and walls, parks, pocket parks, grass areas, lakes, and wetlands. These solutions not only expand urban green spaces but also significantly contribute to thermal regulation and efficient water management.

Green roofs and walls help mitigate the urban heat island effect and cool cities, while lakes and wetlands enhance biodiversity conservation and water resource management. Many of these measures have the potential to be widely adopted in cities, but government support and constructive incentives are needed, as the implementation costs may largely be under the responsibility of the property owners (Kumar et al., 2024).

Schmitz (2014) also highlights the benefits of incorporating vegetation on rooftops, alongside the use of materials with lower albedo, higher heat capacity, and enhanced thermal conductivity. Thermal comfort analysis simulations conducted by the author in the Batel neighborhood, located in the Southern Structural Sector of Curitiba, revealed improved values of mean radiant temperature (Trm) and Universal Thermal Climate Index (UTCI) following modifications to floors and roofs. Additionally, the Schmitz emphasizes that increasing soil permeability not only boosts relative humidity (RH) but also enhances rainwater drainage.

In relation to the addition of vegetation, studies by Schmitz and Mendonça (2011), based on monitoring points along Curitiba's main traffic corridors, emphasize that streets and lots with tree cover exhibit a reduced thermal amplitude in both summer and winter. This reduction is attributed to the shading provided by the trees and the increase in relative humidity, both of which help stabilize ambient temperature variations (Weingartner, 1994; Mascaró & Mascaró, 2009).

The thermal comfort indices analyzed by Martini (2013) revealed that tree-lined streets stayed within the "thermal comfort" range for 69.8% of the time, while streets lacking trees were only in comfort for 52.1% of the time, being classified as experiencing "moderate heat stress." These findings emphasize the importance of urban tree cover as a valuable tool for climate mitigation and enhancing well-being in cities. Additionally, differences in wind were observed, with significantly higher levels in streets with tree cover, particularly those with a tunnel-shaped arrangement, compared to streets without trees. This is attributed to wind channeling, which occurs when vegetation forms narrow, well-defined corridors (Mascaró & Mascaró, 2010).

Martini (2013) further emphasizes the crucial role of the planting configuration role in the climatic effectiveness of tree cover. In landscape arrangements with intertwined canopies (Figure 09), where trees are planted on both sides of the street to form a tunnel, there was a more significant reduction in solar radiation and improved thermal conditions throughout the year. In contrast, the isolated planting of separate canopies (Figure 10) allowed more solar radiation to penetrate, diminishing the positive impact on the microclimate. An intermediate arrangement (Figure 11), with intertwined canopies on one side of the street and isolated canopies on the other, yielded moderate results.

The choice of species also influences thermal outcomes. Trees with broad canopies and dense foliage, such as Tipuanas and Angicos, commonly found in Curitiba, absorb more radiation and provide better shading. In contrast, species with smaller and less dense canopies, like the native Ipê, have a limited effect (Martini, 2013). Additionally, deciduous species are beneficial in regions with distinct seasons, as they offer shade in the summer and allow sunlight to penetrate in the winter when they shed their leaves (Ochoa de la Torre, 1999). However, evergreen species, which retain their foliage year-round, can have undesirable effects, such as excessive shading in the winter and blocking cooling winds in the summer (Mascaró & Mascaró, 2010).

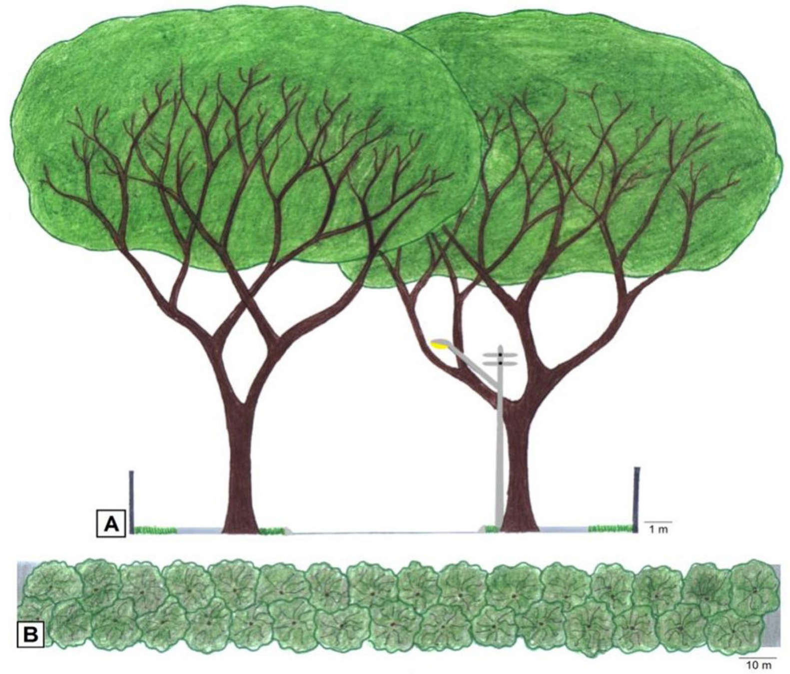


Fig. 09: Landscape arrangement 1: a – street profile b – top view. Source: Martini (2013)

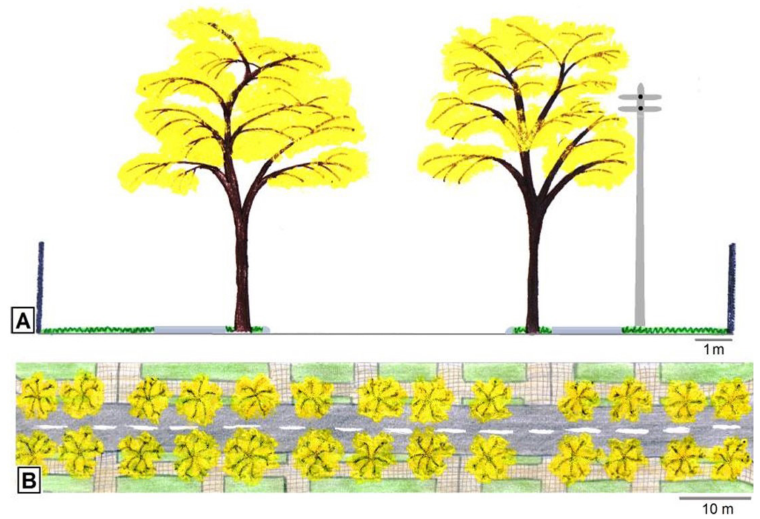


Fig. 10: Landscape arrangement 2: a – street profile b – top view. Source: Martini (2013)

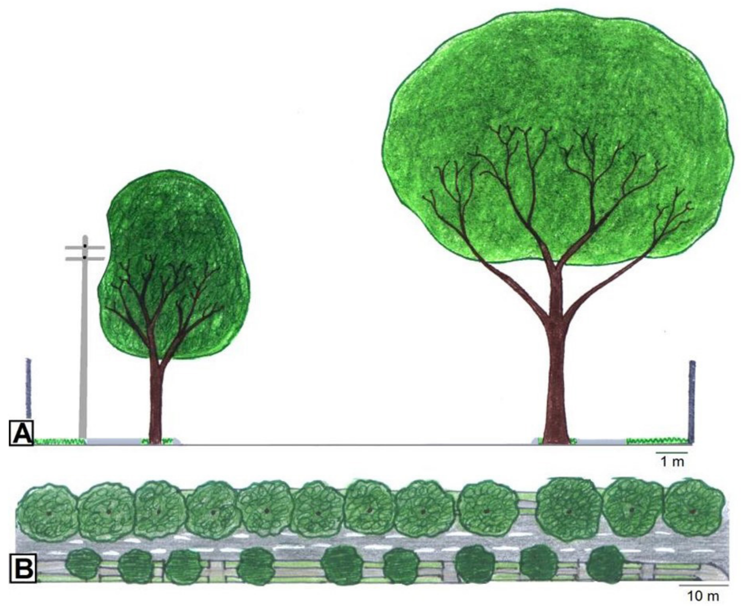


Fig. 11: Landscape arrangement 3: a – street profile b – top view. Source: Martini (2013)

1.4 Nature-based solutions

1.4.1 Definitions of the concept

Nature-based solutions (NBS) are strategies that utilize natural elements and processes to provide urban infrastructure and services in an integrated manner, contributing to cities' resilience in the face of climate and socio-environmental challenges (World Bank, 2021).

According to Sowińska-Świerkosz and García (2022), four essential characteristics define the Nature-Based Solutions (NBS) approach. The first is "actions inspired and powered by nature," which emphasizes the role of green and blue infrastructure as remedies and as a means of complementing or enhancing conventional solutions. The second is "actions tackling challenges," as NBS aim to address urgent and global issues such as climate change, biodiversity loss, water and food security, human health, and socio-economic development.

The third characteristic, "actions providing multiple benefits," refers to the positive impacts of NBS across three dimensions: social (promoting physical and mental well-being, reducing heat-related mortality, and strengthening social cohesion), environmental (enhancing biodiversity, creating habitats, reducing flood risks, and improving water resilience), and economic (generating green jobs and reducing water and energy costs).

Finally, the authors highlight "actions with a certain level of effectiveness and efficiency," in which actions must be locally adapted, technically feasible, and sustainable. The effectiveness of NBS, in this regard, depends on participatory governance, local adaptation, economic efficiency, and the delivery of tangible environmental, social, and financial benefits.

Interventions can range from structural to non-structural actions and emerge as a valid alternative to address issues caused by unplanned urbanization, such as erosion, extreme heat, landslides, and flooding (Ozment et al., 2019; Sudmeier-Rieux et al., 2021). By proposing a variety of strategies across multiple sectors that incorporate natural elements and processes, Nature-Based Solutions (NBS) not only help reduce disaster risk and enhance the climate resilience of the targeted area but also contribute to promoting biodiversity, recreation, human health, and sustainable urban development (World Bank, 2021).

NBS are mostly applied across spatial settings inside or around cities and can be described through the 14 following typologies as presented in Figure 12 (World Bank, 2021):

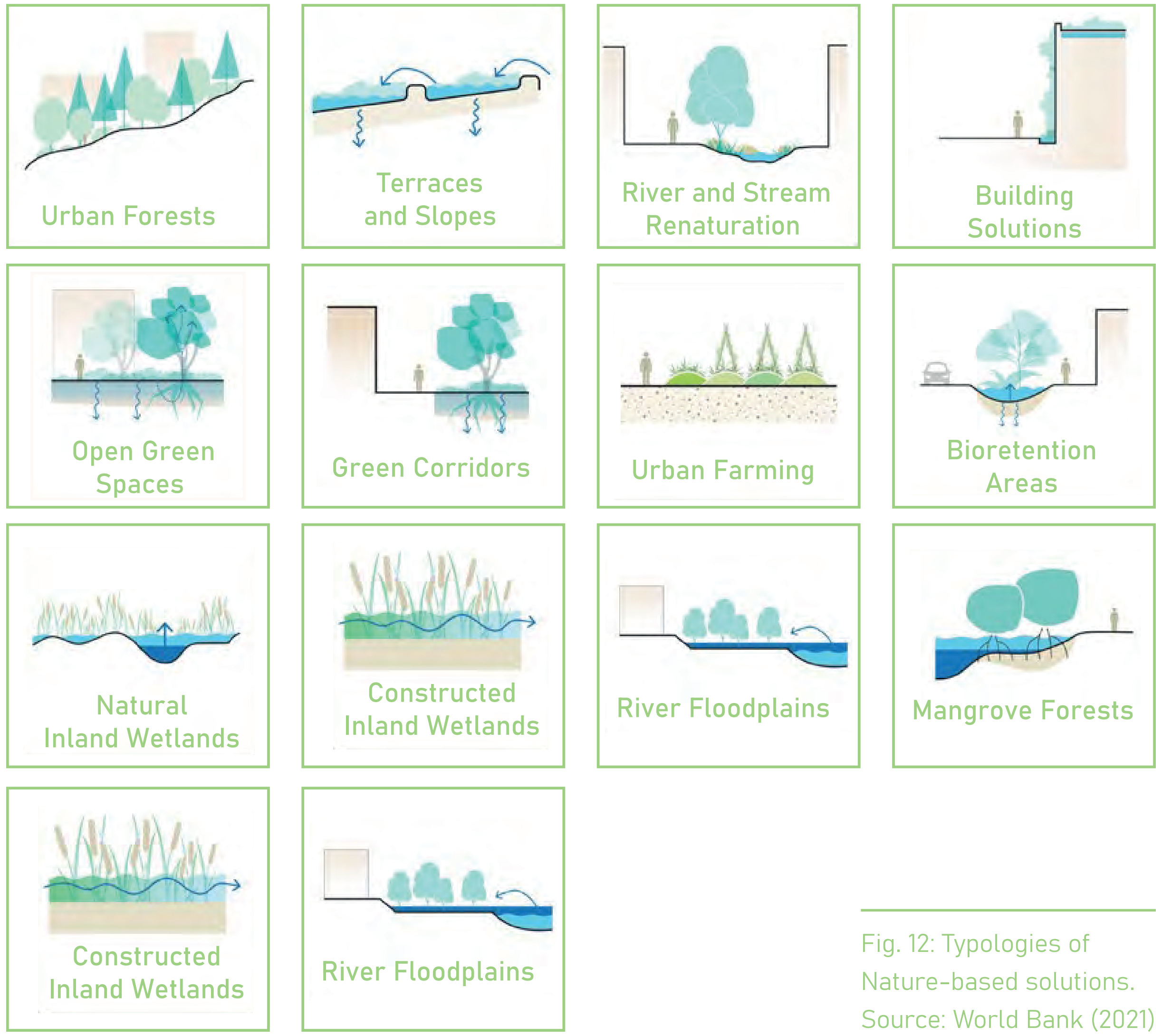


Fig. 12: Typologies of Nature-based solutions. Source: World Bank (2021)

1.4.2 Principles of applicability

According to the World Bank (2021), the implementation of a Nature-Based Solution (NBS) depends on five key principles that are critical in determining its applicability:

1. Assess the functions, benefits, costs, and suitability considerations of NBS

This principle assesses the socio-economic aspects of proposed Nature-Based Solutions (NBS) and helps identify areas that are technically and economically suitable for their implementation. 'Functions' in this context refer to the NBS's capacity to deliver benefits to both the environment and the broader population. The suitability of the NBS is then evaluated by considering these factors in conjunction with local climate conditions, terrain characteristics, available space, and maintenance requirements.

2. Apply an integrated systems approach to NBS for resilience in urban landscapes

NBS are generally more effective when integrated with policies, plans, and projects, allowing for a holistic approach. Combining NBS with existing infrastructure can enhance system capacity and help achieve desired outcomes (Figure 13). As a result, NBS are often implemented as components of broader interventions, such as risk management plans, sustainable maintenance strategies, and land-use planning. Furthermore, due to their multi-functional nature, many NBS can perform a range of functions and deliver diverse benefits across multiple sectors.

3. Consider the principles of ecosystem conservation by adopting a hierarchy of ecosystem-based approaches

NBS approaches should follow a hierarchy, prioritizing the protection of existing ecosystems, followed by restoration, and finally, the creation of new NBS. Although distinct, these three strategies are complementary and should be jointly assessed in the development of a comprehensive strategy. Adopting this hierarchy reinforces the importance of strategic planning and the formal integration of urban ecosystems (such as wetlands, urban forests, and mangroves) into zoning policies to prevent further degradation.

4. Consider the integration of NBS across a range of spatial scales

NBS operate at three scales: river basin, city, and neighborhood. At the basin scale, they are applied near the source of problems to prevent impacts on urban areas. When implemented at the city scale, they complement land use planning and help manage risks, considering local environmental and social characteristics. At the neighborhood scale, NBS focus on smaller interventions

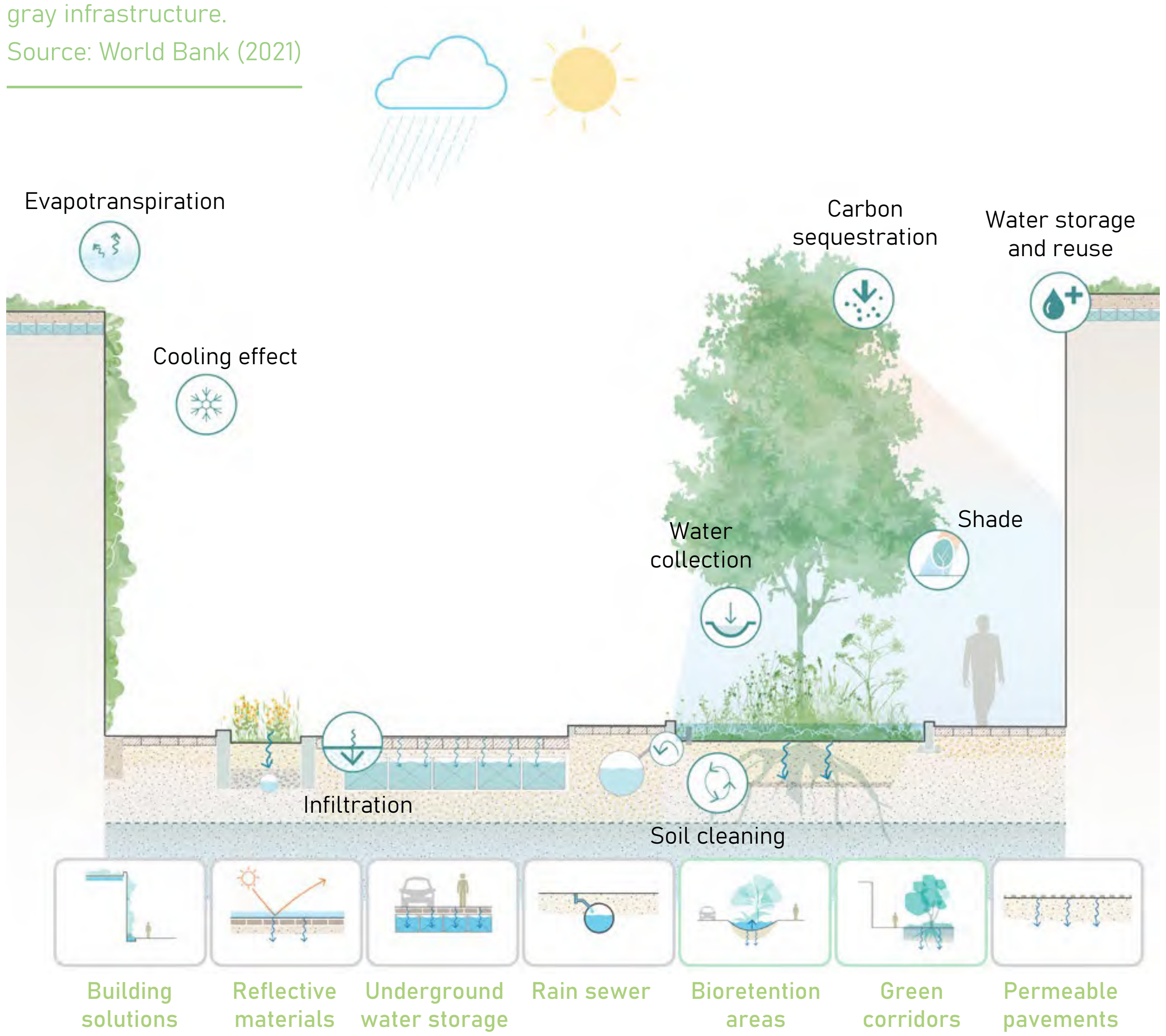
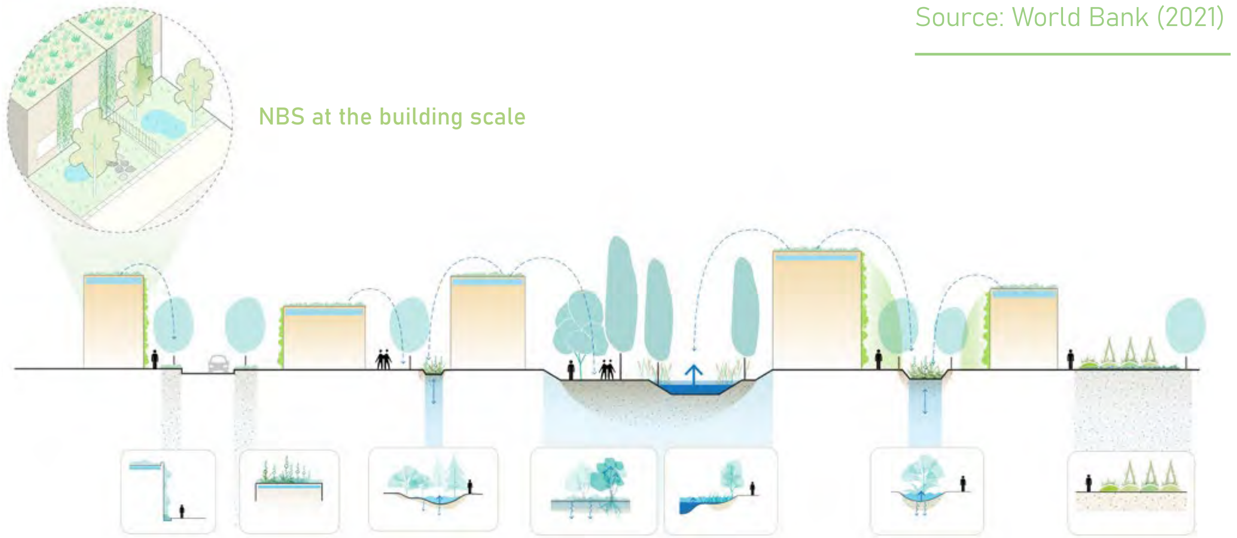


Fig. 13: Example of a hybrid solution integrating green and gray infrastructure. Source: World Bank (2021)

that increase water retention, reduce heat, and improve environmental quality, thereby strengthening local resilience, Figure 14 illustrates these strategies. Cooperation between public and private sectors is essential for the success of these actions.

Fig. 14: Schematic section of NBS at the neighborhood scale. Source: World Bank (2021)



5. Adopt a multistakeholder and interdisciplinary approach

Finally, this last principle is based on the requirement for a collaborative, interdisciplinary, and cross-sectoral approach that involves multiple actors—such as governments, civil society, the private sector, and universities—throughout all phases of the project (Frantzeskaki, 2019). The success of Nature-Based Solutions (NBS) depends on the development of long-term strategies that combine urban resilience and sustainable development, integrating areas such as risk management, urban planning, and climate adaptation (Jha et al., 2012). In urban environments with limited space, this approach favors more efficient and sustainable solutions (Nillesen, 2018). Due to their integrative nature, NBS have the potential to overcome traditional fragmented planning and promote a more systemic and coordinated urban management (World Bank, 2021).

1.4.3 Detailed description of strategies

Based on the catalog of Nature-Based Solutions with detailed descriptions developed by the World Bank (2021), this section summarizes four categories of strategies with potential application in urban streetscapes at neighborhood scales—the focus of this study, as further elaborated in Chapter 3 of this thesis. These categories are: Building Solutions, Open Green Spaces, Green Corridors, and Bioretention Areas.

Building Solutions

This category of intervention involves the integration of vegetation into building rooftops and facades, both in existing structures and new developments (World Bank, 2021). Solutions range from simple systems using climbing plants rooted directly in the ground to more advanced configurations with lightweight substrates and automated irrigation systems. These solutions are highly adaptable and suitable for a wide range of urban contexts. They can be implemented at different scales, across varying population densities and climatic zones, provided that the structural conditions are adequate and water resources are available to support ongoing maintenance.

These solutions provide a range of environmental benefits, including thermal regulation and stormwater management (Eisenberg & Polcher, 2020). The presence of vegetation helps purify the air, supports increased biodiversity in urban areas, and contributes to mitigating floods and reducing the urban heat island effect (Eisenberg & Polcher, 2020).

From a social perspective, green roofs and facades enhance quality of life, strengthen community bonds, and enable educational and productive uses (Gehrels et al., 2016). Additionally, they offer aesthetic improvements to the built environment, increase property value, and reduce energy costs associated with artificial cooling (World Bank, 2021; Hop & Hiemstra 2012).

According to Eisenberg and Polcher (2020), examples of application include different typologies adapted to specific contexts and objectives:

▪ Extensive green roofs (Figure 15a) use a thin layer of substrate and drought-resistant plant species; they are low maintenance and generally not accessible to the public.

▪ Intensive green roofs (Figure 15b) have deeper substrates, allowing for the cultivation of a greater diversity of plants and the use of the space for activities such as leisure, urban agriculture, and social gatherings.

▪ Ground-based green façades (Figure 15c) use climbing plants grown directly in beds at ground level and require basic care.

▪ Facade-bounded green façades (Figure 15d) employ automated irrigation systems and lightweight substrates, making them suitable for buildings with structural constraints.

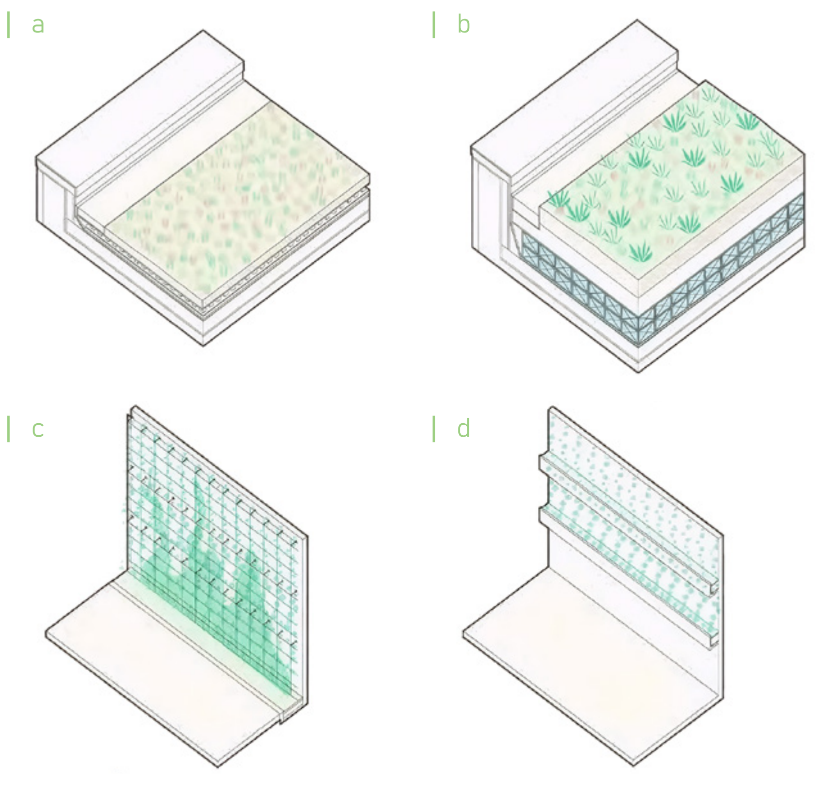


Fig. 15: (a) Extensive green roofs, (b) Intensive green roofs, (c) Ground-based green façades, (d) Facade-bounded green façades.
Source: World Bank (2021)

According to the World Bank (2021), implementation costs vary by solution type: extensive green roofs cost between US$60 and US$270/m², intensive systems exceed US$180/m²; ground-based green façades range from US$35 to US$55/m², and more complex façades cost between US$480 and US$1,450/m². Regarding maintenance, intensive systems require continuous monitoring, including pruning, irrigation, and management, with annual costs of US$4.20 to US$18/m², while extensive systems demand minimal intervention and biannual inspections. Technical feasibility depends on structural capacity, substrate type, solar orientation, and maintenance access. In arid regions, constant irrigation may limit economic and operational viability.

Open Green Spaces

Green spaces encompass vegetated areas of various scales, ranging from residential gardens to large urban parks. Their management can follow three main strategies: preservation, revitalization of existing areas, and the creation of new green spaces.

From an environmental perspective, open green spaces play a vital role in flood regulation by absorbing rainwater and in mitigating urban heat islands through shading and evapotranspiration (Gehrels et al., 2016). They also contribute to reducing air pollution, promoting biodiversity, and supporting carbon sequestration (Eisenberg & Polcher, 2020).

As for social aspects, these structures provide thermal comfort, reduce heat-related illnesses, and enhance both physical and mental health (Kaplan & Kaplan, 1982). Additionally, they strengthen community ties, encourage tourism and recreation, and generate positive economic impacts, such as increased property values and higher tax revenues (Halprin 1981; Wendel et al. 2012; Dunnett et al. 2002).

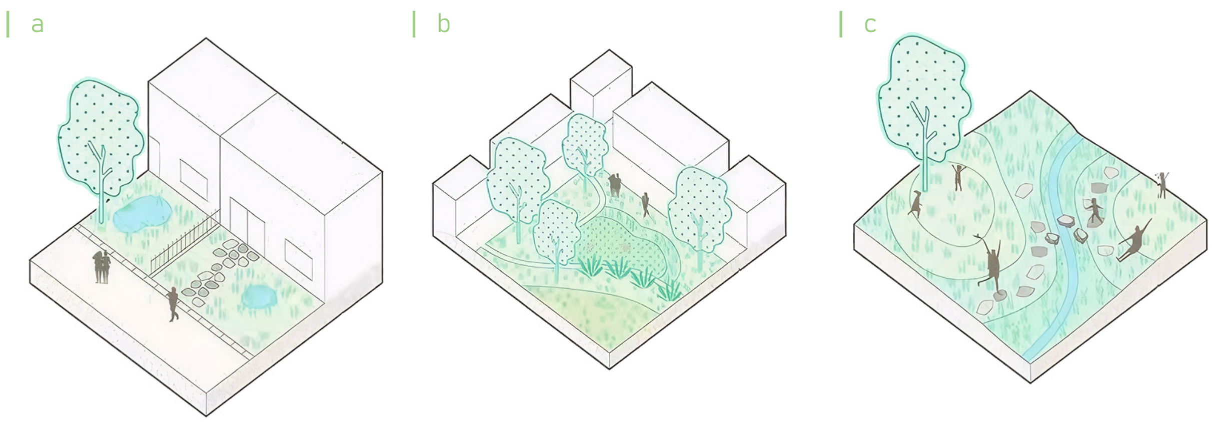
Notable examples of specific strategies include (World Bank, 2021):

▪ Climate-proof residential gardens (Figure 16a), which, when integrated into larger green infrastructure networks, have a significant cumulative impact on reducing stormwater runoff. Each garden helps manage water from rooftops and buildings, enabling its capture and reuse.

▪ Pocket Parks (Figure 16b), characterized by small public spaces embedded in dense urban areas, primarily designed to serve the immediate local community. They often include recreational amenities such as playgrounds, outdoor fitness stations, urban gardens, dog areas, and other small-scale leisure activities.

▪ Natural Playgrounds (Figure 16c), which incorporate natural materials such as trees, plants, rocks, and water to create environments that stimulate children's sensory and creative development, while also contributing to stormwater management.

Fig. 16: (a) Climate-proof residential gardens, (b) Pocket Parks, (c) Natural Playgrounds.
Source: World Bank (2021)



According to the World Bank (2021), the implementation costs of urban parks vary by type, ranging from under US$68/m² (very low cost) to over US$270/m² (high cost). Annual maintenance costs range between US$0.40 and US$2/m², depending on the design, usage, vegetation, and climate. Effective management requires ongoing maintenance, public funding, potential community partnerships, and planning for safety and vandalism prevention to foster a sense of collective ownership. Proper selection of soil and plant species is essential for optimal performance, with preference given to resilient native species.

Green Corridors

Green corridors are linear natural structures essential to urban ecology. Composed of vegetation such as trees and shrubs, these corridors connect different green areas within cities, regardless of their scale. By forming a continuous network of green infrastructure, they not only complement existing parks and public spaces but also contribute to habitat preservation. This type of solution becomes even more crucial in cities where green spaces are highly fragmented, as the lack of vegetated connections significantly limits the landscape's ability to cope with extreme events by reducing rainwater infiltration and retention.

Green corridors offer a range of well-documented benefits. They help manage flooding by absorbing rainwater and promoting its infiltration into the soil (Gehrels et al., 2016). They also help reduce urban heat — shaded areas can be 1°C to 5°C cooler than open spaces, and up to 17°C cooler than parking lots (Architecture 2030, 2020). Even a small increase in tree cover can lead to noticeable drops in air temperature (Architecture 2030, 2020). Additionally, green corridors play an important role in carbon capture (Tang et al., 2016), and support biodiversity (Vollaard et al., 2018). For human health, they enhance thermal comfort, reduce UV exposure, and contribute to better air quality (Gehrels et al., 2016).

According to the World Bank (2021), implementation strategies vary depending on the scale and urban context and include:

▪ Urban green corridors (Figure 17a) are characterized by plant trees with large canopies —more effective if deciduous — along streets, railways, and infrastructure corridors, designed for multiple uses such as bike paths, walking, and water management.

▪ Street tree canopies (Figure 17b) are large tree canopies that enhance the city's image and provide economic and environmental benefits.

▪ Green avenues (Figure 17c) enhance cities economically and environmentally by reducing heat, managing floods, and supporting biodiversity.

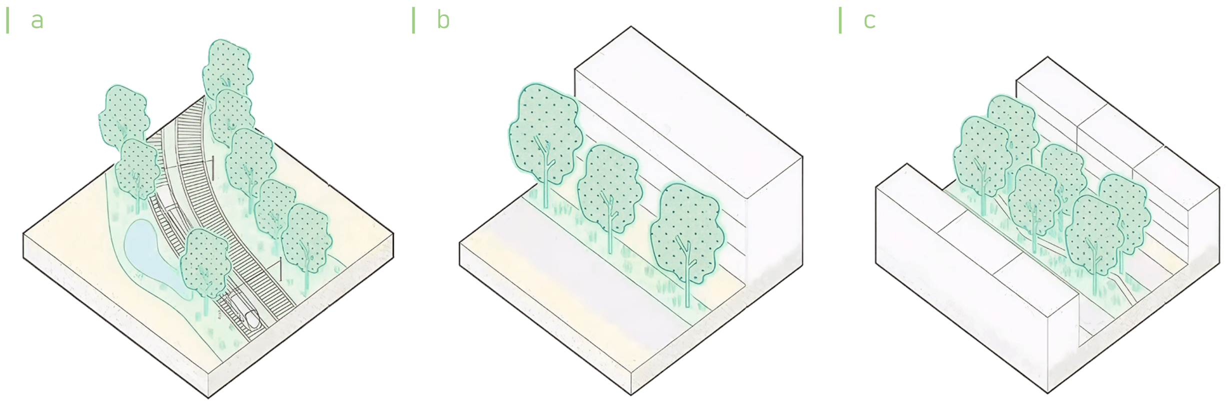


Fig. 17: (a) Urban green corridors, (b) Street tree canopies, (c) Green avenues. Source: World Bank (2021)

The costs of planting street trees range from US$6,680 to US$11,666 over a 50-year period, depending on the installation method, irrigation, anchoring, aeration, and tree protection (GBU, 2019). Maintenance—which includes inspections, leaf cleanup, and pruning—costs between US$547 and US$2,252 per tree during the same time frame (GBU, 2019). Care requirements vary by environment: young trees need regular irrigation until their root systems are well established (World Bank, 2021). In high-traffic areas, pruning should maintain a clear height of 2.5 to 3 meters (World Bank, 2021). For healthy growth, roots require at least 12 m³ of space with a minimum depth of 1.5 meters (Eisenberg & Polche, 2020), and the distance between the tree pit and the curb or building should be at least 1.8 meters (DDOE, 2012).

Bioretention Areas

Bioretention systems serve as complementary solutions to traditional urban drainage and sewage infrastructure. These features are composed of shallow, vegetated depressions designed to capture, infiltrate, redirect, and treat stormwater, effectively regulating both its volume and flow rate. Their performance is influenced by factors such as soil composition, terrain depth, and the types of vegetation used. Highly adaptable, bioretention systems can be tailored to a variety of urban environments, assuming different forms to suit specific site conditions. They are particularly beneficial in older urban areas with combined sewer systems or limited permeable surfaces, where the risk of polluted runoff is significantly higher.

These structures represent a multi-functional solution with positive impacts on both the environment and urban life. They play a key role in water management, significantly reducing the volume and intensity of stormwater runoff (Ruangpan et al., 2020), while also contributing to rainwater purification by removing contaminants and supporting soil stability (Kennen & Kirkwood, 2015; World Bank, 2021). Additionally, they help lower urban temperatures through plant evapotranspiration and contribute to carbon sequestration (World Bank, 2021; European Commission, 2020).

From a social and economic perspective, bioretention areas help increase urban property values, and generate green jobs, also benefiting local wildlife and providing spaces for social interaction, recreation, and environmental education (Kim & Song, 2019).

Specific strategies consist of:

- Bioswales and Rain Gardens (Figure 18a) are characterized by shallow, densely planted depressions with a variety of trees, shrubs, and grasses designed to capture and infiltrate stormwater (World Bank, 2021).

- Detention Ponds (Figure 18b) are deeper structures with lower biological diversity, intended to temporarily hold stormwater runoff for flood control (World Bank, 2021; Eisenberg & Polche, 2020).

- Retention Ponds (Figure 18c) are permanent water bodies with vegetated edges that provide water storage for potential reuse (World Bank, 2021).

- Permeable pavements (Figure 18d) are surfaces made up of porous layers that allow water infiltration, thereby reducing surface runoff. However, they are not recommended for high-traffic roads or areas prone to contaminant spills (LIDC, 2007; World Bank, 2021; WRI & WBG, 2019).

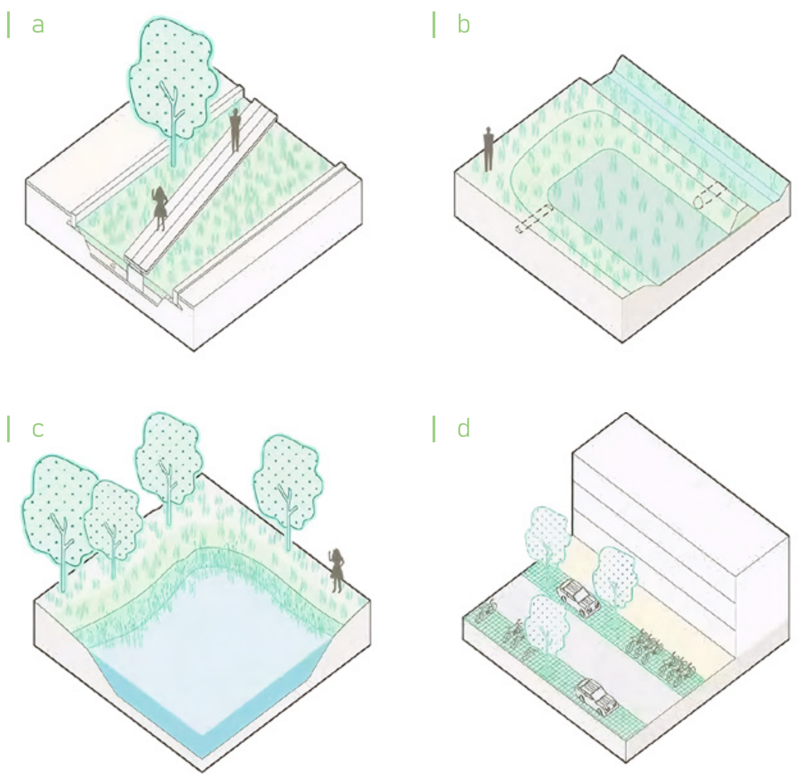


Fig. 18: (a) Bioswales and Rain Gardens, (b) Detention Ponds, (c) Retention Ponds, (d) Permeable pavements. Source: World Bank (2021)

Investments for constructing stormwater management systems vary significantly, starting at around US$ 60/m² for detention ponds and reaching approximately US$ 534/m² for bioretention basins. Between these extremes are infiltration trenches, bioswales, and public rain gardens, whose costs reflect their varying levels of complexity and functionality (World Bank, 2021; Ruangpan et al., 2020).

Regarding maintenance, annual expenses range from 0.5% to 10% of the initial investment (FCERM & EA, 2021). Detention ponds have the lowest maintenance costs, while infiltration trenches typically require higher spending (World Bank, 2021). To ensure the efficiency of bioretention systems, regular maintenance is essential, including monthly inspections for debris removal, invasive plant control, pruning, and repairs to damaged areas, preventing sediment clogging (World Bank, 2021).

1.5 Urban acupuncture

As previously seen, in face of the climate crises, cities will increasingly become more susceptible to extreme weather events and it is essential to consider the urgent demand for intervention. Unfortunately, many of the urban management projects require not only a long execution period, but also major budget investment (Balicka et al., 2021).

On the other hand, the overall implementation of small-scale projects fail to notice their capability of affecting wider regions such as the neighborhood and city scale. (Moussavi et al. 2024). As a result, urban acupuncture emerges as an approach aiming to combine the benefits of the local and punctual projects with the need for a broader intervention in the city.

1.5.1 Fundamentals of Urban Acupuncture

Urban acupuncture (UA) can be defined as a social-environmental theory that focuses on small-scale, strategic interventions designed to generate a catalytic effect on the urban fabric, fostering positive transformations within cities (Balicka et al., 2021).

The analogy refers to the Chinese medicine, considering the urban environment as a living body in which, by identifying its points of vulnerability (or stress), urban interventions are able to act as a treatment (Lerner, 2014; Casagrande, 2020). In addition to these defining characteristics, urban acupuncture incorporates a set of fundamental principles that shape its methodology and application, as presented in Figure 19.

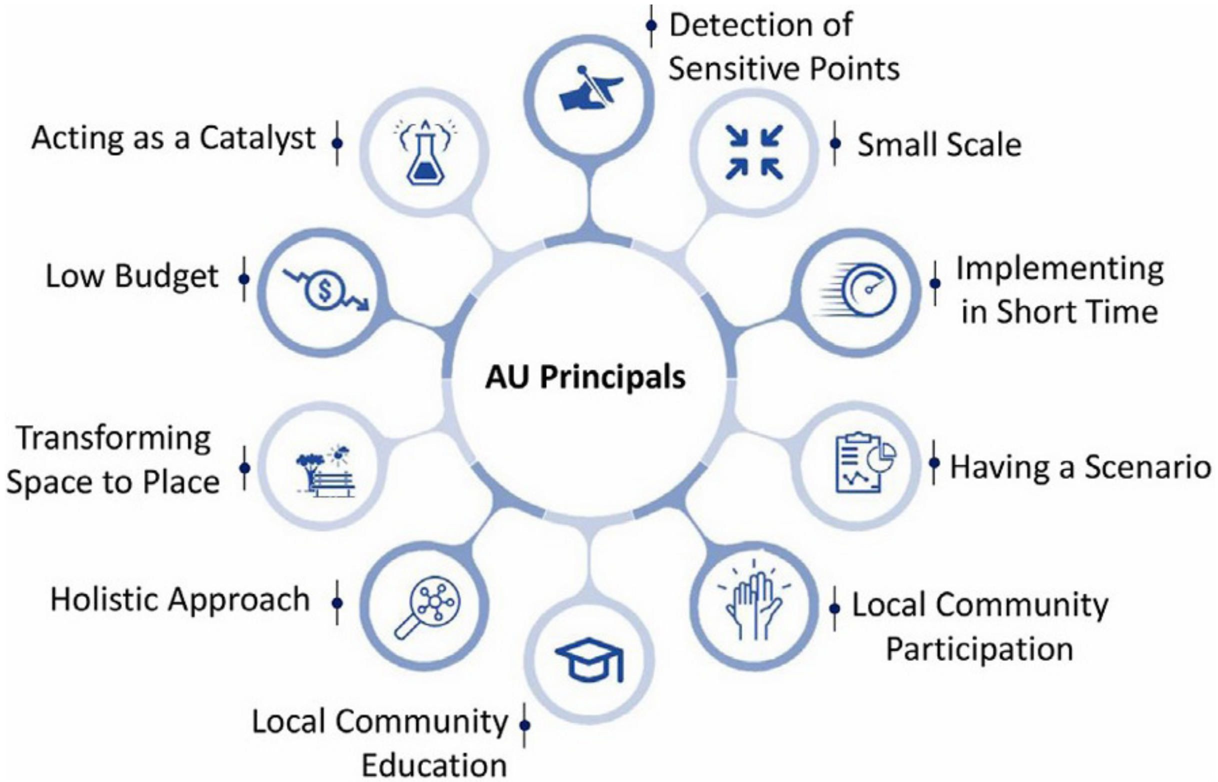


Fig. 19: Principles of UA. Source: Moussavi et al. (2024)

The time of execution is one of these factors, according to Jaime Lerner (2014), one of the most important advocates of the theory, a rapid action makes it possible to avoid the complexity of an extensive bureaucracy and political obstacles. The transformation of the Rua XV de Novembro, located in the city center of Curitiba, into a pedestrian street (Figure 20 and 21) is a good example of his application as mayor of the city, being completed in 72 hours (Lerner, 2014).

Furthermore, low-budget proposals are another important aspect of the urban acupuncture. Affordable solutions facilitate the implementation of these rapid interventions and create a space for testing and experimentation, allowing for a certain degree of flexibility for the designs (Balicka et al., 2021).

Community participation also plays a key role in the effectiveness of the approach. Promoting public involvement in the design process enables a balanced distribution of power between government entities and citizens. This bottom-up approach

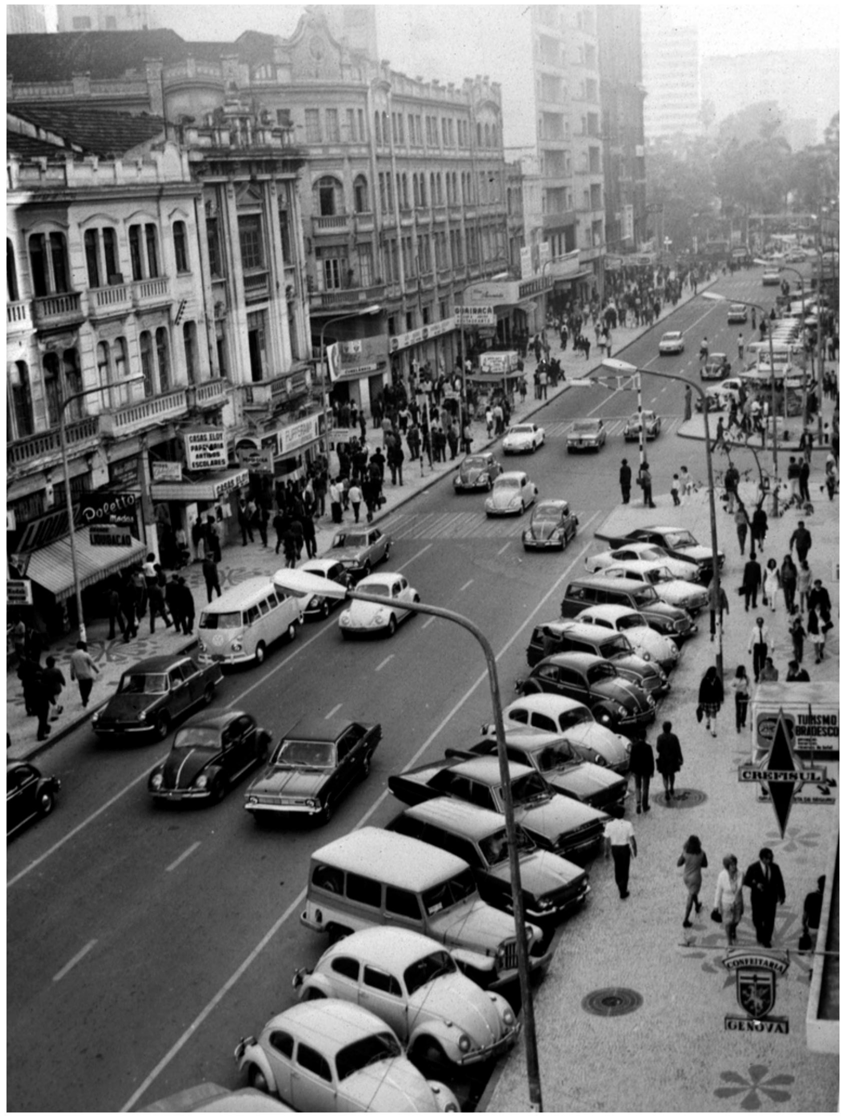


Fig. 20: Historical picture
Rua XV de Novembro.
Source: Band News FM

Fig. 21: Rua XV de Novembro
in the 70s.
Source: www.turistoria.com.br

minimizes the risk of manipulating public opinion and ensures the project addresses deeper issues that may otherwise remain unknown to the designers (Dias et al., 2018; Starzewska-Sikorska et al., 2022).

Additionally, community-driven projects should prioritize residents' education, particularly by raising awareness of local challenges and the need for action (Lerner, 2014; Moussavi, 2014). Engagement and understanding are fostered through the creation of future scenarios, increasing the likelihood of proposal acceptance and long-term impact (Moussavi, 2014; Nassar, 2021).

Finally, UA should follow a holistic approach, integrating each intervention into a cohesive framework that addresses economic, environmental, infrastructural, historical, and political factors (Salman & Hussein, 2021). Lerner (2014) highlights the importance of citizens' sense of belonging, and the connection to their surroundings and cultural identity. Therefore, proposals should act to transform ordinary spaces into meaningful and engaging places (Moussavi, 2014).

1.5.2 Urban Acupuncture approaches

The notion of urban acupuncture, a concept initiated by Morales and which term was coined by Jaime Lerner, has undergone numerous variations over time (Salman & Hussein, 2021). This approach, characterized by its social and local scale, small-scale nature, and low-budget implementation, has been adapted to address contemporary issues, including the climate crisis.

Urban Environmental Acupuncture (UEA) promotes the use of multiple small-scale Nature-Based Solutions (NBS) and green-blue infrastructure as effective interventions to drive larger environmental impacts. This approach is especially beneficial in urban areas where space for planting is limited, offering a strategic way to address environmental challenges.

By integrating these solutions, UEA fosters sustainable development, enhances urban biodiversity, and contributes to climate resilience (Starzewska-Sikorska et al., 2022; Stangel, 2023).

Eco-acupuncture (EcoA) is a term suggested by Ryan (2013) which includes the topic of climate change to the approach, aiming to accelerate the post-carbon transition. The interventions should address the intricate interactions between the built environment and systems of energy, water, food and transport.

Blue Urban Acupuncture (BUA) emphasizes the significance of blue areas in integration with the approach. It presents the possibility of revitalization of water bodies into recreational spaces with minimal required management, as well as an alternative and complementary intervention option to other urban natural systems. (Bell et al., 2020; Balicka et al., 2021).

Biophilic Urban Acupuncture (BUA) applies biophilic techniques to urban acupuncture interventions, prioritizing mental health and well-being. It transforms neglected, everyday spaces into interactive and visually appealing locations, fostering a stronger connection between people and their environment (Reinhold, 2018).

Digital Urban Acupuncture (DUA) analyzes and diffuses the city flows of information and knowledge, reassessing the user's identity and expression in the age of universal communication. Thus, it also reviews the notions of privacy and citizenship rights in developing the public space (Iaconesi & Persico, 2014; Iaconesi & Persico, 2017).

Urban Dark Acupuncture (UDA) as the name suggests, refers to the incorporation of dark locations in the cityscape to preserve the night sky. This approach aims to raise awareness to the topic of the negative effects of artificial lighting by intervening in strategic locations which can also serve as opportunities to educate citizens on the importance of darkness for environmental and human well-being (Amilawangi, 2020; Stone, 2019).

1.5.3 UA for mitigation and adaptation

Analyzing adaptation and mitigation strategies alongside UA principles, it becomes clear that this methodology is highly useful for urban resilience. Many examples show that applying a strategy extensively can generate large-scale effects at both neighborhood and city levels. As discussed, widely distributing vegetated area contributes to urban climate mitigation (Akbari et al., 2001). Similarly, green roofs—while limited in impact when used alone—combined with cool materials can help combat global warming by reducing surface temperatures and lowering urban heat peaks by up to 2°C (Santamouris et al., 2012; Erell et al., 2010; Gartland, 2010).

Starzewska-Sikorska et al. (2022) highlight that urban environmental acupuncture (UEA) mitigates heat stress by strategically distributing green areas and cold air corridors to regulate urban temperatures. Higher vegetation density strengthens its climatic impact, and even small green spaces aid in cooling. Vegetation diversity and structure are crucial, with permeable soils and varied plant types being most effective. Trees along roads and vegetation on façades and rooftops also help reduce urban heat, making cities more sustainable and comfortable.

Strategically placing multiple small blue and green spaces aligned with wind patterns can be more beneficial than a single large feature. This suggests that even in dense urban environments, such elements can be effectively integrated (Gunawardena et al., 2017). Starzewska-Sikorska et al. (2022) note that UEA elements differ from conventional blue-green infrastructure due to their smaller scale—such as pocket parks, tree clusters, or roadside lawns.

Starzewska-Sikorska et al. (2022) explores Nature-Based Solutions (NBS) as a tool for urban acupuncture. They highlight thirty of the most viable NBS solutions for this design methodology (Table 05).

	Technical/Economic aspects					Environmental aspects				
NBS strategy	Spatial disposition	Labour intensity	Expected efficacy	Approx. lifespan	Investment costs	Water management	Soil protection	Heat stress	Air quality	Social aspect
Compacted pollinators' module	Point	Moderate	Long term	Short	Moderate	No	No	No	No	Yes
Fruit trees/shrubs	Area	Moderate	Medium term	Long	High	Yes	Yes	Yes	Yes	Yes
Green covering shelters	Area	Low	Immediate	Short	Moderate	No	No	No	No	Yes
Green facades with climbing plants	Area	Low	Long term	Long	Moderate	No	No	No	Yes	Yes
Green pavements	Linear	Moderate	Immediate	Long	Moderate	Yes	Yes	Yes	No	Yes
Green pergolas/green arbours	Point	Moderate	Medium term	Long	High	No	No	No	Yes	Yes
Green roof/roof terrace	Area	Moderate	Immediate	Medium	High	Yes	No	No	No	Yes
Ground cover plants	Area	Low	Immediate	Medium	Low	Yes	Yes	Yes	No	Yes
Ground crops of vegetables/herbs	Area	Moderate	Immediate	Short	Low	No	No	No	No	Yes
Hanging wall planters (as green street furniture)	Point	Low	Immediate	Short	Low	No	No	No	Yes	Yes
Hedge/hedgerow	Linear	Moderate	Medium term	Medium	Moderate	Yes	Yes	Yes	Yes	Yes
Herb spiral	Point	Low	Immediate	Medium	Low	No	No	No	No	Yes
Hydroponic mobile living walls/ vertical gardens	Point	Low	Immediate	Short	Moderate	No	No	No	No	Yes
Large shrubs	Area	Low	Immediate	Long	Low	Yes	Yes	Yes	Yes	Yes
Lawn	Area	High	Immediate	Medium	Moderate	Yes	Yes	Yes	No	Yes
Linear wetlands stormwater filtration	Linear	Moderate	Long term	Short	High	Yes	No	Yes	No	Yes
Natural pollinators' modules	Point	Moderate	Long term	Short	Moderate	No	No	No	No	Yes
Park trees	Area	Low	Long term	Long	High	Yes	Yes	Yes	Yes	Yes
Rain gardens (under-drained)	Point	Low	Immediate	Short	Moderate	Yes	No	Yes	No	Yes
Rain gardens in planter (self-contained)	Point	Low	Immediate	Short	Moderate	Yes	No	No	No	Yes
Road-side swales for retention and infiltration	Linear	Moderate	Immediate	Long	Moderate	Yes	No	No	No	No
Rockery	Linear	High	Immediate	Medium	High	No	No	No	No	Yes
Street planters (as green street furniture)	Point	Low	Immediate	Short	High	No	No	No	Yes	Yes
Street trees	Linear	Moderate	Medium term	Long	Moderate	Yes	Yes	Yes	Yes	Yes
Urban meadows	Area	Low	Immediate	Short	Low	Yes	Yes	Yes	No	Yes
Urban wilderness/succession area	Area	Moderate	Immediate	Long	Low	Yes	Yes	Yes	Yes	No
Verges/flower beds with native perennials	Point	Low	Immediate	Long	Moderate	No	No	No	No	Yes
Vertical vegetable/herb gardens	Point	High	Immediate	Short	Moderate	No	No	No	Yes	Yes
VRSS* slopes with green fences	Point	Low	Immediate	Medium	Moderate	No	Yes	No	Yes	Yes
Wall-mounted living walls	Area	High	Immediate	Short	High	No	No	No	Yes	Yes

Expected efficacy:
Immediate (0-1 year)
Medium term (< 5 years)
Long term (> 5 years)

Approximate lifespan:
Short (< 10 years)
Medium (11-30 years)
Long (> 30 years)

* Vegetated reinforced soil slope

Table 05: Nature-Based Solutions (NBS) adapted to urban acupuncture and their characteristics.
Source: Starzewska-Sikorska et al.(2022) - adapted by the author

2. BEST PRACTICES

To further the understanding of urban acupuncture methodology and the application of nature-based solutions in addressing the impacts of urban climate dynamics and the ongoing climate crisis, three urban projects were selected for comprehensive analysis. Among these, two are situated within an oceanic climate zone (Cfb) as defined by the Köppen-Geiger classification, consistent with the climatic conditions of Curitiba, which serves as the primary case study for this thesis.

The Green Revitalization of the Impulse Region - Germany and the GZM Metropolitan Area - Poland, are components of the international program Integrated Environmental Management of Small Green Spots in Functional Urban Areas Following the Idea of Acupuncture (SALUTE4CE). This initiative brought together a consortium of ten partners from five countries, who collaborated from 2019 to 2022 to develop a comprehensive framework for implementing Urban Environmental Acupuncture (UEA) in conjunction with nature-based solutions, aimed at mitigating the effects of climate change in European urban contexts (Stangel, M., 2023).

The third project refers to the urban revitalization of Eindhoven - Netherlands. While the term urban acupuncture is not explicitly employed, the approach centers on targeted interventions at strategic locations throughout the city utilizing Nature-Based Solutions (NBS) to reinforce climate resilience—particularly in relation to flooding, urban heat islands, and overall enhancement of environmental quality (UNaLab, n.d.-b).

The city acted as a frontrunner initiative of the UNaLab (Urban Nature Labs) project, funded by the European Union under the Horizon 2020 program. Over the course of five years (June 2017 to May 2022), the project collaborated with 29 partners from 12 European and 3 non-European countries, advancing the development and implementation of NBS in urban settings to foster more sustainable, climate-adaptive cities (VTT Technical Research Centre of Finland, n.d.).

2.1 Metropolis GZM

Project: Salute4ce

Location: Chorzów, Ruda Śląska and Świętochłowice - Poland

The cities of Chorzów, Ruda Śląska, and Świętochłowice, located in Poland's Upper Silesian and Zagłębie Metropolis (GZM), as presented in Figure 22, are among the study sites of the SALUTE4CE project.

The area's climate is classified as Dfb (Köppen-Geiger) with significant rainfall throughout the year, including the driest month. The average annual temperature is 8.4°C, ranging from -3.5°C in January to 18.7°C in July. Annual precipitation totals 689 mm, peaking in July (96 mm) and reaching its lowest in February (32 mm) (Salute4ce, 2020b).

With a heavily industrialized history and rapid urbanization, the region has experienced extensive soil sealing, leading to significant environmental challenges. As population density has increased, so has the area's vulnerability to climate-related phenomena such as heat waves, urban heat islands, and heavy rainfall. In response, recent efforts have focused on promoting sustainable development, seeking to balance urban growth with environmental resilience (Stangel, M., 2023).

The main goals of the Action Plan for this region are, firstly, the enhancement of the community's quality of life, followed by the development of the social, technical, and transport infrastructure, with a focus on the revitalization of degraded areas, and finally, the improvement of the environmental condition of the area (Salute4ce, 2021a). As for the general long-term vision for urban green spaces, the priority should be on climate change adaptation, embedding Nature-Based

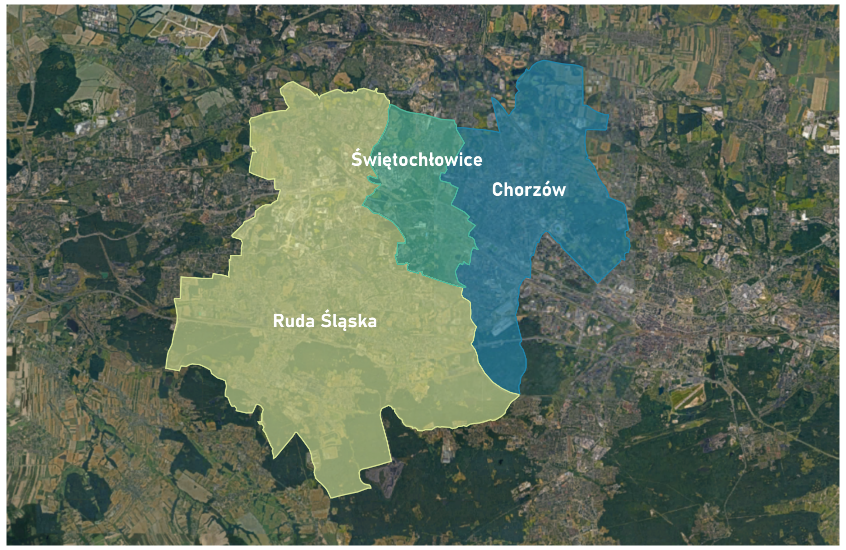


Fig. 22: Chorzów, Ruda Śląska and Świętochłowice. Source: Google maps - adapted by the author

Solutions (NBS) into urban planning, and expanding green infrastructure. The chosen sites will serve as key hubs for community engagement, boosting urban biodiversity, mitigating climate risks, and enhancing the local landscape. Additionally, the Action Plan aims to raise awareness of ecosystem benefits and foster collaboration among residents, stakeholders, and authorities (Salute4ce, 2021a).

A total of 27 potential sites for urban acupuncture interventions were selected within the functional areas of the three cities (Figure 23). In order to identify priorities and incorporate bottom-up insights into local needs and opportunities, an initial selection was made based on suggestions gathered from municipal employees and the community through workshops and discussions. This was followed by a refinement process, applying suitability and necessity criteria based on city analyses and research data (Stangel, M., 2023).

From Ruda Śląska, ten locations were selected, primarily underutilized open spaces with insufficient greenery and lack of proper development. In Świętochłowice, eight municipal housing courtyards were designated as intervention sites. As for Chorzów, nine sites were identified, mostly in the city center, comprising neglected, paved yards and courtyards with scarce greenery, as well as two deteriorated squares and a parking lot with potential for substantial environmental and functional enhancements (Stangel, M., 2023).

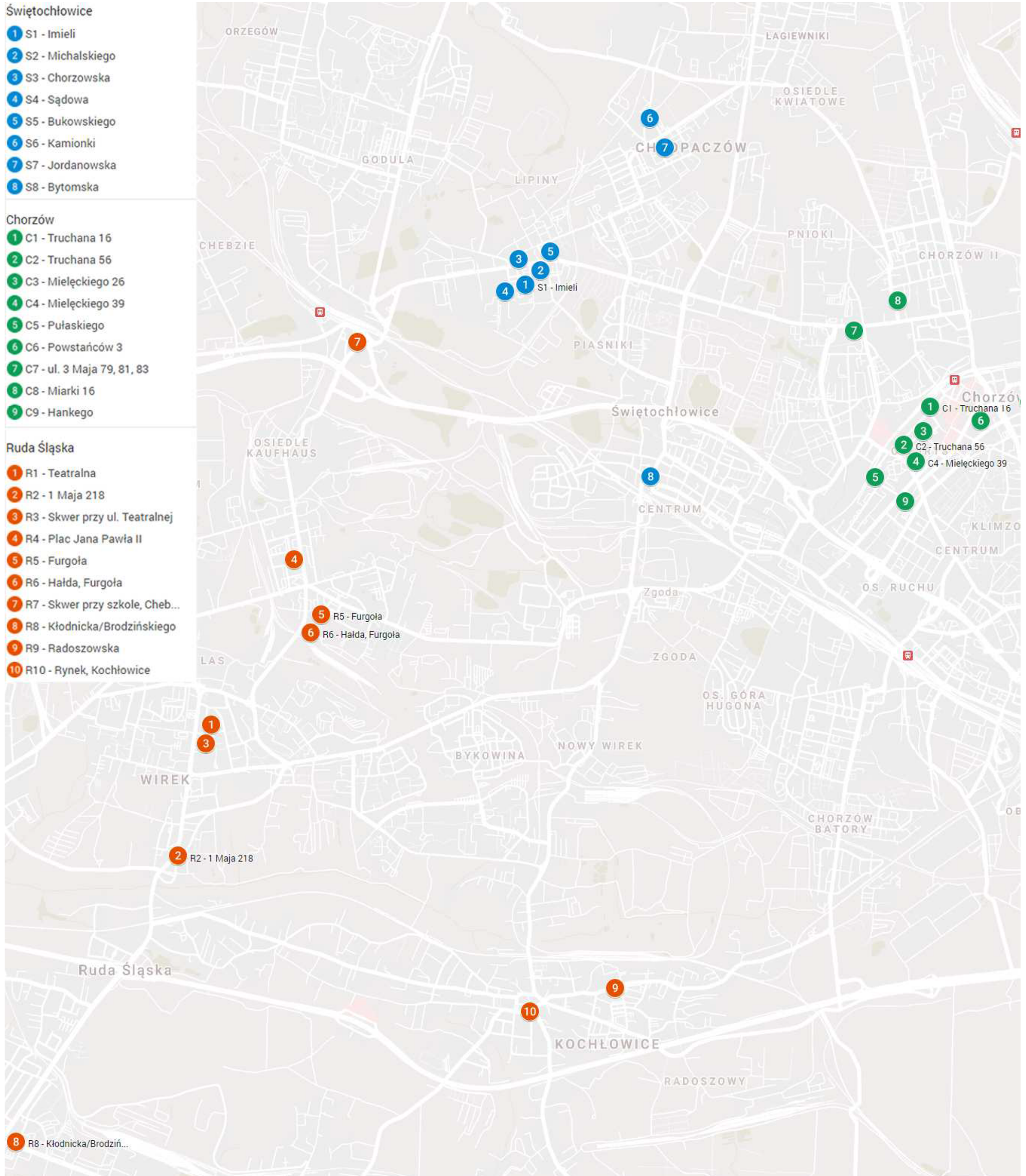


Fig. 23: 27 potential intervention spots. Source: Salute4ce (2021a)

Finally, four additional sites were selected in the city of Chorzów as pilot projects to be developed according to designs by Franta&Franta Architekci. These locations vary in typology, size, and development needs, providing valuable reference points for future interventions. By showcasing different approaches to urban development, they help facilitate the decision-making process and contribute to a more informed and strategic planning framework (Salute4ce, 2020b; Salute4ce, 2020c).

2.1.1 Site 1: Bankowa Street

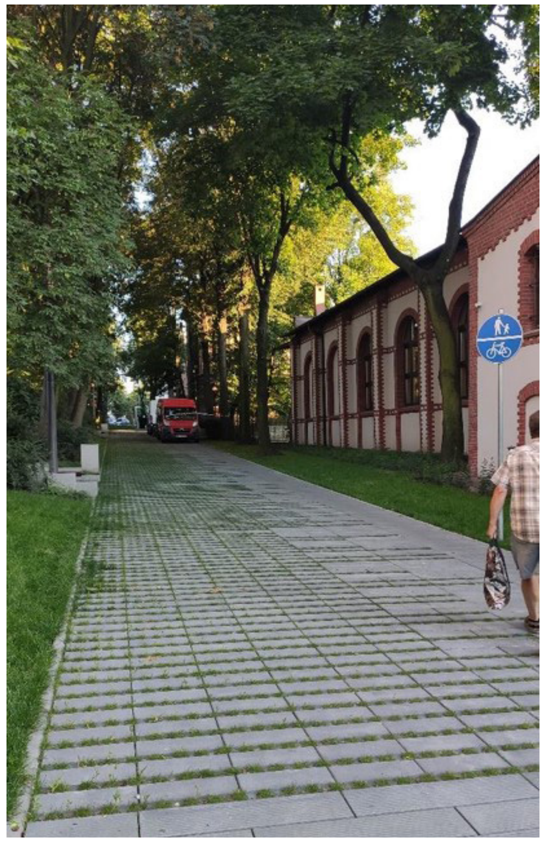
The first intervention site is located in the city center of Chorzów. Identified as vulnerable to surface urban heat island effects, the area consists of a neglected pedestrian asphalt pathway with deteriorating pavement and limited plant diversity (Salute4ce, 2020b; Salute4ce, 2021b). Figure 24 shows the area prior to the intervention.

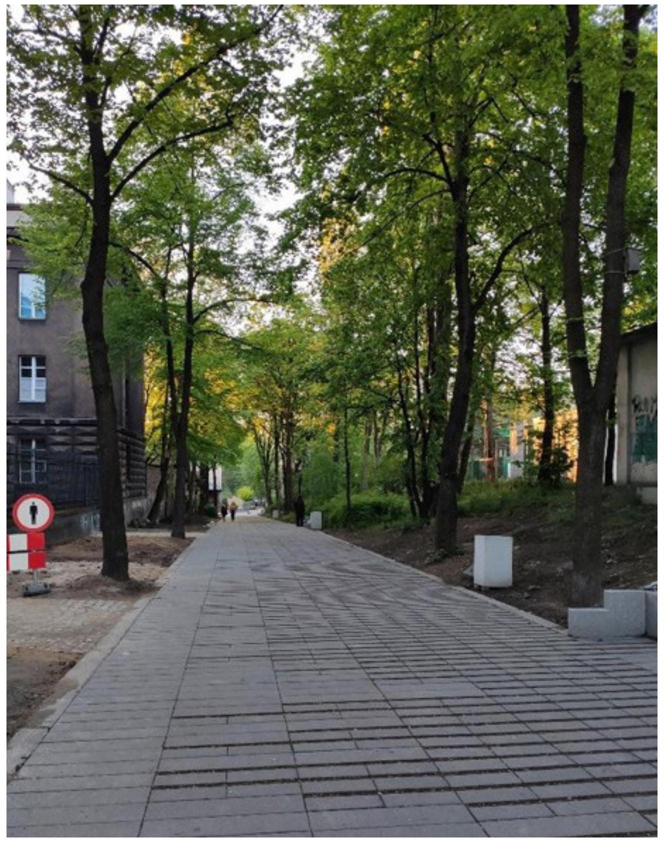
The project consists in the transformation of the area into an inviting green corridor, providing a new recreational space for the community. The design incorporates a high quality semi-permeable paving, comfortable seating areas, and additional vegetation to enhance the natural environment (Figure 25). The main objectives include improving thermal comfort, reducing surface sealing to promote better water drainage and retention, and promoting biodiversity by prioritizing the use of native plant species. By integrating these elements, the intervention aims to create a more sustainable, aesthetically pleasing, and climate-resilient urban space (Salute4ce, 2021b; Stangel, M., 2023). These results can be observed in Figure 26 and 27, which present the completed project in the area.

Fig. 24: Bankowa Street general view.
Source: Salute4ce (2020c)

Fig. 25: Proposal for Bankowa Street.
Source: Salute4ce (2020c)

Fig. 26 and 27: Finalized project of Bankowa Street.
Source: Salute4ce (2021b)





2.1.2 Site 2: Moniuszki Street

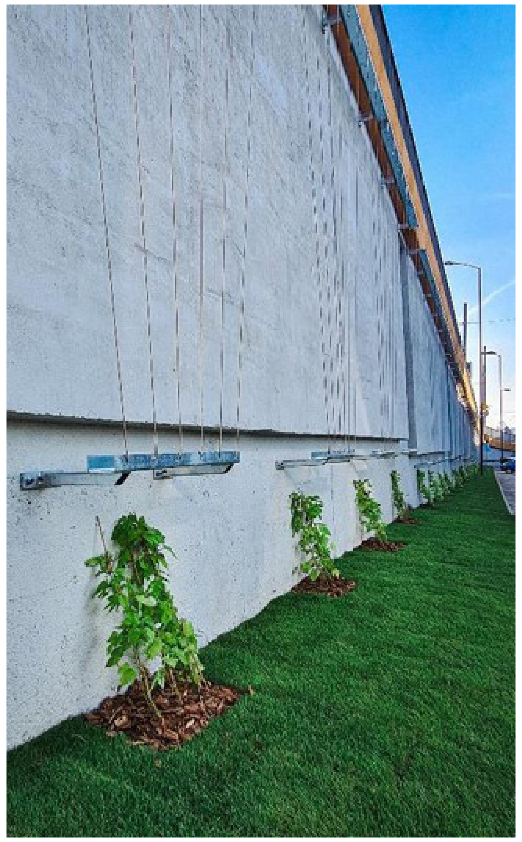
For the second realized project, another city center site was selected, also located in an area sensitive to surface urban heat island effects. The location consists of a section of roadside bordered by a concrete retaining wall with limited greenery (Figure 28).

Aiming to develop a community-friendly and visually appealing environment, the intervention proposes the introduction of a green verge along the boundary wall, along with the creation of a green belt following the street edge, and the revitalization of the existing stairs to improve accessibility and aesthetics, as illustrates Figure 29. The addition of the new vegetation not only enhances the area's ecological value and thermal comfort, but also contributes to expanding the city's green network, establishing a stronger connection with the existing greenery in the nearby municipal market square (Salute4ce, 2020b; Salute4ce, 2021b). The completed project is documented in Figures 30 and 31, with the green wall in its initial stage of growth.

Fig. 28: Moniuszki Street general view.
Source: Salute4ce (2020c)

Fig. 29: Proposal for Moniuszki Street.
Source: Salute4ce (2020c)

Fig. 30 and 31: Finalized project of Moniuszki Street.
Source: Salute4ce (2021b)



2.1.3 Site 3: Sienkiewicza Street

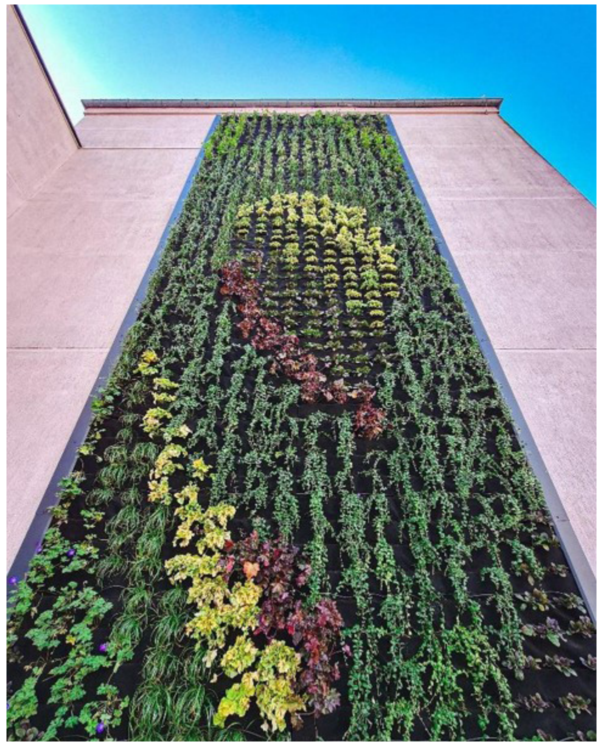
Like the first two, the third intervention site is also located in Chorzów's city center and is affected by surface heat island effects. The selected area includes the entrance of the Chorzów Cultural Center, specifically the access square and the building's north façade. This space is currently dominated by sealed concrete surfaces, lacks vegetation, and has no clear separation from the street (Figure 32).

Due to limited space, the proposal focuses on incorporating a green wall on the façade (Figure 33). This intervention aims to enhance the site's visual appeal while also improving thermal comfort, promoting biodiversity by introducing native species, and expanding green areas within the city center (Salute4ce, 2020b; Salute4ce, 2021b). The final version of the project can be seen in Figures 34 and 35.

Fig. 32: Sienkiewicza Street general view. Source: Salute4ce (2020c)

Fig. 33: Proposal for Sienkiewicza Street. Source: Salute4ce (2020c)

Fig. 34 and 35: Finalized project of Sienkiewicza Street. Source: Salute4ce (2021b)



2.1.4 Site 4: Armii Krajowej Street

The last selected project is a residential courtyard in central Chorzów, facing the same thermal challenges as the previous sites. Previously used for parking, as presented in Figure 36, the site consists of a shaded, paved area devoid of vegetation and enclosed by a concrete retaining wall

To address these issues, the design focused on the pavement and landscape improvement by integrating vegetation and permeable concrete slabs in order to define a clear distinction between communication and green zones. Additionally, a mini playground and a resting area were proposed, offering local residents new opportunities for recreation. Moreover, shade-tolerant plants were added along the retaining wall, while climbing vines softened the concrete fence, enhancing both the greenery and visual appeal of the space. To foster community engagement, flower pots were also proposed, with residents encouraged to take part in their upkeep (Salute4ce, 2021b; Stangel, M., 2023).

Figure 37 presents the project's concept, while Figures 38 and 39 feature the completed implementation.

Fig. 36: Armii Krajowej Street general view. Source: Salute4ce (2020c)

Fig. 37: Proposal for Armii Krajowej Street. Source: Salute4ce, (2020c)

Fig. 38 and 39: Finalized project of Armii Krajowej Street. Source: Salute4ce (2021b)

2.2 Impulse Region

Project: Salute4ce

Location: Erfurt, Weimar, Jena, and Apolda - Germany

The project area is composed of four cities: Erfurt, Weimar, Jena, and Apolda, which integrate the Impulse Region (Figure 40). The initiative aimed to address the impacts of climate change through Urban Environmental Acupuncture (UEA) by focusing on redeveloping green spaces and establishing a network of small-scale, scientifically driven interventions across the area (Salute4ce, 2022a).

The four cities have climates that can be classified as either humid continental or oceanic, with warm and sometimes humid summers, and relatively cold winters. Average summer temperatures range from 21–22 °C for highs and around 11 °C for lows, while winter highs vary between 2–3 °C and lows between -2 and -3 °C.

The topography of the region, located in basins, creates microclimates characterized by temperature inversions in winter and insufficient air circulation in summer, which can lead to heat accumulation. Annual precipitation is moderate, ranging from 502 to 565 mm, distributed throughout the year. Snowfall is light and occurs mainly from December to February, but snow cover rarely persists for long (Salute4ce, 2020a).

According to the Implementation Strategies Report (Salute4ce, 2022a), the project aims to strengthen the cultural landscape by creating new recreational space near the city while prioritizing fauna and flora conservation. Additionally, it seeks to develop green connections, offering attractive routes to larger green spaces in residential areas with limited vegetation.

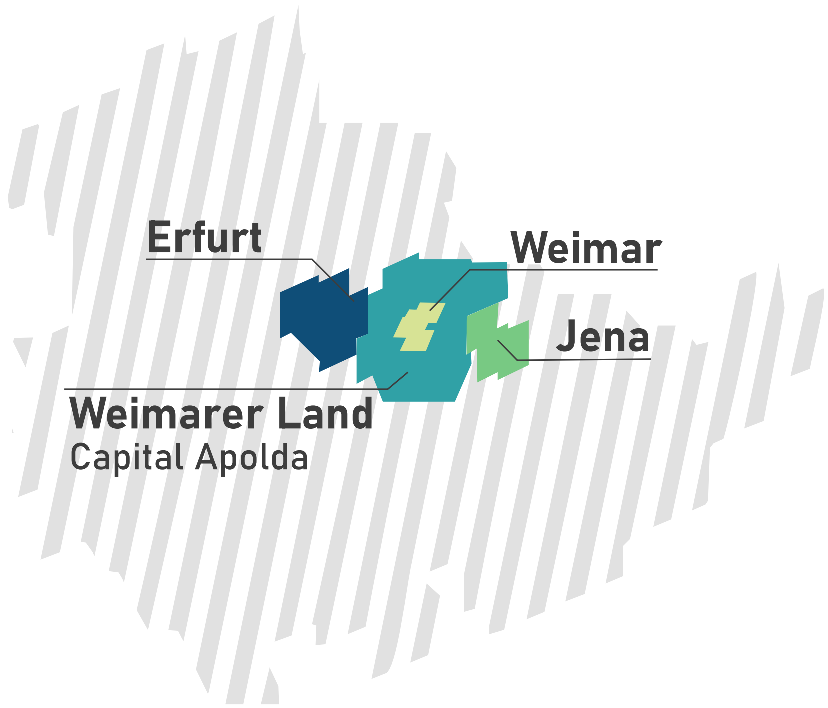


Fig. 40: Impulse Region.
Source: www.impulsregion.de - adapted by the author

The revitalization of vacant open spaces is also a key focus, incorporating natural elements into their design. To mitigate urban heat island effects, the project emphasizes green development, partial dismantling of sealed surfaces, and the prevention of excessive re-sealing. Lastly, it aims to increase the presence of green roofs and facades, further enhancing urban sustainability and ecological balance.

The action plan involves various stakeholder groups, each contributing to different aspects of the project. A key group is technical experts, including professionals in urban planning, green space management, nature conservation, and climate protection. Their expertise ensures technical support and a strong scientific foundation.

Additionally, strategic partners such as property owners and housing companies help develop the mission statement and refine planning details, preventing potential conflicts of use. Political power also plays a crucial role in legitimizing decisions and implementation. Department heads, committees, and associations are kept informed and invited to provide input, ensuring the project has the necessary political backing.

Finally, public participation is essential to the project's success. Building a culture of green space protection requires social acceptance and support for climate initiatives. Early involvement of the community helps build motivation while minimizing frustration, resistance, and dissatisfaction (Salute4ce, 2022a).

To foster engagement, the proposal incorporates various forms of citizen participation. These include citizens' meetings, where residents discuss local issues and share recommendations, and workshops, which encourage creative problem-solving and active involvement in planning. Additionally, surveys are used to systematically gather public insights, ensuring informed decision-making.

The first part of the plan begins with a pilot phase, focusing on four sites selected for analysis and intervention within the framework of green and blue infrastructure (Salute4ce, 2020a; Salute4ce, 2022a). These sites vary in scale, environmental conditions, cultural significance, and development priorities, allowing for a diverse and comprehensive assessment.

Building on this foundation, the next step involved developing future climate scenarios based on these specific site types. By analyzing projected climatic changes, the team identified the most suitable vegetation for each area, ensuring resilience and adaptability. This strategic approach not only enhances long-term ecological benefits but also optimizes maintenance efforts and reduces costs associated with new plantings.

Although this process required extensive research and analysis, these pilot areas are intended to serve as reference models for future projects in similar locations. The in-sights gained will help refine strategies for broader urban revitalization efforts. In total, 27 additional sites (Figure 41) across the four cities have been identified as potential candidates for further revitalization.

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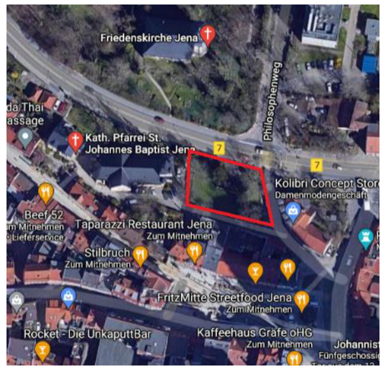

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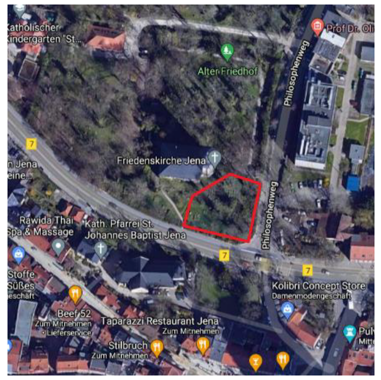

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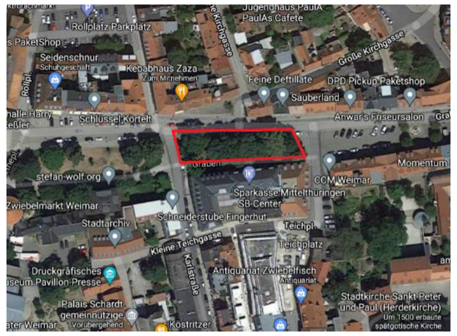

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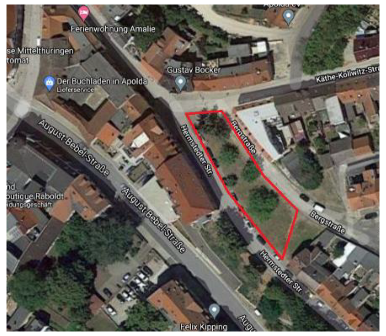

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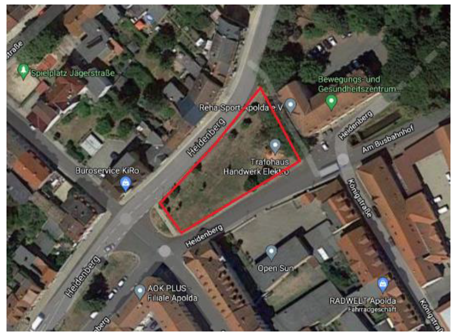

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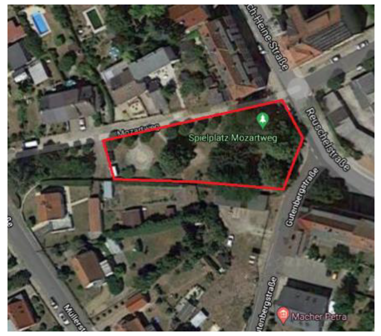

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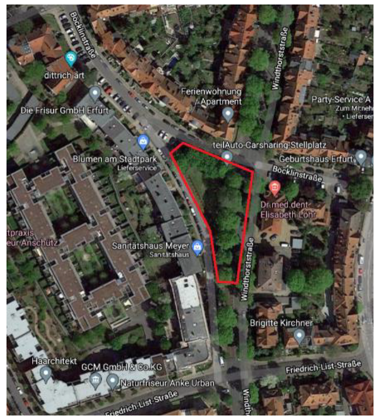

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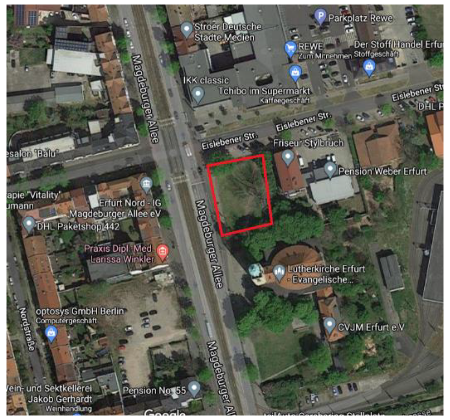

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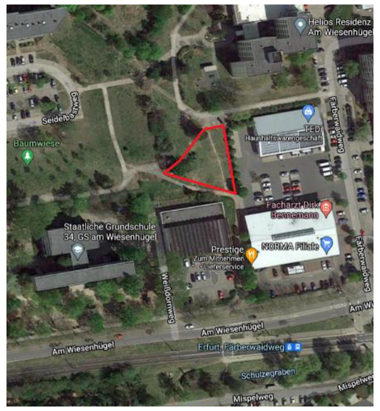

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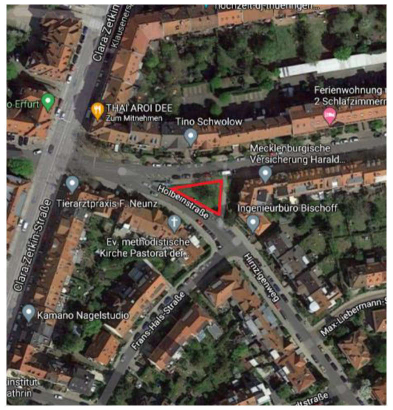

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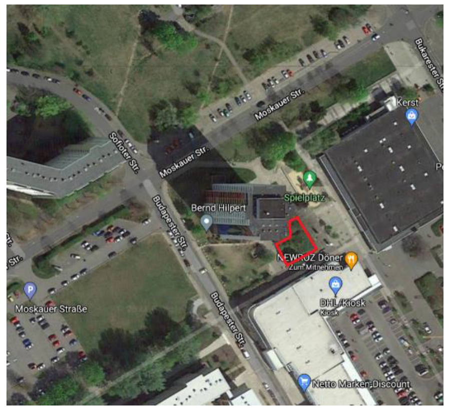

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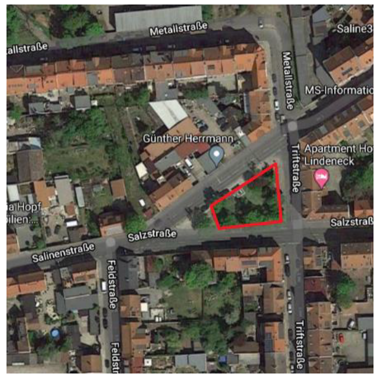

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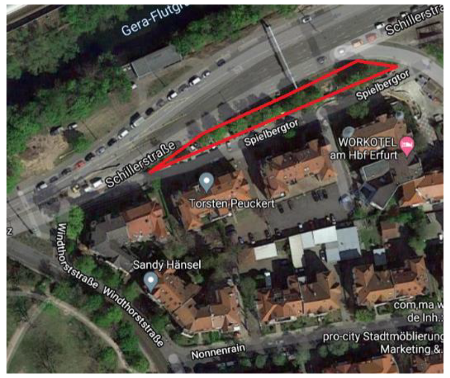

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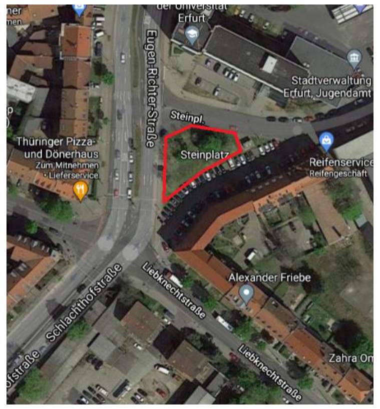

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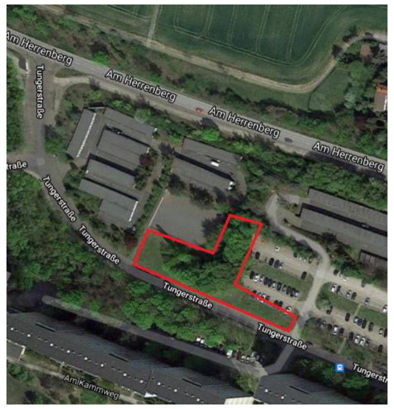


Fig. 41: 27 potential intervention spots. Source: Salute4ce (2022a)

2.2.1 Site 1: Schützenhofstraße, Jena

The first investment area is located in the northern urban zone of Jena (Figure 42 and 43), within a green corridor nestled between buildings. This site is particularly vulnerable to high heat stress and suffers from a lack of accessible and functional green spaces. Given the area's aging population, the proposal aims to enhance urban resilience by introducing a series of pocket parks at a nearby school site. These green spaces are designed to promote intergenerational connections while providing a welcoming and comfortable climate oasis.

Several new "stay" areas were proposed, as shown in Figures 44 and 45, with a particular focus on addressing warmer summer days. The plan included the installation of benches in shaded locations, as well as the enhancement of the landscape. The introduction of flowering meadows and perennial plantings not only increases the site's ecological value but also improves its aesthetic appeal, making the recreational spaces more inviting and enjoyable for the residents (Salute4ce, 2020d).

Fig. 43: Aerial view of the investment area in Jena. Source: Salute4ce (2020d)

Fig. 44: New plantings in the design site in Jena Source: Salute4ce (2022b)

Fig. 42: General view of the investment area in Jena. Source: Salute4ce (2020a)

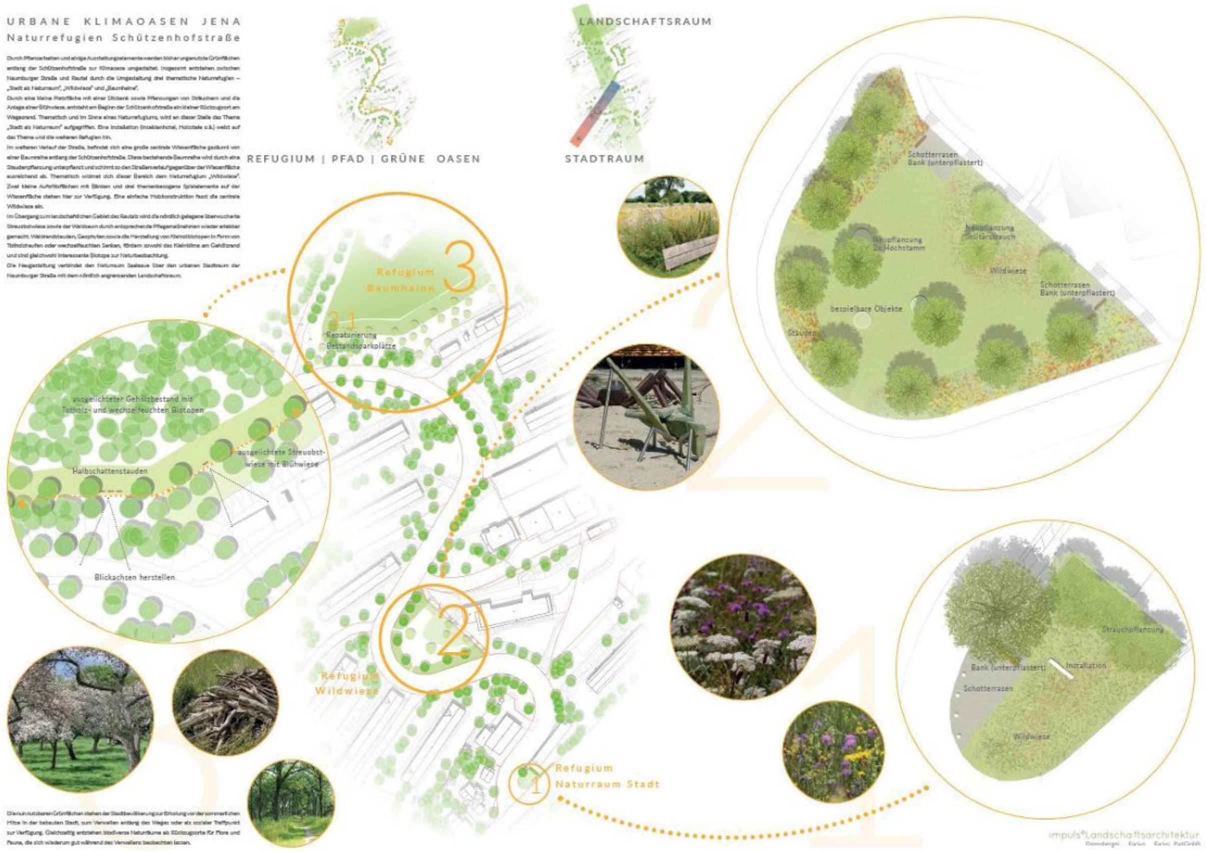


Fig. 45: Proposal for the investment area in Jena. Source: Salute4ce (2020d)

2.2.2 Site 2: Körnerstraße, Erfurt

A football field is the focus of the second intervention, located in the city of Erfurt (Figure 46 and 47). The proposal aims to enhance the existing facility— a hard court surrounded by a lawn, characterize by being an unsafe area —by transforming it into a family-friendly recreational space while strengthening the community's connection with local flora and fauna.

New vegetation plays an important role in the design. Additional trees and bushes, including fruit-bearing species, will create shaded areas, improving comfort and attractiveness. The greenery will also act as a buffer from the nearby street,

Fig. 46: Aerial view of the investment area in Erfurt. Source: Salute4ce (2020d)

Fig. 47: General view of the investment area in Erfurt. Source: Salute4ce (2020a)

ensuring a safer and smoother transition between the leisure space and the city. The vegetation is also intended to serve as a barrier to the street nearby, creating a safer and smoother transition between the leisure facility and the city.

To further enrich the space, the intervention includes topographical adjustments to integrate seating steps into the landscape, offering new ways to engage with the area. Additionally, designated feeding and retreat areas for local wildlife will be introduced, fostering a closer interaction between visitors and nature (Salute4ce, 2020a; Salute4ce, 2020d).

2.2.3 Site 3: Postgarten, Apolda

The third intervention site is in a well-established area at the heart of Apolda, specifically in the northern Bahnhofsstraße district (Figure 48, 49 and 50). The project focuses on revitalizing the garden of the former post office, built in 1898. After a period of vacancy in the 1990s, the historic building was recently re-purposed as a senior citizens' home with daycare services.

As presented in Figure 51 with the project's proposal, and Figure 52 with the site's new plantings, the design aims to transform the historic garden into a public climate oasis, enhancing both the neighborhood and the quality of life for residents. This space will serve as an intergenerational meeting point, promoting community interaction and offering new cultural possibilities.

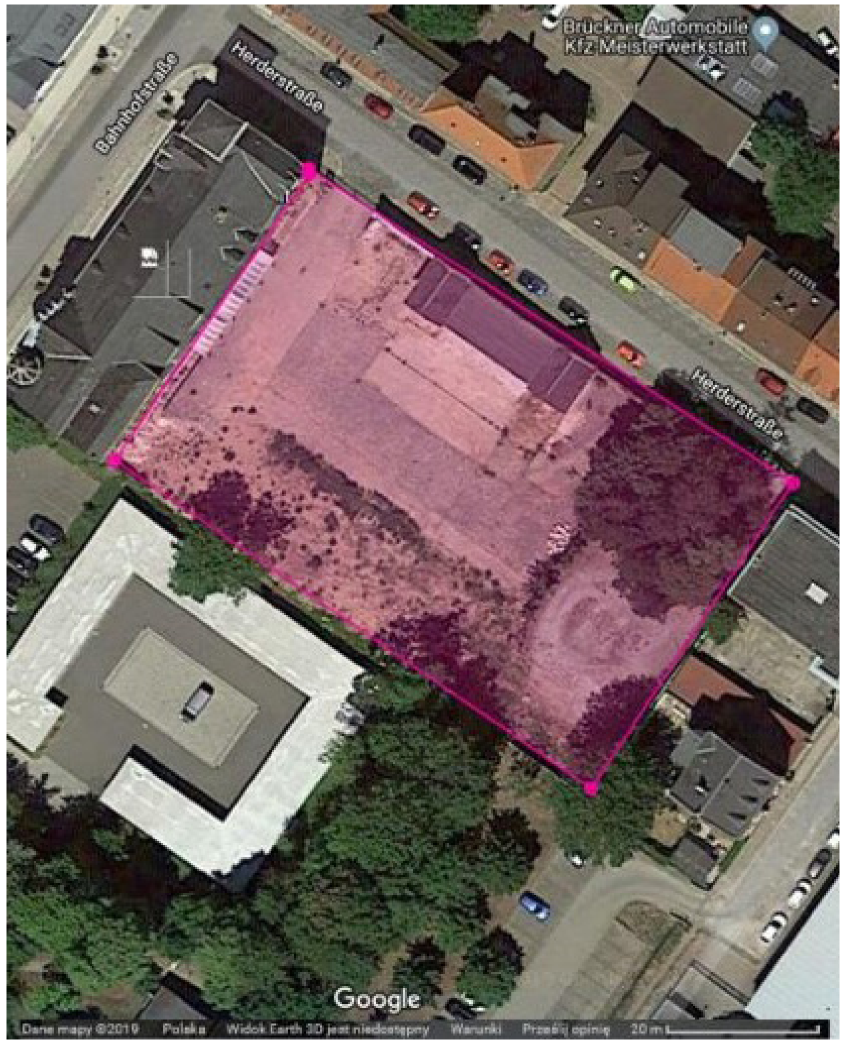


Fig. 48: Aerial view of the investment area in Apolda. Source: Salute4ce (2020d)

Fig. 49 and fig 50: General view of the investment area in Apolda. Source: Salute4ce (2020a)

The interventions include converting sections of the old façades into green walls, creating seating areas to encourage social engagement and increasing local urban biodiversity through carefully selected planting. These measures will not only improve the aesthetics and livability of the area, but will also contribute to better air quality and a healthier microclimate (Salute4ce, 2020d; Salute4ce, 2022b).

Fig. 51: Proposal for the investment area in Apolda. Source: Salute4ce (2020d)

Fig. 52: New plantings in the design site in Apolda. Source: Salute4ce (2022b)

2.2.4 Site 4: Insektenweide, Weimar

The final intervention takes place in Weimar, on a plot of wild fallow land with natural overgrowth, situated within a residential area (Figure 53 and 54). Originally, the site was intended to be part of the adjacent kindergarten's outdoor space but remained unused.

The project aims to transform this area into an insect-friendly flower meadow, as presented in Figure 55, providing an extra food supply and selected native plants. This initiative aligns with the city's broader goal of integrating diverse wildflower meadows into urban spaces. Moreover, the project addresses the growing issue of insect mortality while offering an educational experience for the local community, particularly engaging young children from the nearby kindergarten.

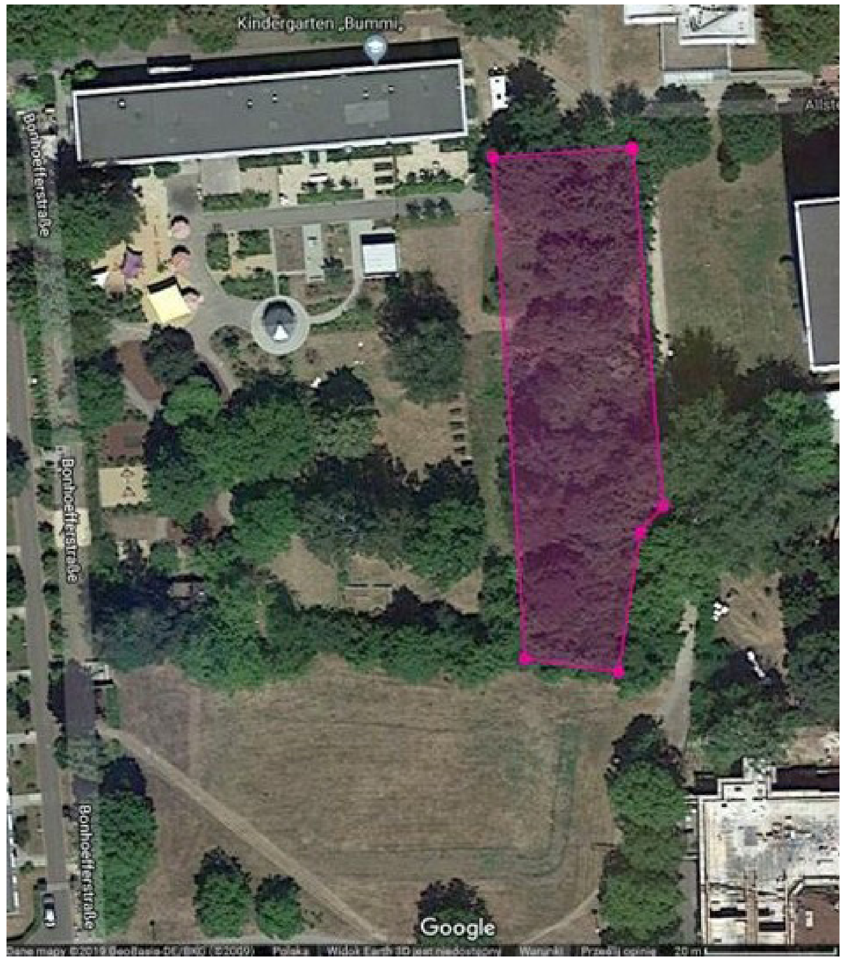


Fig. 53: Aerial view of the investment area in Weimar. Source: Salute4ce (2020d)

The plan includes clearing old stairs, fences, and walls to improve public accessibility. Additionally, it prioritizes the preservation and enhancement of the site's natural vegetation and introduces supplementary seeding areas. Informational boards were installed to raise environmental awareness, while benches were strategically placed around the perimeter providing an attraction for visitors and a way to engage with and appreciate the revitalized green space (Salute4ce, 2020a; Salute4ce, 2020d; Salute4ce, 2022b). The full site plan of the proposal is shown in Figure 56.

Fig. 54: General view of the investment area in Weimar. Source: Salute4ce (2020a)

Fig. 55: New flower meadow in the investment area in Weimar. Source: Salute4ce (2022b)

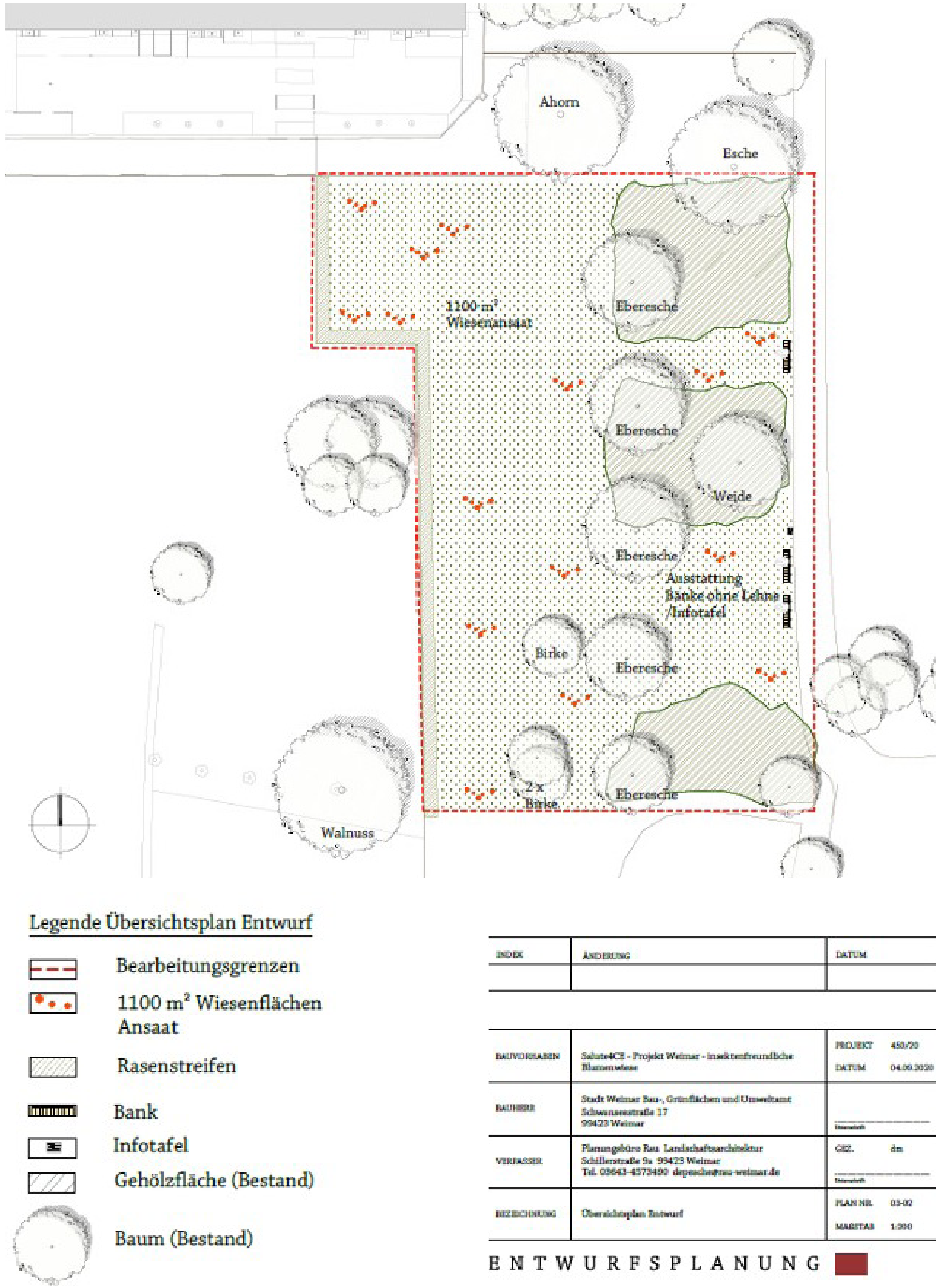


Fig. 56: Proposal for the investment area in Weimar. Source: Salute4ce (2020d)

2.3 Eindhoven

Project: UNaLab

Location: Eindhoven - Netherlands

Eindhoven is the fifth largest city in the Netherlands, covering an area of 89 km² with a population density of 2,639 inhabitants per km² (Westerink et al., 2017; CBS, 2019). The region has a temperate oceanic climate, characterized by mild summers, moderate winters, and high humidity. The average temperature is 9.4 °C, and the annual rainfall amounts to 776 mm (KNMI, 2019).

The city is largely covered by impervious urban, commercial, and industrial surfaces, which, combined with clayey soils with low infiltration rates, local streams, and a high groundwater table, promotes water accumulation and surface runoff, increasing the risk of pluvial flooding (UNaLab, n.d.-a). Moreover, in recent years, Eindhoven's city centre has frequently recorded the highest temperatures in the Netherlands, occasionally surpassing 40 °C (Urban Green-Blue Grids, n.d.). These vulnerabilities are further intensified by rapid population growth and climate change, which not only increase the frequency of extreme rainfall events but also exacerbate urban heat stress and negatively impact air quality (UNaLab, 2022).

The project involves the implementation of Nature-based Solutions (NBS) across multiple areas of the city to address the environmental and climate-related risks previously identified. A core strategy has been the conversion of sealed, paved surfaces into green and permeable spaces, with a particular emphasis on the city center. This transformation aims to enhance stormwater management and resilience to heavy rainfall and flooding by increasing soil infiltration and easing the burden on the urban drainage system. In addition, these interventions help mitigate urban heat stress and contribute to creating healthier, more pleasant environments for residents (UNaLab, 2022).

Living labs involving community and stakeholder participation were conducted prior to the proposals to promote engagement, align expectations, and anticipate potential challenges. Subsequently, ten locations in the city center (Figure 57) were selected to be redesigned as demonstration sites for the application of Nature-based Solutions (NBS). These interventions aimed to enhance environmental resilience and urban liveability and serve as replicable models for future initiatives (UNaLab, 2022; UNaLab, n.d.-b).

Fig. 57: Demonstration points in Eindhoven. Source: UNaLab (2022)

One of the most significant intervention areas is the Vestdijk Boulevard. Previously dominated by intense vehicular flow and impermeable paving, the area has been re-imagined as a green urban boulevard. The redesign reduced car traffic to a single lane, resulting in improved air quality and enhanced accessibility for pedestrians and cyclists. Vegetation was carefully selected to increase biodiversity and improve the visual appeal of the area. Additionally, a climate-adaptive water storage system and enhanced soil conditions were introduced to manage flooding and promote water infiltration. The reduction of impervious surfaces has also contributed to mitigating urban heat stress (UNaLab, n.d.-b). Figures 58 and 59 present before-and-after views of the site intervention.

Fig. 58: Vestdijk Boulevard before (top) and after (bottom) the intervention. Source: Google maps

Fig. 59: Vestdijk Boulevard before (top) and after (bottom) the intervention. Source: Google maps

In addition to the major revitalization of Vestdijk, several smaller streets in Eindhoven also received greening interventions (Figures 60 and 61). In Waagstraat, sections of pavement were replaced with a grassed swale, trees, and improved soil to enhance water infiltration. Bilderdijklaan was redesigned for pedestrians and cyclists, incorporating vegetation to boost climate resilience and biodiversity. On Willemstraat, greenery was added to a former bicycle parking area, while in H. Boexstraat and Dommelstraat, tree pits were expanded and infiltration planters installed to improve stormwater management (UNaLab, n.d.-b).

Fig. 60: Waagstraat before (top) and after (bottom) the intervention.
Source: Google maps

Fig. 61: Willemstraat before (top) and after (bottom) the intervention.
Source: Google maps

The Clausplein Square redevelopment was another significant initiative (Figure 62). This proposal, presented in Figure 63, focused on a larger-scale green revitalization of the area adjacent to a residential tower and the multi-functional building 'De Witte Dame', situated above an underground car park. Much of the former concrete and stone surface was replaced with 1,930 m² of low-maintenance vegetation, including perennials, grasses, shrubs, and 15 newly planted trees. A 279 m³ underground retention system was installed atop the parking structure to collect rainwater and irrigate the plants through capillary action (Figure 64). This system supports vegetation and reduces pressure on the municipal drainage by lowering runoff (Urban Green-Blue Grids, n.d.). Figure 65 presents the completed project.

Fig. 62: Clausplein Square before (top) and after (bottom) the intervention.
Source: Google maps

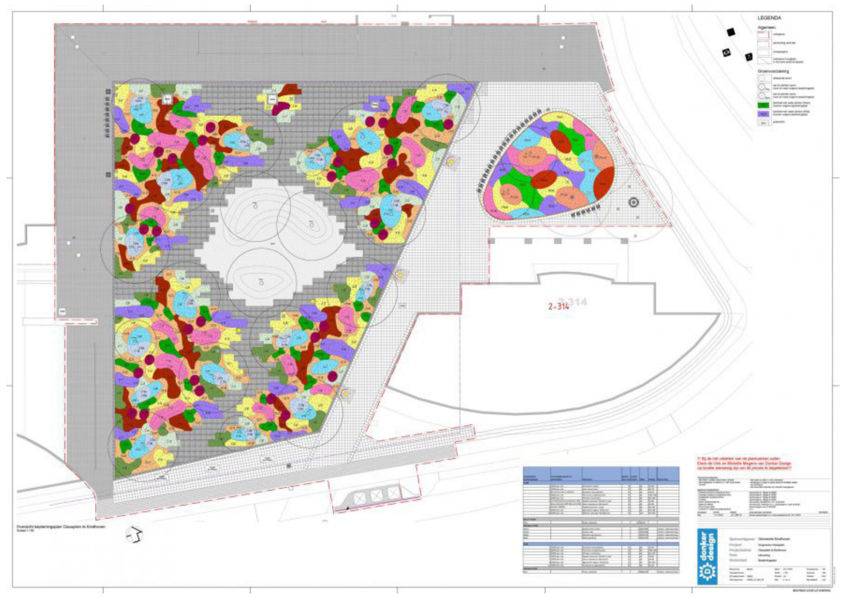


Fig. 63: Clausplein Square beplantingsplan. Source: Gemeente Eindhoven

Fig. 64: Clausplein Square before renovation. Source: Gemeente Eindhoven

Fig. 65: Clausplein Square project conclusion. Source: Gemeente Eindhoven

In certain cases, vegetation was also incorporated into architectural features, exemplified by the green façades implemented on a building along Oude Stadsgracht (Figure 66) and within the former industrial site of Nutsbedrijven Regio Eindhoven. Aligned with community preferences, these interventions were designed to enhance urban liveability and contribute to the mitigation of local heat stress (UNaLab, n.d.-b).

Fig. 66: Oude Stadsgracht before (top) and after (bottom) the intervention. Source: Google maps

As part of the redesign, a green roof covering around 110 m² was added atop the entrance of the City Hall (Figure 67). The area adjacent to the Dommel River was also revitalized, incorporating increased natural vegetation to improve both the aesthetic appeal and biodiversity of the site. These enhancements were thoughtfully planned to align with and reinforce the ecological role of the river corridor, including the creation of a green terrace planted with trees, perennials, and grasses, as well as the introduction of native plant species along the river's edge (UNaLab, n.d.-b).

Fig. 67: Eindhoven City Hall before (top) and after (bottom) the intervention. Source: Google maps

Fig. 68: Thermal photo of NBS in Vestdijk. Source: UNaLab (2022)

Following the interventions, temperature comparisons were conducted in the Vestdijk area, as shown in Figure 68. The results highlight how the presence of vegetation contributes to reducing maximum temperatures and improving thermal comfort in the surrounding area (UNaLab, 2022).

Additionally, a previous study by Costa et al. (2021) evaluated the effectiveness of Nature-based Solutions (NBS) for flood mitigation in Eindhoven. According to the authors, NBS efficiency depends on surface area, location, and type. Larger NBS areas lead to greater reductions in flood extent and water depth. The study found that, for green parking interventions, efficiency increases proportionally with the area implemented. Furthermore, distributing water storage systems across residential zones proved more effective than concentrating them. Among the NBS types assessed, water storage systems were the most efficient—outperforming green roofs and green parking, particularly during prolonged rainfall events—while also requiring less space and offering lower implementation costs. In contrast, fully greening all flat roofs was considered largely unfeasible due to issues related to property ownership and structural limitations.

2.4 Comparative analysis

When analyzing the three projects together, one can observe the adoption of a similar methodology based on the selection of multiple strategic locations across the city as a way to demonstrate and test interventions, with potential for replication in other areas in the future. Additionally, the projects highlight how prior knowledge of local characteristics — including environmental, social, and urban aspects — and of the possible applications of Nature-based Solutions (NBS) can play a key role in enabling more effective and context-sensitive decision-making.

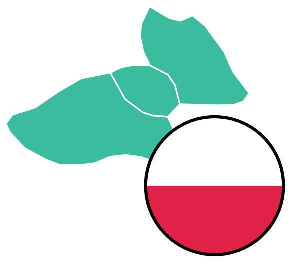
The importance of actively involving the local population and various stakeholders throughout different stages of the implementation process is also evident. This participation not only helps to generate engagement and social acceptance of the interventions but also aligns expectations, incorporates local knowledge, and enhances the legitimacy and effectiveness of the proposed solutions.

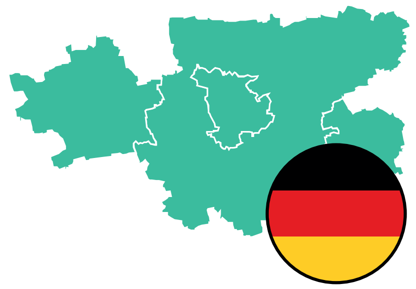
The analysis of the interventions reveals that each site presents unique requirements and challenges for implementing new structures shaped by factors such as physical scale, urban function, and geographic context. These distinct conditions necessitate context-sensitive, customized approaches. Moreover, beyond addressing environmental objectives, all three projects explicitly integrate social considerations into their designs, aiming to improve both the quality of life and the utilization of urban spaces. The interventions thoughtfully account for the demographic, cultural, and functional characteristics of the local communities, underscoring the importance of holistic solutions centered on the needs of users.

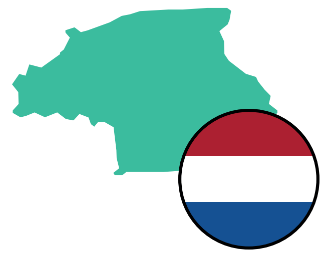
In implementing Nature-Based Solutions (NBS), there is a clear focus on public spaces, which generally offer greater ease for interventions and construction due to their accessibility and lower administrative complexity. This preference is reinforced by Costa et al. (2021), who highlight the challenges associated with implementing multiple green roofs in private areas. According to the authors, this strategy faces significant obstacles, as many private buildings are not structurally prepared to support the additional weight and rely on voluntary investments from owners. These factors limit the feasibility and scale of such interventions in private settings, underscoring the importance of prioritizing public locations to ensure greater effectiveness and replicability of NBS.

Moreover, the proposals span multiple scales, ranging from large-scale projects involving extensive areas and significant financial investment to smaller, localized interventions. This study primarily focuses on the latter, as these targeted, small-scale actions can serve as important catalysts when viewed collectively within the broader urban context. By examining these interventions in an integrated way, their cumulative positive impacts can be enhanced, fostering a more effective and sustainable transformation of the urban environment at the citywide level.

Table 06 presents a comparative overview of the three case study projects discussed in this section.







	GZM – Poland (SALUTE4CE)	**Impulse Region – Germany** (SALUTE4CE)	**Eindhoven – Netherlands** (UNaLab)
Climate (Köppen)	Dfb (humid continental climate)	Cfb/Dfb (temperate oceanic climate/humid continental climate)	Cfb (temperate oceanic climate)
Main environmental challenges	Heat islands, soil sealing, flooding	Heat stress, microclimates, sealed surfaces, biodiversity loss	Urban heat stress, flooding, air quality
Methodological approach	Urban Environmental Acupuncture + NBS	Urban Environmental Acupuncture + NBS	NBS implemented in strategic locations (Without using the term UA)
Type of intervention	Green courtyards, streetscape improvements, pocket parks	Revitalization of vacant lots, sports fields, gardens, green corridors	Transformation of sealed surfaces into green urban infrastructure
Key NBS Strategies	Urban greening, permeable surfaces, green walls, courtyards revitalization, biodiversity promotion	Pocket parks, flowering meadows, green corridors, green roofs/façades, topographic adjustments	Green boulevards, climate-adaptive drainage, green roofs, infiltration planters, swales, green façades, large-scale rainwater retention
Stakeholder Involvement	Workshops, municipal employees, community engagement, local architects	Technical experts, political bodies, property owners, public participation (surveys, workshops)	Living labs, public and stakeholder co-creation, community-driven planning
Scale of intervention	Small to medium-scale, localized actions in selected urban plots	Small-scale, dispersed interventions with varied typologies	Mixed scale: large-scale (e.g., boulevard) and smaller decentralized interventions
Expected results	Improved thermal comfort, water retention, urban biodiversity, community engagement	Enhanced microclimate resilience, increased green coverage, ecological connectivity	Flood mitigation, heat stress reduction, improved air quality, enhanced public space use
Potential for replication	High – based on modular, context-sensitive approaches within urban centers	High – sites serve as prototypes for future applications in similar settings	High – designed as demonstration sites for broader adoption and upscaling

Table 06: Best practices comparative analysis.
Source: The author

3. CASE STUDY: CURITIBA, BRAZIL

3.1 The context of Curitiba

Curitiba is the capital of the Brazilian state of Paraná and the main city of the Curitiba Metropolitan Region (RMC), presented in Figure 69, which is composed of 29 municipalities. The city covers an area of 435.28 km² and, as of 2024, has an estimated population of 1,829,225 residents (IBGE, n.d.), distributed across 10 administrative regions and 75 neighborhoods.

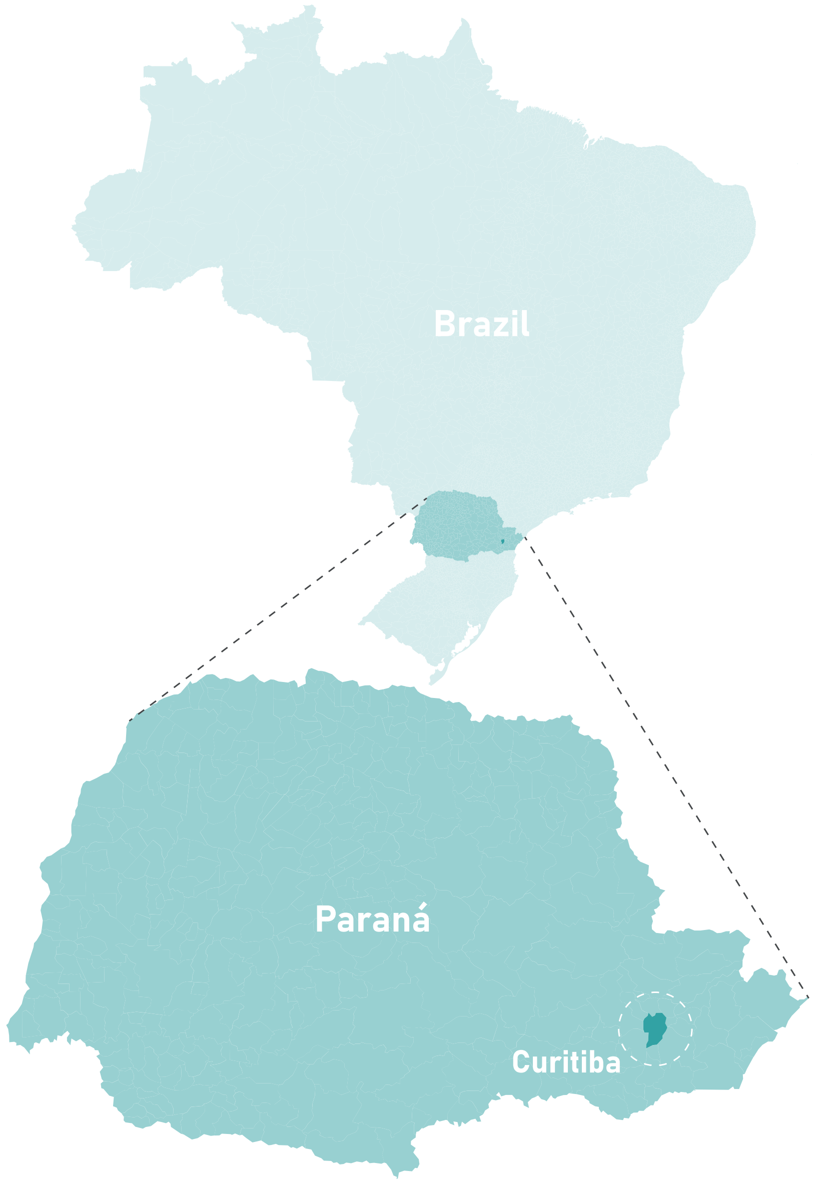


Fig. 69: Curitiba location
Source: The author

3.1.1 Sustainable development background

Known as the Green Capital and Ecological Capital (Rabinovitch & Leitman, 1996; Buccheri Filho, 2012), Curitiba stood out on the urban planning scene during the 1970s. At the time, the municipality implemented important interventions to mitigate risks related to flooding in its watersheds, creating an integrated complex of parks and lagoons. Under the leadership of Mayor Jaime Lerner, these spaces were transformed into living and leisure areas for the community, consolidating the city as a benchmark in sustainable urban planning (Perez-Lancellotti & Ziede, 2020; Rudy et al., 2022).

As previously mentioned, Jaime Lerner was one of the pioneers in introducing and defending the concept of urban acupuncture. In Curitiba there are numerous examples of his interventions, which are considered low-budget and of rapid implementation (Perez-Lancellotti & Ziede, 2020).

The Rua das Flores (Figure 70) is one of the most emblematic examples. The proposal of the pedestrian promenade, located in the central region of Curitiba, initially faced strong public resistance, as many believed that removing a high-traffic road would harm local businesses and reduce accessibility. However, contrary to expectations, the intervention, completed in just 72 hours, proved to be a success. It became Brazil's first pedestrian promenade and quickly inspired similar initiatives in other cities (Lerner, 2014).

Fig. 70: Rua das Flores
Source: André Rodrigues, Gazeta do Povo

Other notable projects include the Ópera de Arame (Figure 71), built in just 60 days as part of a project to revitalize an old quarry, and the Passaúna Park (Figure 72), which covers an area of 6.5 hectares and was completed in just 28 days, with the aim of protecting the Paraná River's water supply (Lerner, 2014).

It is possible to observe, however, that urban interventions at the time were largely characterized by top-down strategies, influenced by the current dictatorial political regime. Only with the re-democratization of the country did a transition begin towards a bottom-up model, which prioritizes greater popular participation in urban planning (Perez-Lancellotti & Ziede, 2020).

Fig. 71: Ópera de Arame
Source: Gazeta do Povo

Fig. 72: Parque Passaúna
Source: Prefeitura municipal de Curitiba

It should also be noted that, initially, these interventions were not focused on tackling the climate crisis. Nevertheless, with growing global concern about the matter and the increasingly evident impacts of climate change in subtropical regions such as Curitiba, the city's urban planning has progressively come to value this agenda. Consequently, the initiatives carried out by Lerner came to be recognized for their multiple benefits in reducing the effects of climate change and improving local resilience (Perez-Lancellotti & Ziede, 2020).

In 2015, additional mitigation and adaptation strategies were officially incorporated into Curitiba's Master Plan (Ordinary Law No. 14.771/2015), under the name "Plano de Mitigação e Adaptação às Mudanças Climáticas". In addition, the city has established partnerships with international organizations, such as Local Governments for Sustainability (ICLEI) and the Cities Climate Leadership Group (C40), with the aim of drawing up inventories of greenhouse gas (GHG) emissions and expanding the capacity of local governments to act (Teixeira & Pessoa, 2020; Evans et al., 2005).

Furthermore, in 2017, Curitiba committed to the 2030 Agenda, aligning its management with the Sustainable Development Goals (SDGs) and the Global Compact, both initiatives promoted by the United Nations (Prefeitura Municipal de Curitiba, 2020b).

The implementation of such actions faces several barriers, one of the main ones being the high cost associated with developing and promoting new strategies (Di Giulio et al., 2017). In Curitiba, for example, obtaining the scientific basis to support decision-making represents a significant challenge. Moreover, there is a need for considerable budgets to maintain the required infrastructure (Prefeitura Municipal de Curitiba, 2020a).

It is also noticeable that, despite the goodwill of political agents and local institutional actors, there is a significant bureaucratic difficulty, which is often due to limited authority or, in other cases, the slowness and complexity of the implementation process (Teixeira & Pessoa, 2020).

Another challenge faced by the city is the lack of popular interest and engagement, and the gap in the dialog between civil society and the government (Prefeitura Municipal de Curitiba, 2020a). In an interview (Teixeira & Pessoa, 2020), the Superintendent of Works and Services at Curitiba's Municipal Environment Secretariat (Interviewee 1) mentioned that, on some occasions, public participation can even be detrimental to the implementation of strategies, due to the absence of technical knowledge and rejection of new projects:

> The participation of civil society actors in decision-making can get in the way in two situations. [...] the lack of technical knowledge; and excessive criticism of the actions created, implemented and improved by management. (Interviewee 1, 2017)

It is therefore possible to recognize how the methodology of urban acupuncture, previously applied in Curitiba's urban development process, can be reinterpreted within the city's current context. Initially implemented through a top-down approach, it now offers the potential to address challenges related to community engagement in urban planning initiatives. Furthermore, as advocated by former mayor Jaime Lerner, it presents a practical means of bypassing excessive bureaucracy through swift implementation and small-scale interventions.

This approach also demonstrates strong potential for supporting mitigation and adaptation efforts in response to urban climate challenges and the broader climate crisis. Its outcomes include enhanced local thermal comfort for residents and increased urban resilience on a citywide scale.

3.1.2 Urban climate

Located at approximately 930 meters above sea level, at latitude 25.5°S and longitude 49°W, Curitiba has a mesothermal climate with mild summers and is defined as Cfb according to the Köppen climate classification, also known as a Temperate oceanic climate (Mendonça & Dubreuil, 2005).

One of the remarkable characteristics of the city's climate is its high daily and annual variability. The average annual temperature is 17°C, with around 20°C during the summer, when absolute temperatures can reach up to 40°C, and around 13°C in winter, with records of negative absolute temperatures, as presented in Table 07. The average annual rainfall is 1550 mm, with the summer months being the wettest and the winter months being the drier (Mendonça & Dubreuil, 2005; Alvares et al., 2013).

The city of Curitiba is particularly noteworthy in urban climate studies due to its marked characteristics in terms of land use and occupation and the distribution of green areas, which are decisive in creating a distinctive local microclimate (Leal, 2012). Various studies confirm the presence of the heat island phenomenon in Curitiba's urban agglomeration, but its characteristics tend to differ from the classic model in some respects.

Table 07: Curitiba's climate, analyzed period 1991-2020
Source: INMET; Instituto das águas do Paraná - adapted by the author

	Min. Temperature (°C)	Mean Temperature (°C)	Max. Temperature (°C)	Rainfall (mm)
Jan	17,60	21,30	27,10	213,5
Feb	17,80	21,40	27,20	184,2
Mar	16,80	20,30	26,10	143
Apr	14,80	18,50	24,40	79,3
May	11,80	15,50	21,10	86,9
Jun	10,30	14,30	20,30	108,8
Jul	9,30	13,80	20,10	95,6
Aug	10,10	14,90	21,90	80,9
Sep	11,90	16,00	22,30	131,1
Oct	13,90	17,70	23,70	152,3
Nov	15,00	18,90	25,00	121,6
Dec	16,70	20,70	26,70	144,6

Mendonça and Dubreuil (2005), using remote sensing techniques, confirmed the presence of a generally warmer and more uniform thermal zone in the urban area compared to the surrounding rural environment. However, they also identified multiple Heat Islands (HIs) interspersed with Cool Islands (CIs) across the intra-urban landscape. The authors suggest that rising temperatures are associated with the expansion of urbanization, while their uneven distribution reflects the varied patterns of land use and land cover.

When analyzing the city's longitudinal profile, Leal (2012) notes that, despite intra-urban thermal variations, it is possible to establish a correlation between central areas—characterized by high occupancy and intense anthropogenic activity—and higher recorded temperatures. In contrast, peripheral residential regions with lower building density tend to exhibit milder temperatures.

According to Dumke, 2007, Curitiba can be described as a polycentric city, characterized by an urban geometry composed of linear, high-rise axes with varying degrees of urban density and irregularly distributed green areas. This sets it apart from the heat island model proposed by Oke (1987), which is typically formed by a centralized, high-rise commercial core surrounded by a gradual decrease in urban density.

The densification and widespread verticalization of the city have taken place along the so-called Structural Axes —urban corridors laid out in a star- or tentacle-like pattern that radiates from and intersects the central area, originally designed to direct urban growth and traffic flow (Danni-Oliveira, 2000), Figure 73 illustrates this urban structure. Zoning regulations in these areas encouraged the development of high-rise buildings along these axes, which have effectively evolved into urban sub-centers. These zones are marked by high population density due to the predominance of commercial and service activities (Young, 2005). As a result, as can be observed in Figure 74 and 75, deep urban canyons emerge, significantly impacting thermal conditions, natural lighting, air circulation, and overall atmospheric quality (Danni-Oliveira, 2000).

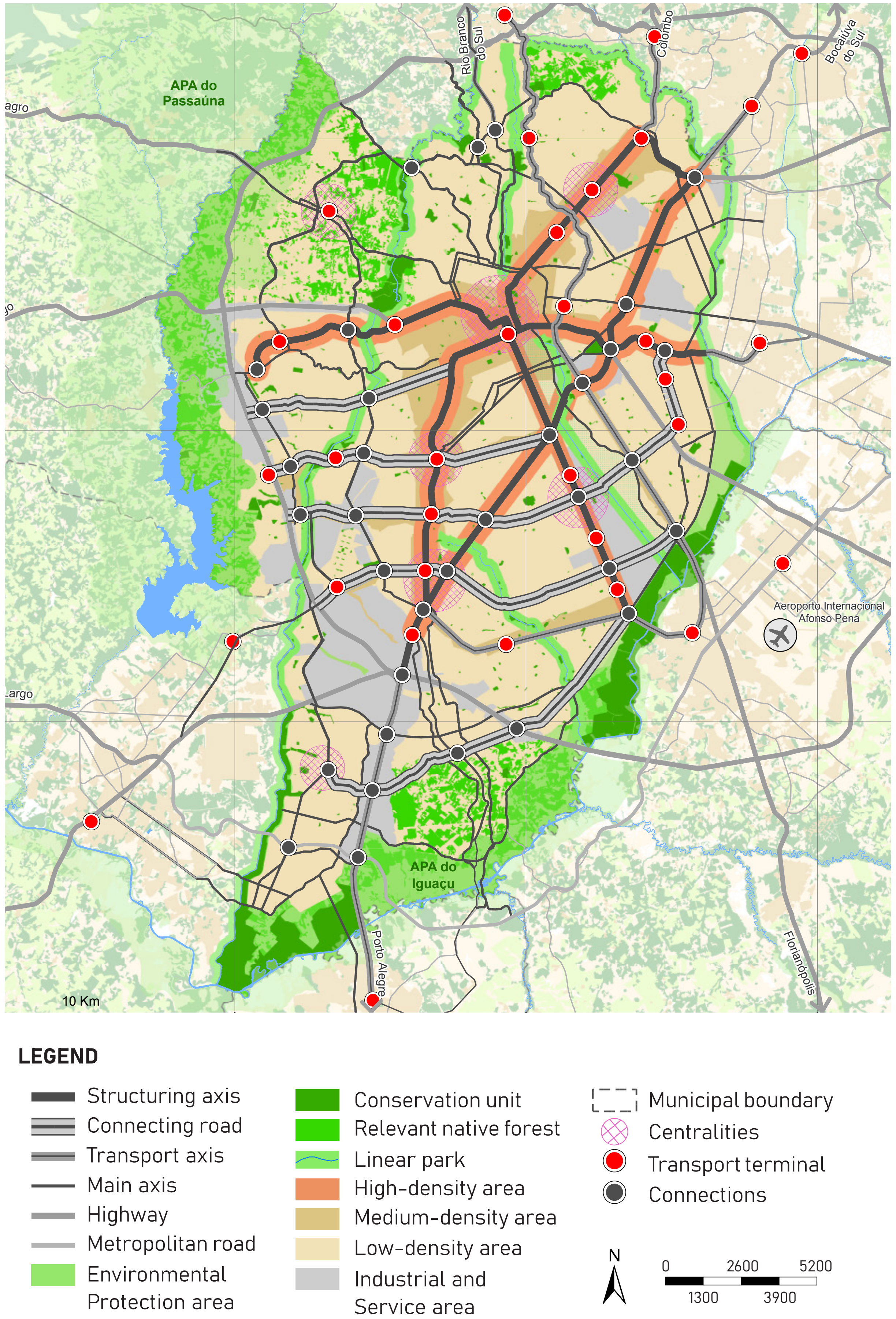


Fig. 73: Curitiba Urban Master Plan.
Source: IPPUC

The pronounced verticalization along these axes creates a concrete barrier that significantly alters surface roughness. This urban structure can either channel winds along the streets or hinder their circulation, depending on local conditions. The formation of these urban canyons facilitates the accumulation of pollutants, a process intensified by the high volume of vehicle traffic typical of these areas (Danni-Oliveira, 2000). Additionally, the height of the buildings reduces sunlight exposure at pedestrian level, especially during the winter months. This configuration proves to be inadequate for the local climate, as it contributes to increased thermal discomfort caused by cold conditions (Suga, 2005).

Fig. 74: Structural Axis - South, Av. República Argentina
Source: Prefeitura de Curitiba

Fig. 75: Structural Axes - North and South
Source: https://blog.construtoralaguna.com.br/

In addition to the structural axes, Lemos (2011) identified that the increase in temperature in urban centers is linked to factors such as high population density, industrial areas, major roadways, and landfills. Moreover, Danni-Oliveira and Mendonça (2000), observed that during radiative nights recorded in 1996 and 1997, the most urbanized areas—especially the city center and surrounding neighborhoods—experienced temperatures 2°C to 3°C higher than those in less developed areas, with the most verticalized regions standing out.

The influence of anthropogenic heat on the local microclimate is evident. Danni-Oliveira (2000) highlights the significant impact of vehicle traffic on the modification of urban climate conditions. Complementing this perspective, Krüger and Rossi (2002), when analyzing seven neighborhoods in the city noted that areas with higher human activity, intense traffic, less vegetation cover, and large impermeable surfaces recorded higher temperatures.

Based on temperature and humidity data collected at 44 points in Curitiba during the four seasons of the year, Leal (2012) identified five groups defined as Microclimatic Units in the intraurban area of the city (Table 08 and Figure 76). The author notes that the areas experiencing the highest temperatures in Curitiba are primarily concentrated in the central and south-central regions of the city, with particular focus on the neighborhoods of Tarumã, Cidade Industrial de Curitiba, and Sítio Cercado. In contrast, the coolest temperatures were recorded in peripheral residential areas located to the north, northwest, and southernmost parts of the municipality, including the neighborhoods of Cachoeira, Barreirinha, Lamenha Pequena, São João, and Santa Cândida.

Temperature variations across the city also reflect the irregular distribution of green areas among its neighborhoods. Currently, 32% of Curitiba's territory is covered by vegetation (Martinez et al., 2023), and as of 2023, the city features 30 parks and 15 woodlands (Curitiba City Hall, June 2023). While the municipality reports a green space index of 69 m² per inhabitant (Curitiba City Hall, September 2023), this metric has been questioned by some researchers, who raise concerns about the criteria used and the spatial distribution of these areas (Mendonça, 2002).

Microclimatic Units	Average Temperature	Common Characteristics
Unit I	Summer: 19.3 to 19.6°C Winter: 12.2 to 12.4°C	Includes points in the traditional center (Central Zone - ZC and Historic Special Sector - SH), with a large number of buildings and concentrated activities. Lack of permeable areas, with urban forests limited to squares.
Unit II	Summer: 18.9 to 19.3°C Winter: 11.4 to 11.9°C	Includes medium-high to medium-density residential areas (Residential zone - ZR4 and ZR3) and areas along structural urban axes (Special Structural Sector - SE). Covers the central-south region, quite urbanized and verticalized, with structural transport axes and high building density along them.
Unit III	Summer: 18.8 to 19.0°C Winter: 11.2 to 11.5°C	Includes low-density residential areas (Social Housing Sector - SEHIS, Residential zone - ZR2 and ZR1). Lack of squares and forests nearby; urban forests limited to squares and street trees.
Unit IV	Summer: 18.6 to 18.8°C Winter: 11.0 to 11.4°C	Includes medium-low density residential areas (Residential zone - ZR2, Social Housing Sector - SEHIS, Special Sector with Environmental Protection Character - SE-CF and High-Density and Connectivity Urban Structuring Corridors - CONEC). This unit is located on the city's outskirts, with points in forested areas.
Unit V	Summer: 18.0 to 18.6°C Winter: 10.9 to 11.3°C	Includes very low-density residential areas (Residential zone - ZR2 and ZR1) or controlled occupation zone (ZR-CON). This unit is on the city's edge, with points in forested areas and near urban parks.

Table 08: Curitiba's Microclimatic Units.
Source: Leal (2012)

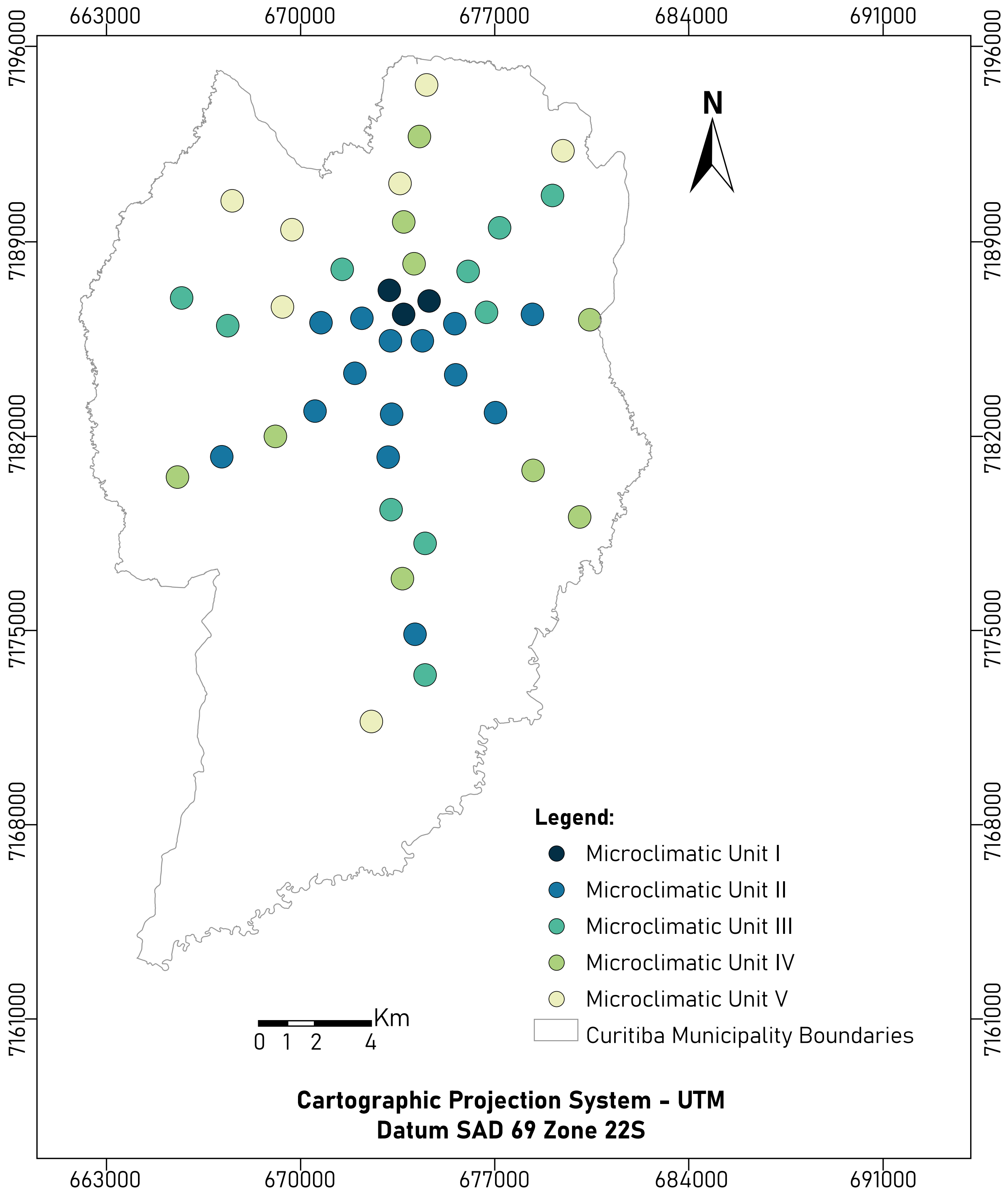


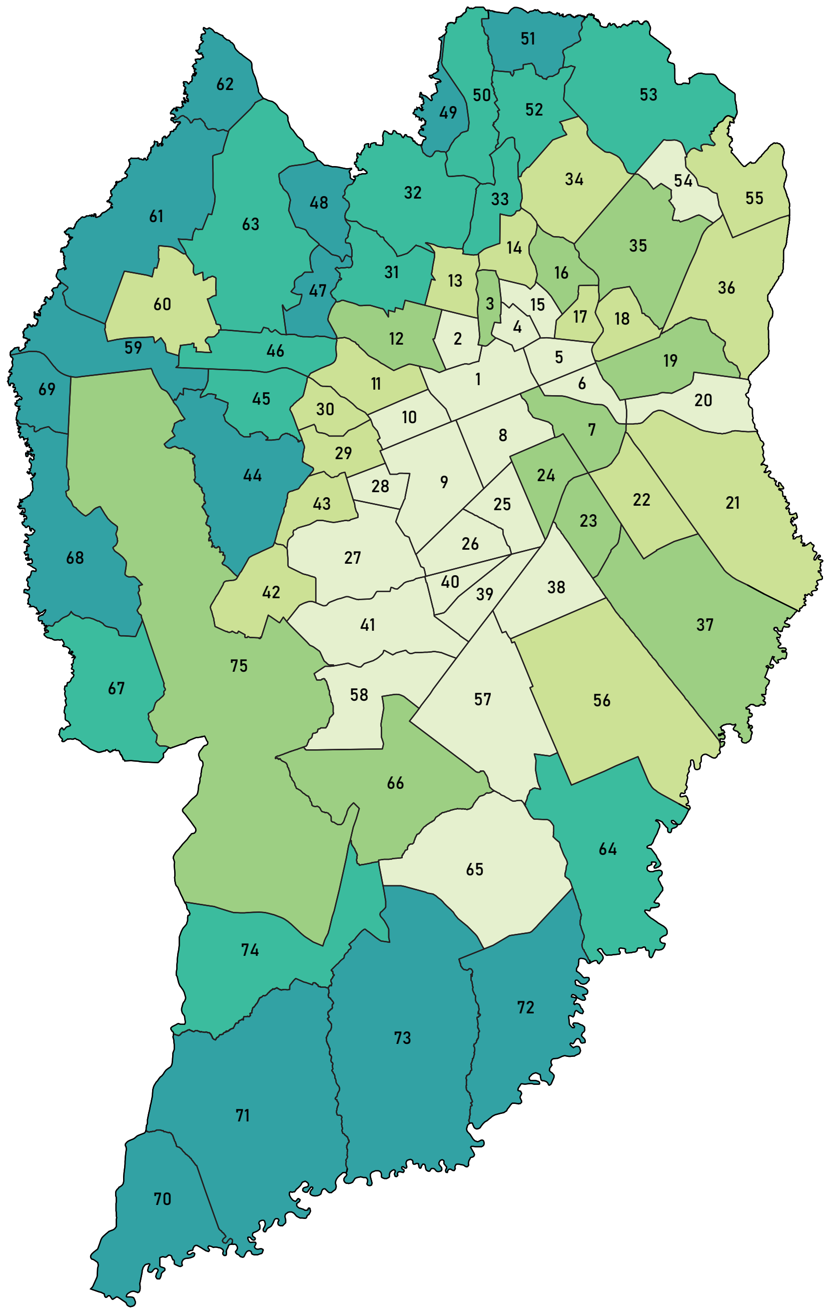
Fig. 76: Curitiba's Microclimatic Units map.
Source: Leal (2012)

Leal (2012) notes that vegetation is unevenly distributed in the city, a finding supported by Martinez et al. (2023), who highlight that municipal parks and woodlands are mostly concentrated in the northern and far southern regions, many of which are located in environmental preservation areas with limited public access. According to the authors, as presented in Figure 77, the central and south-central neighborhoods are particularly underserved in terms of green infrastructure, with vegetation cover as low as 2.7% in Parolin, 3.5% in Capão Raso, and under 5% in Rebouças, Centro, Guaíra, Batel, Lindóia, and Tingui. Hildebrand (2001) further underscores this disparity by pointing to overlapping park influence zones in the north and their absence in the south.

According to Leal (2012), vegetation helps disrupt the continuity of elevated temperatures across Curitiba's urban landscape. Areas with a higher concentration of permeable surfaces, forest fragments, or public green spaces generally recorded lower temperatures and higher relative humidity levels, effectively functioning as urban cooling islands. According to the author, this effect becomes even more pronounced in low-density built environments—such as housing complexes with limited vegetation—which tend to exhibit temperature patterns comparable to those of the city center.

Additionally, Cunico et al. (2002), report differences in the rate of air heating between built-up areas and green public squares, with the latter warming more gradually and showing a delay of 2 hours and 30 minutes, ultimately resulting in lower temperatures in these areas. In a comparative study of tree-lined and non-tree-lined streets in neighboring urban areas, Martini (2013) found that streets with vegetation cover had an average temperature 1.7°C lower than those without tree planting. These tree-lined streets also showed a 6.9% increase in relative humidity and a 0.04 m/s reduction in wind speed. In addition to measuring thermal stress using portable meteorological stations, the author conducted field surveys to assess the diurnal impact of vegetation on outdoor thermal comfort. The results highlighted significant differences in thermal comfort perceptions between exposed areas and those with tree cover.

	Neighborhood	%
1	Centro	4,15
2	São Francisco	5,25
3	Centro cívico	20,86
4	Alto da glória	6,57
5	Alto da Rua XV	5,93
6	Cristo Rei	9,88
7	Jardim Botânico	27,64
8	Rebouças	3,78
9	Água Verde	7,33
10	Batel	4,36
11	Bigorrilho	18,54
12	Mercês	26,32
13	Bom Retiro	16,49
14	Ahú	12,45
15	Juveve	5,02
16	Cabral	26,26
17	Hugo Lange	14,79
18	Jardim Social	14,38
19	Tarumã	22,05
20	Capão da Imbuia	7,94
21	Cajuru	10,65
22	Jardim das Américas	12,07
23	Guabirotuba	11,93
24	Prado Velho	15,03
25	Parolin	2,7
26	Guaíra	4,24
27	Portão	7,87
28	Vila Izabel	8,58
29	Seminário	17,16
30	Campina do Siqueira	12,68
31	Vista Alegre	35,04
32	Pilarzinho	35,81
33	São Lourenço	33,34
34	Boa Vista	14,43
35	Bachacheri	27,93
36	Bairro Alto	10,1
37	Uberaba	21,72
38	Hauer	7,81
39	Fanny	5,87
40	Lindóia	4,72
41	Novo Mundo	5,52
42	Fazendinha	14,61
43	Santa Quitéria	11,25
44	Campo Comprido	50,51
45	Mossunguê	41,67
46	Santo Inácio	43,66
47	Cascatinha	65,27
48	São João	69,59
49	Taboão	60,48
50	Abranches	44,15
51	Cachoeira	56,09
52	Barreirinha	33,64
53	Santa Cândida	42,79
54	Tingui	4,97
55	Atuba	15,13
56	Boqueirão	13,62
57	Xaxim	9,25
58	Capão Raso	3,52
59	Orleans	57,38
60	São Braz	15,95
61	Butiatuvinha	59,82
62	Lamenha Pequena	78,93
63	Santa Felicidade	39,5
64	Alto Boqueirão	45,75
65	Sítio Cercado	9,32
66	Pinheirinho	24,77
67	São Miguel	49,63
68	Augusta	63,61
69	Riviera	74,78
70	Caximba	65,45
71	Campo de Santana	56,55
72	Ganchinho	63,45
73	Umbara	61,4
74	Tatuquara	36,55
75	Cidade Industrial	28



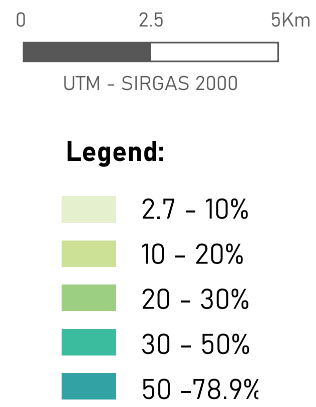


Fig. 77: Spacial distribution and quantification of Curitiba vegetation cover.
Source: Martinez et al.(2023)

Rossi (2012) also investigated pedestrian thermal comfort in the city. The study revealed that during warmer months, thermal comfort was greater in shaded areas with low solar radiation, milder temperatures, and higher humidity and ventilation. Conversely, in colder months, people preferred locations with direct sunlight, higher temperatures, and lower humidity and wind. Thermal sensations varied based on the urban layout and local microclimatic conditions.

Although discomfort from the cold is also mentioned in other studies, which consider the winter season more problematic for city planners than their relatively mild summers (Dumke, 2002; Rossi, 2004; Lima, 2005), Kruger (2015) argues that the advantages brought by the effects of Urban Heat Islands during winter do not necessarily outweigh the effects in summer, as they can be detrimental to indoor thermal comfort by increasing heat stress, especially in low-cost housing. Schmitz (2014) supports this claim by concluding in her research that high temperatures caused by intense urbanization and global warming will also reduce thermal comfort in outdoor spaces, as they amplify extreme indicators for summer, but not for winter.

To analyze the city's thermal comfort in relation to its climate, Krüger et al. (2018) calibrated the Physiological Equivalent Temperature (PET) index for outdoor environments in Curitiba. The study revealed that the local population exhibits a higher tolerance to both cold and heat compared to values reported in European studies, along with a broader thermal comfort range. However, due to limited data,only the indices of "slight cold stress," "no thermal stress," and "slight heat stress" could be established, This suggests that temperatures falling outside these ranges are likely to result in greater discomfort. The established categories are as follows:

Slight cold stress: temperatures below 13°C

No thermal stress: range from 13°C to 25°C

Slight heat stress: range from 25°C to 37°C

3.1.3 Climate records and trends

Analyzing Curitiba's historical temperature records (Figure 78), it is possible to observe an increase in the mean annual temperature of approximately 0.01°C each year from 1960 on, and this trend intensifies from 1980 onwards when the variation becomes +0.02°C. The growth is also evident in the average maximum and average minimum annual temperatures while maintaining a constant temperature range, with a greater number of days with temperatures above 30°C, especially after the 2000s, and a reduction in negative temperatures in the city (Prefeitura Municipal de Curitiba, 2020a; Mendonça, F. & Castelhano, F., 2019).

When examining the projection provided by the municipality for the years 2020 to 2100 (Figure 79), there is an even sharper increase, of an average of +0.05°C per year, reaching a total of approximately +4°C for the period, and an annual average of 26.1°C in 2099. This value is much higher than the basic climatic parameters for the annual average attested by the National

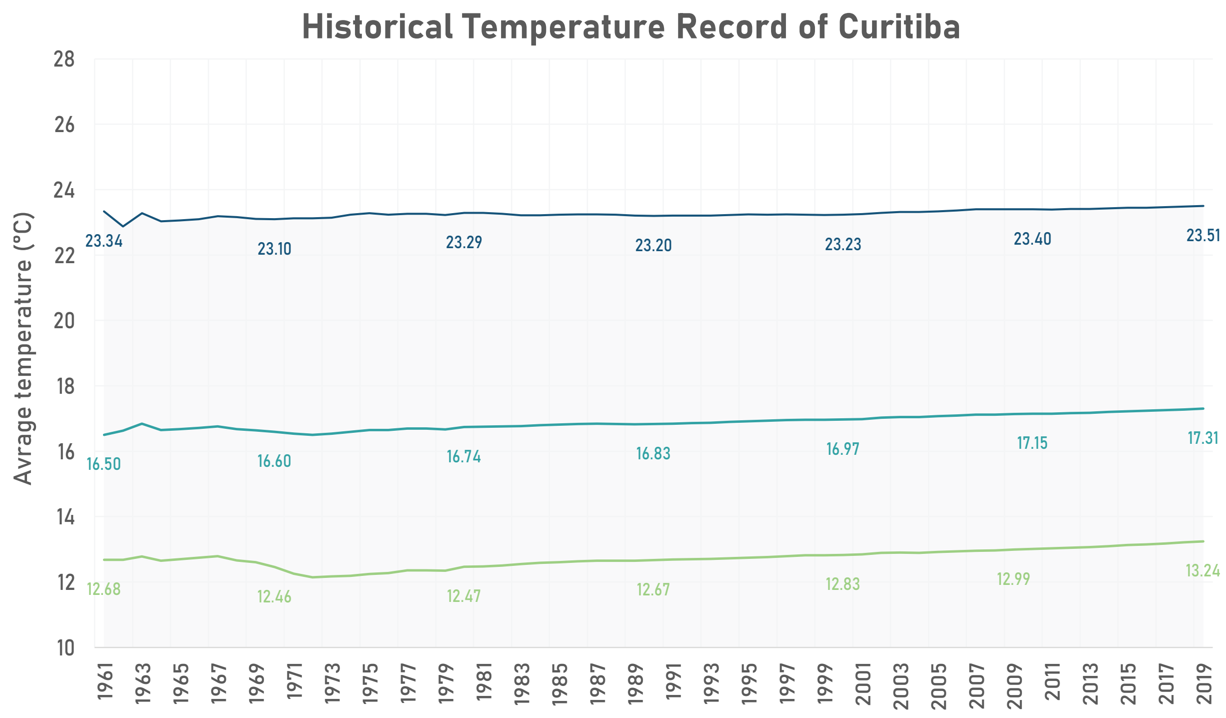


Fig. 78: Historical temperature record of Curitiba.
Source: Prefeitura Municipal de Curitiba (2020a)

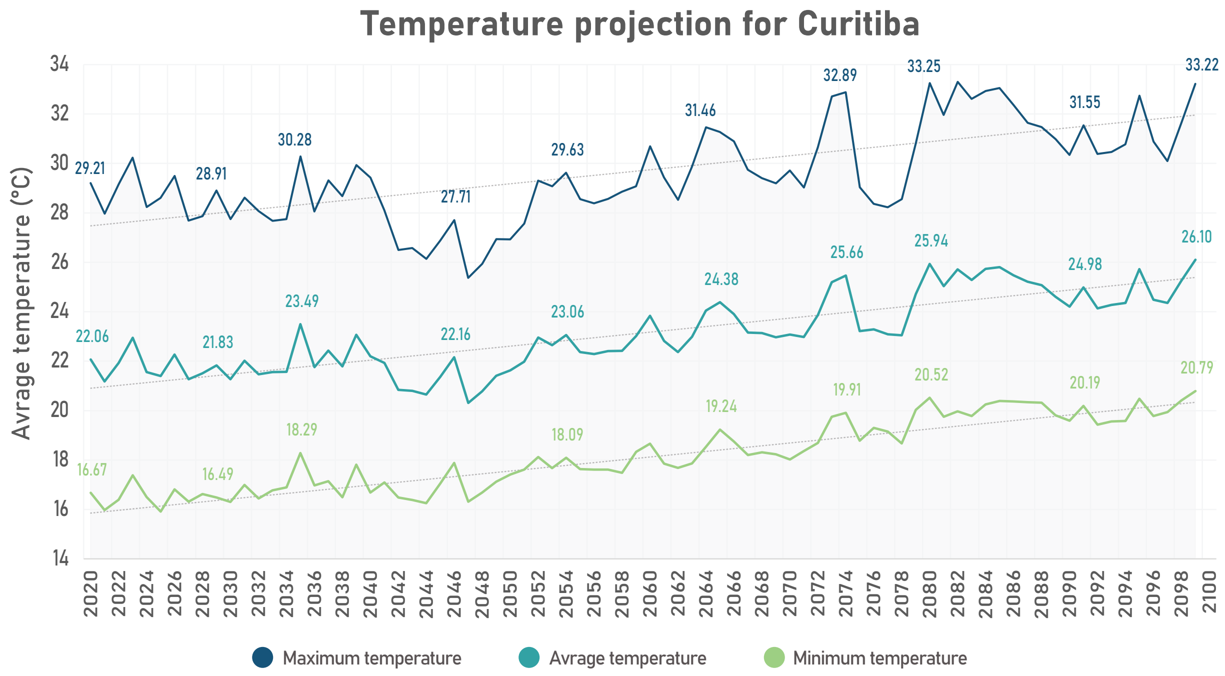


Fig. 79: Temperature projection for Curitiba. Source: Prefeitura Municipal de Curitiba (2020a)

Institute of Meteorology for the period 1991 to 2020 of 17.8°C (Prefeitura Municipal de Curitiba, 2020a; INMET, n.d.). This rise not only intensifies thermal discomfort and the occurrence of extreme weather phenomena, but can also favor the proliferation of epidemics previously attenuated by the local climate, such as dengue, Zika, and other arboviruses (Mendonça & Castelhano, 2019).

According to the study conducted by Silveira et al. (2019), the number of heat wave events in the city has shown an upward trend in frequency, duration, and intensity. Between 1970 and 2016, 47 such events were recorded, increasing from approximately 0.1 per year at the beginning of the assessment period to nearly three per year by the end (Figure 80). As illustrated in Figure 81, the majority of events occurred during the winter (42.5%, or 20 cases), followed by spring (38.3%, or 18), autumn (12.8%, or 6), and summer (6.4%, or 3), although summer registered the most intense events (Figure 82).

Figures 83 and 84 further highlight a trend toward increasingly intense and prolonged heat waves, with average temperatures rising by nearly 2°C over the study period. Event durations also grew, from around 2 days to approximately 3.1 days, peaking at 4.8 days in the 2000s.

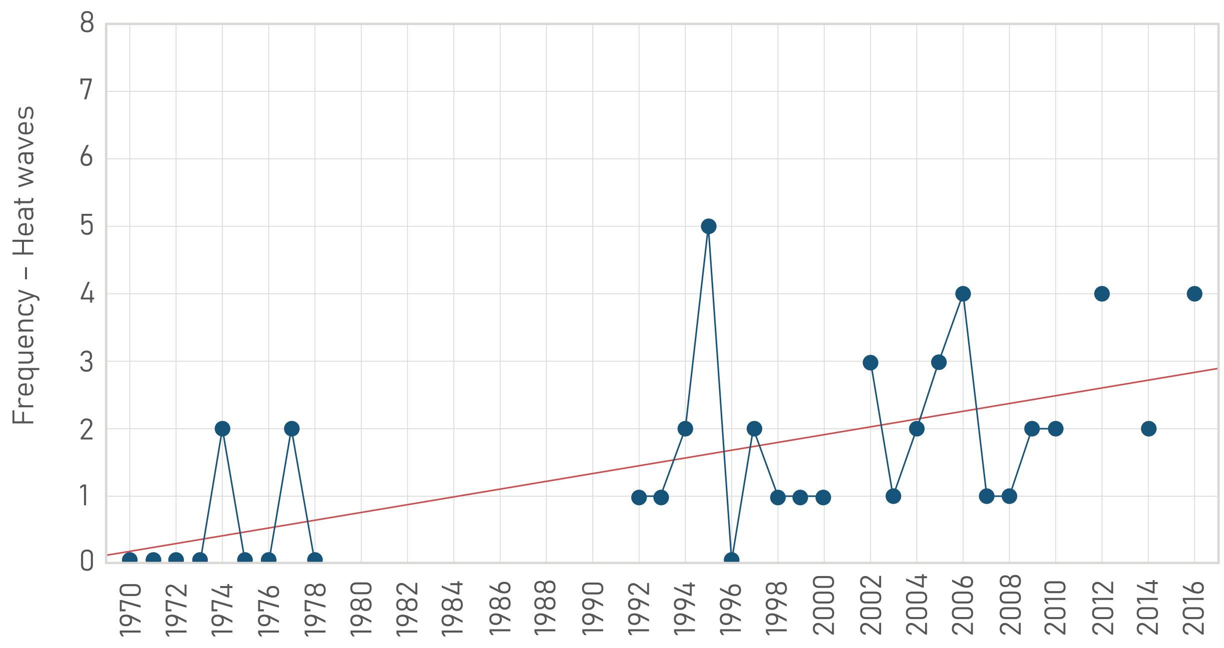


Fig. 80: Annual Frequency of Heat Waves. Note: the absence of markers indicates years with no occurrences, not data gaps, except for the years 1979–1991, 2001, 2011, 2013, and 2015. Source: Silveira et al. (2019)

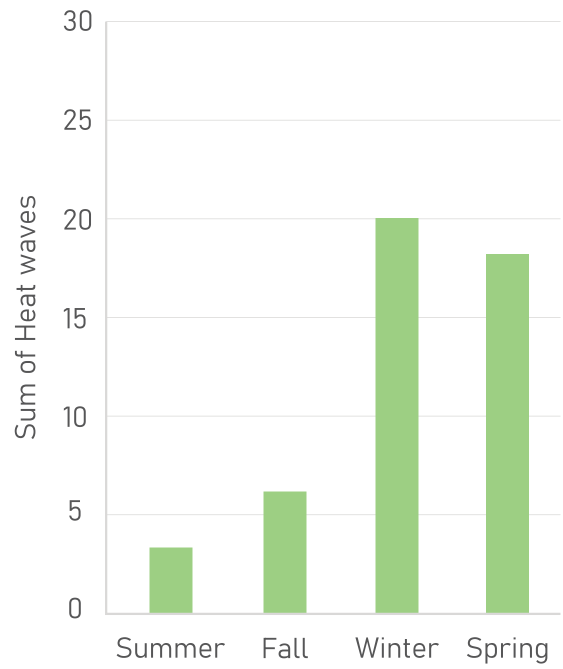


Fig. 81: Sum of Heat Waves by Season Over the 30-Year Analysis Period. Source: Silveira et al. (2019) - adapted by the author

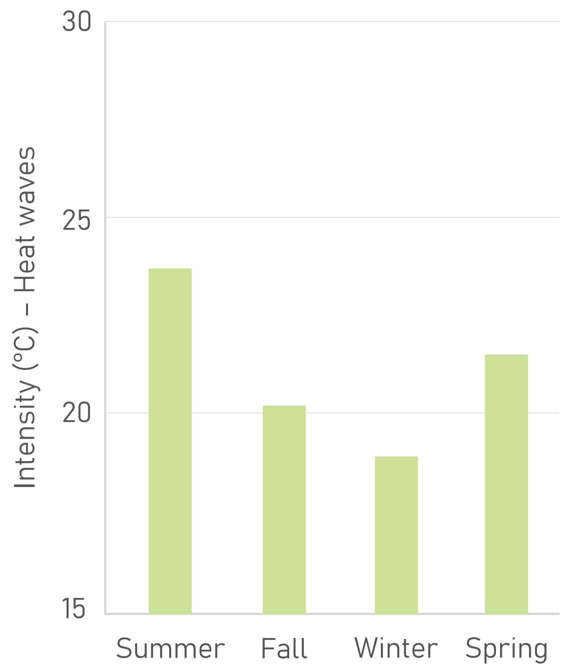


Fig. 82: Average Heat Wave Intensity by Season Over the 30-Year Analysis Period. Source: Silveira et al. (2019) - adapted by the author

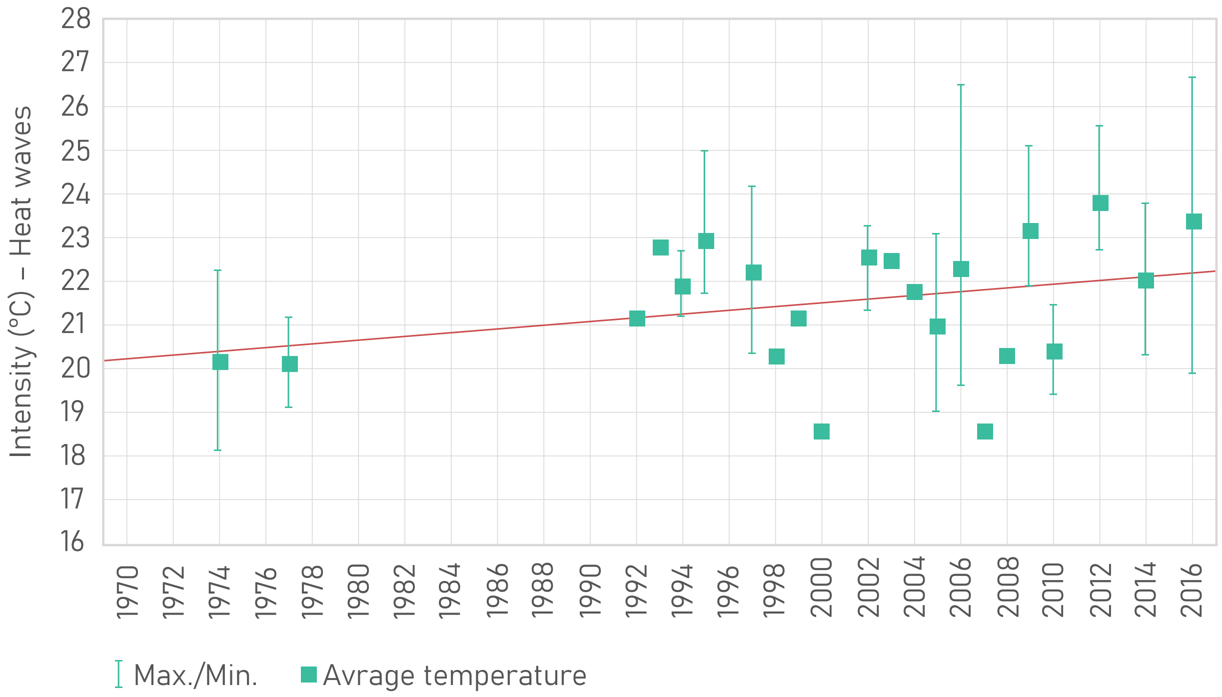


Fig. 83: Annual Average and Extreme Intensity of Heat Waves. Note: the absence of markers indicates years with no occurrences, not data gaps, except for the years 1979–1991, 2001, 2011, 2013, and 2015.
Source: Silveira et al. (2019)

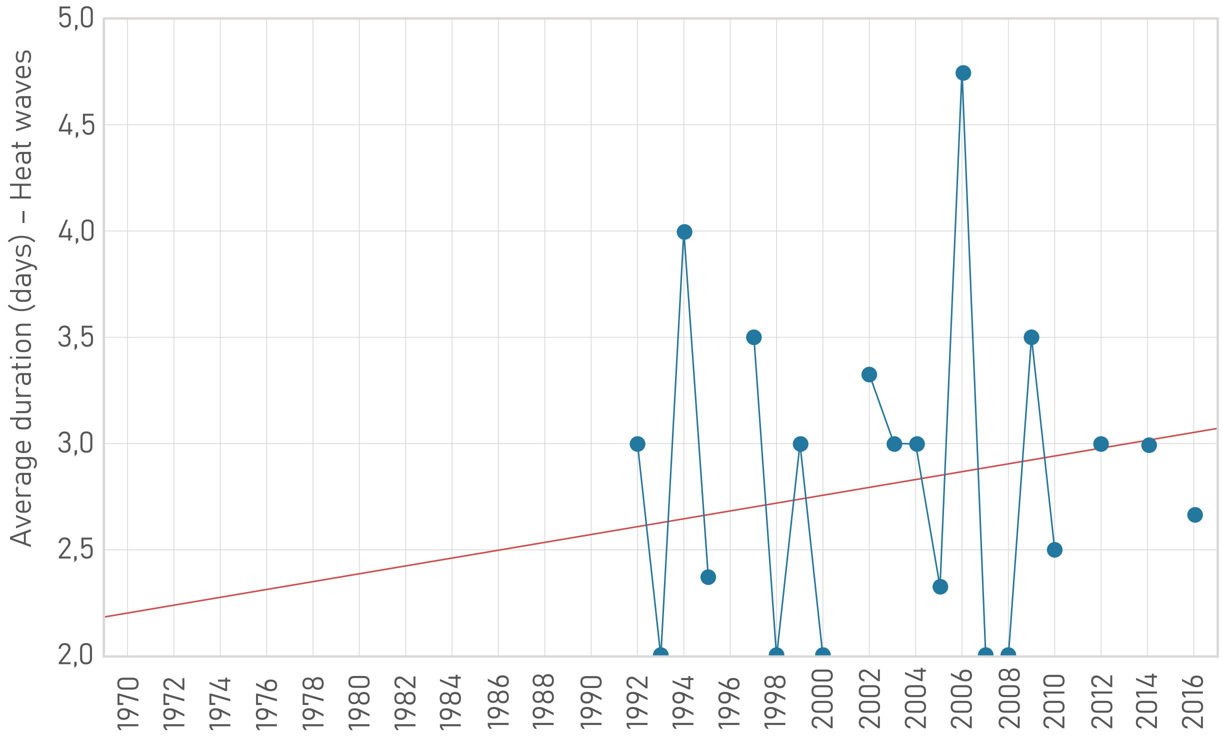


Fig. 84: Annual Average Duration of Heat Waves. Note: the absence of markers indicates years with no occurrences, not data gaps, except for the years 1979–1991, 2001, 2011, 2013, and 2015.
Source: Silveira et al. (2019)

Regarding average monthly rainfall, there has been an increase in rainy periods since the 1980s, accompanied, paradoxically, by a decline in relative humidity in the city (Figure 85). Mendonça & Castelhano (2019) also observed a greater overall rainfall volume, though this does not correspond to more rainy days. This pattern suggests growing irregularity in precipitation, leading to a higher occurrence of extreme weather events. These include prolonged droughts alternating with sporadic but intense storms, resulting in flooding, water shortages, and heightened thermal discomfort (Prefeitura Municipal de Curitiba, 2020a).

With the aim of analyzing and mitigating the risks associated with these events, the city of Curitiba, in 2020, developed risk degree maps for the main threats affecting the municipality, based on a retrospective data analysis. The adopted risk definition considers the interrelation of three factors: the threat posed by hazardous events or trends, the exposure of different regions to these events, and the vulnerability of these areas in terms of their resilience capacity (Prefeitura Municipal de Curitiba, 2020a).

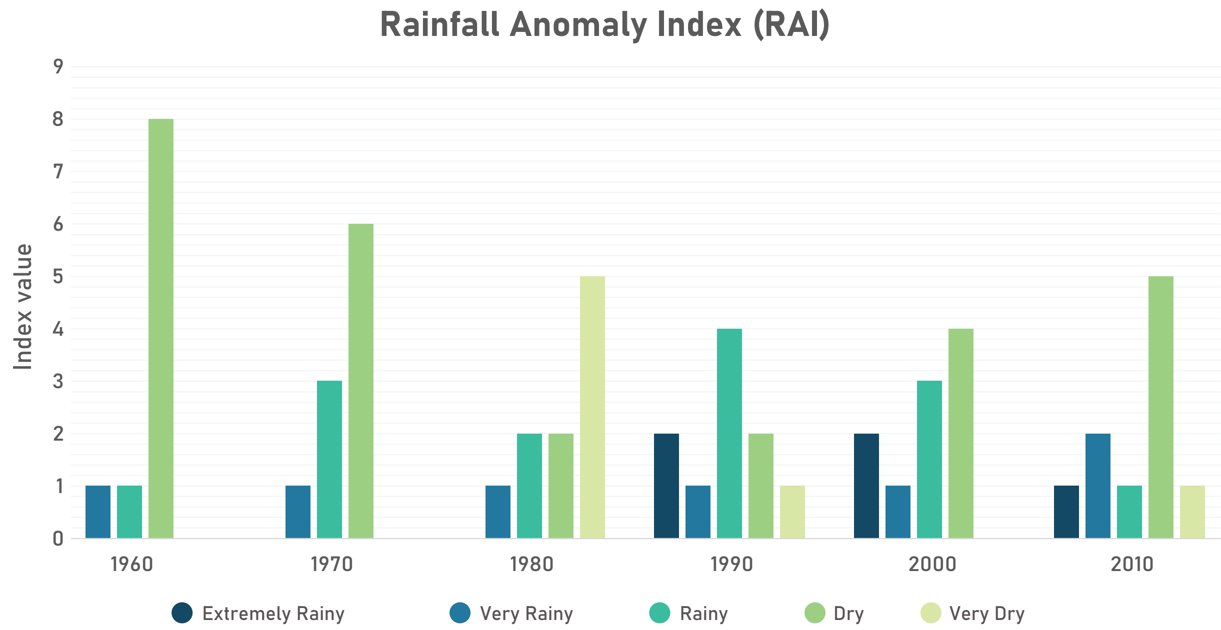


Fig. 85: Rainfall anomaly index for Curitiba
Source: Prefeitura Municipal de Curitiba, 2020a

The first two identified threats are directly related to the city's drainage system's inability to efficiently channel excess water. **Inundation** is characterized by the overflow of water bodies due to heavy rainfall, whereas **flooding**, unlike the former, may or may not be associated with water bodies and is often caused by poor water accumulation management (Prefeitura Municipal de Curitiba, 2020a).

A significant portion of Curitiba's central region lies within the Belém River watershed, where the natural river network has been progressively drained and channeled over time. Additionally, extensive urban impermeabilization has greatly diminished the area's resilience to extreme weather events (Rudy et al., 2022). The consequences of these factors are illustrated in Figures 86 and 87, which show, respectively, the projected inundation and flood risk analysis maps for Curitiba in 2030.

Another significant threat is the presence of **areas susceptible to heat waves** (Figure 88). These events are closely linked to highly urbanized regions, characterized by limited green space coverage and the replacement of native vegetation with impermeable surfaces (Prefeitura Municipal de Curitiba, 2020a). Densely built-up areas with intense human activity tend to record higher temperatures compared to peripheral regions (Oke, 1974). As observed by Leal et al. (2014), the distribution of green spaces in Curitiba is uneven, leading to distinct microclimates. Areas with greater vegetation cover benefit from cooler temperatures and higher humidity, while high-density urban zones, such as the Centro district (1), experience significantly warmer conditions. These findings underscore the crucial role of public green spaces in climate regulation and urban thermal comfort.

Finally, the last risk analyzed is **landslides**, characterized by the movement of solid materials such as soil, rocks, and vegetation along steep inclines. These events primarily occur in areas with high slopes and a history of native vegetation removal. Figure 89 highlights that these events are most concentrated in the northern region of the municipality (Prefeitura Municipal de Curitiba, 2020a).

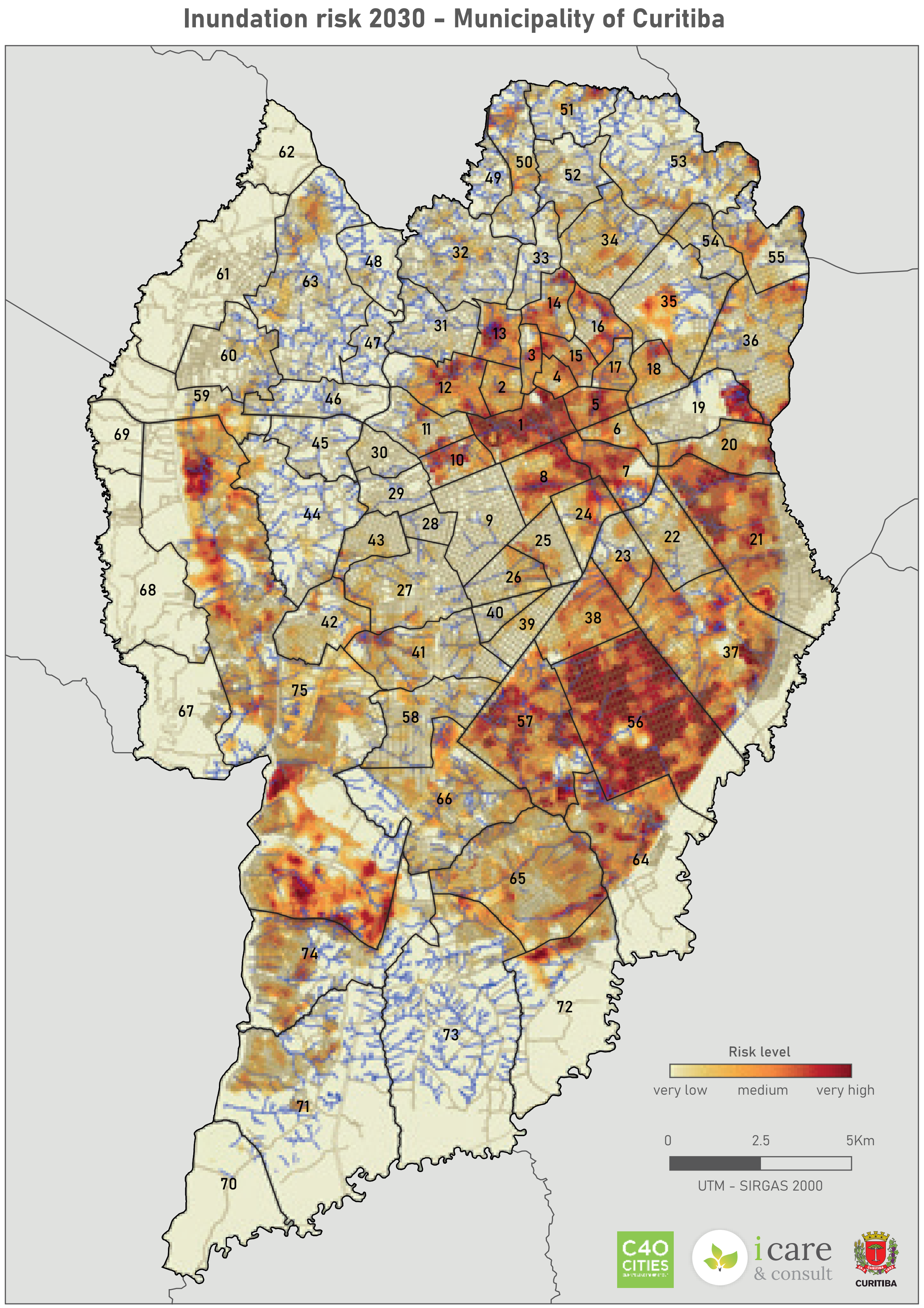


Fig. 86: Inundation risk 2030 - Municipality of Curitiba.
Source: Prefeitura Municipal de Curitiba (2020a)

Flood risk 2030 - Municipality of Curitiba

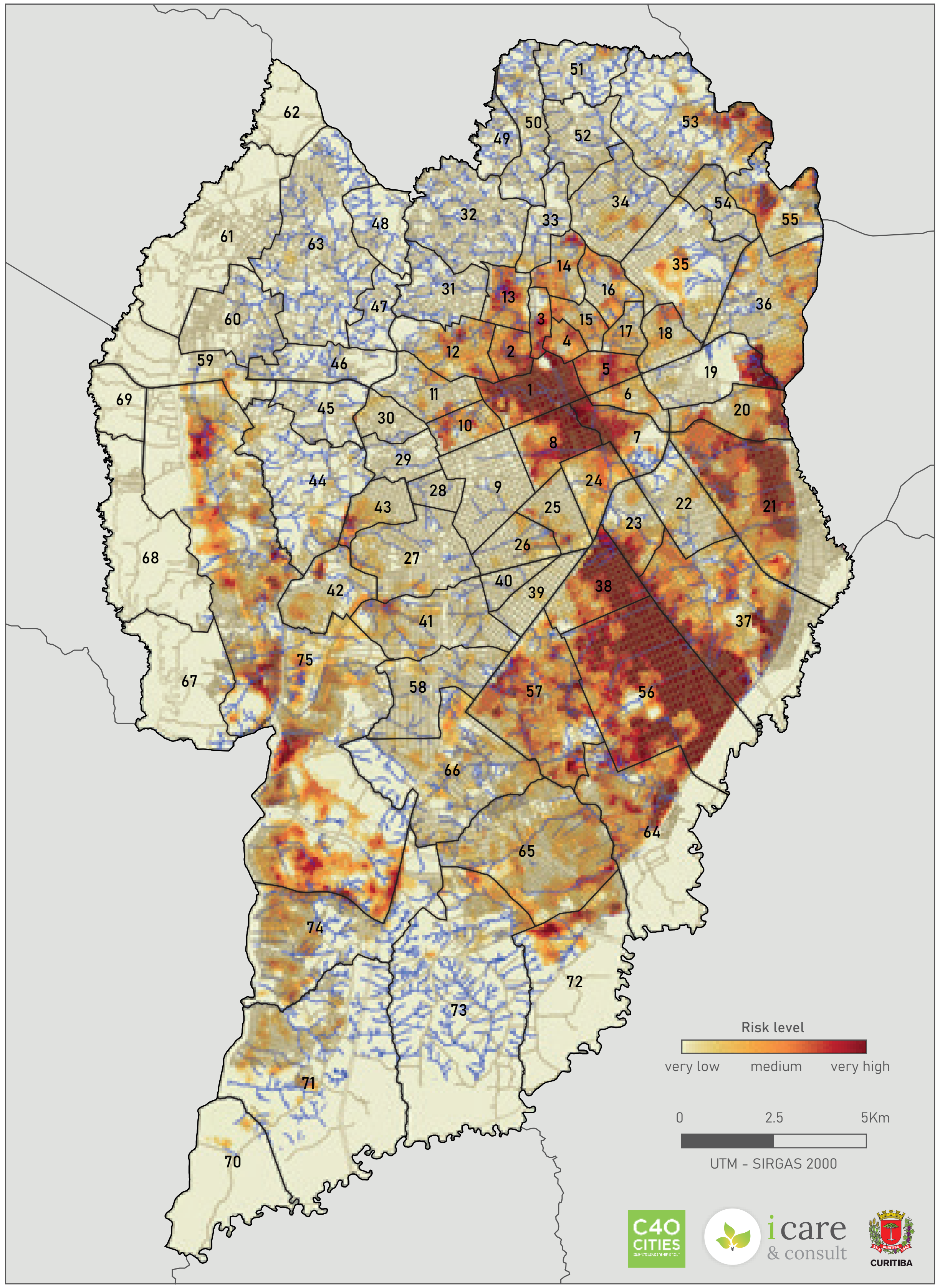


Fig. 87: Flood risk 2030 - Municipality of Curitiba.
Source: Prefeitura Municipal de Curitiba (2020a)

Heat waves risk 2030* - Municipality of Curitiba

*Susceptibility to impact during a heatwave event

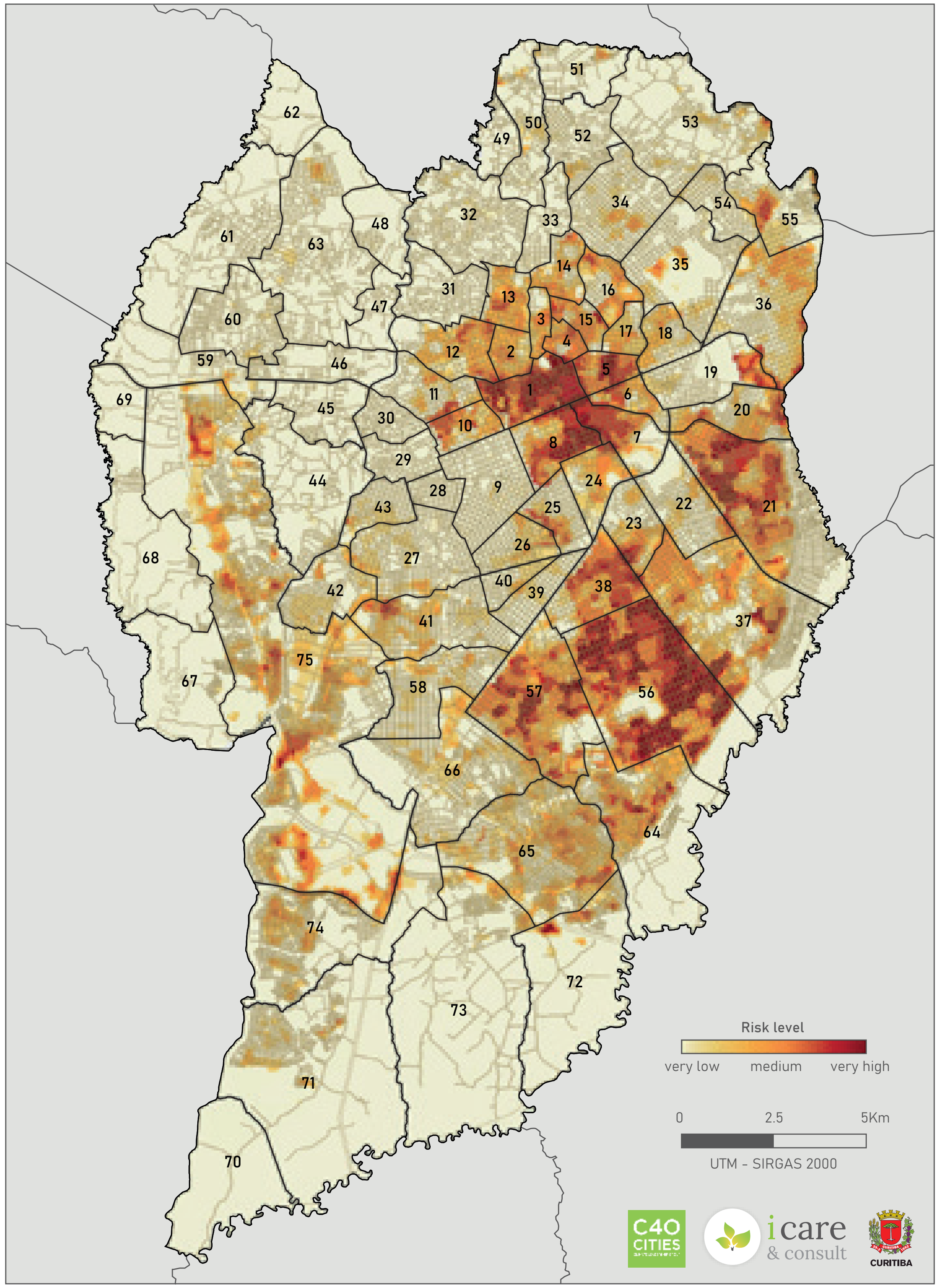


Fig. 88: Heat waves risk 2030 - Municipality of Curitiba.
Source: Prefeitura Municipal de Curitiba (2020a)

Landslides risk 2030 - Municipality of Curitiba

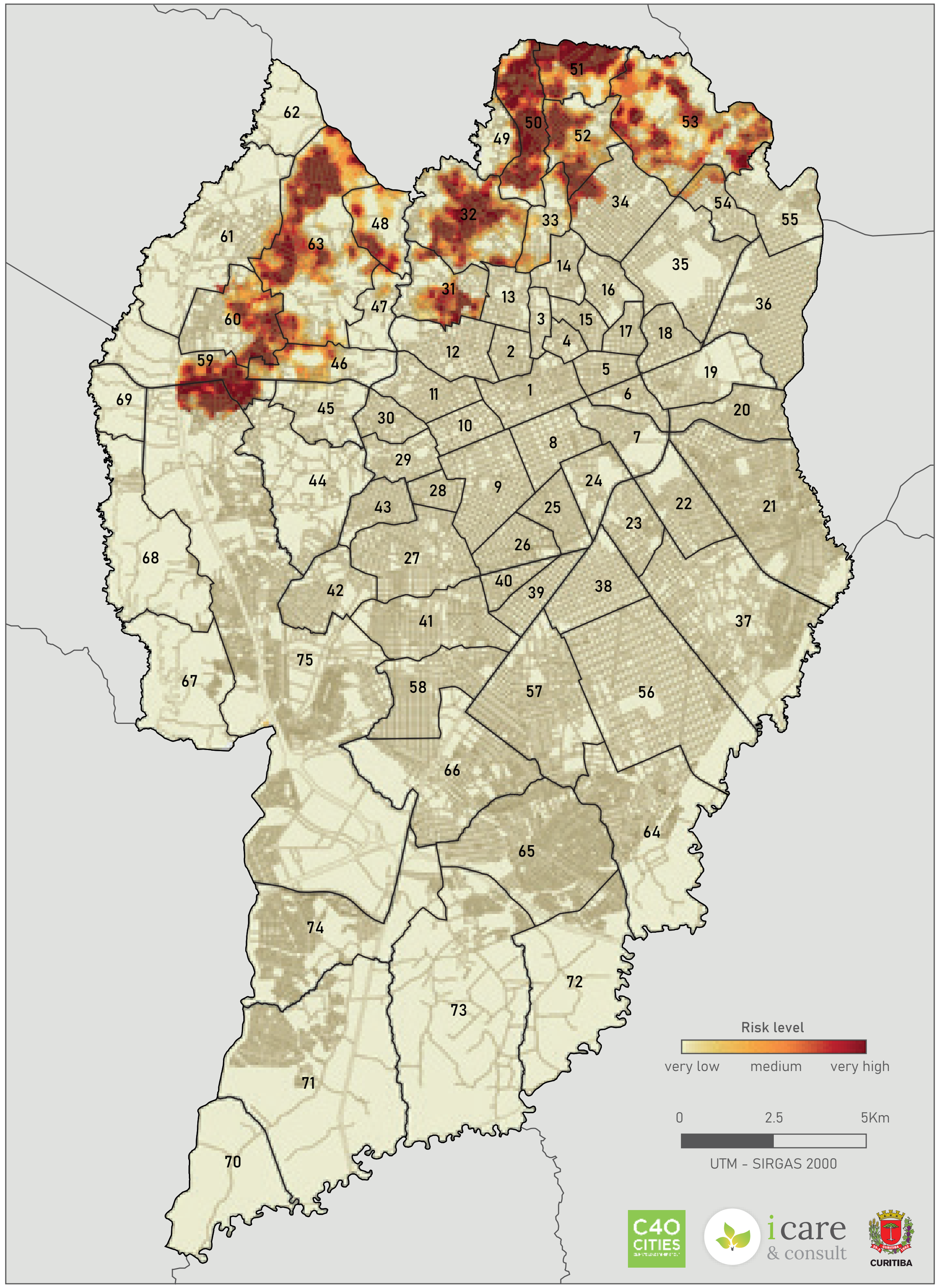


Fig. 89: Landslides risk 2030 - Municipality of Curitiba.
Source: Prefeitura Municipal de Curitiba (2020a)

The graphical analysis suggests that, overall, the highest-risk areas for various threats are concentrated in both the central and eastern parts of the city.

In the central region, neighborhoods such as Centro (1), Alto da XV (5), Jardim Botânico (7), and Rebouças (8) stand out as particularly at risk. Meanwhile, in the eastern portion of Curitiba, areas including Cajuru (21), Boqueirão (56), and Xaxim (57) also exhibit significant susceptibility to environmental threats. These regions share common urban characteristics that contribute to their susceptibility, making them focal points for climate-related challenges and infrastructural vulnerabilities.

Both areas are defined by a high degree of urbanization, though they differ in their development patterns and historical growth. In the central region, temperature variations compared to the city's outer districts reflect the well-documented urban heat island effect described by Oke (1974). This area is highly consolidated, featuring dense construction, heavy vehicular traffic, and a scarcity of permeable surfaces, all of which contribute to elevated temperatures and reduced resilience to climate extremes.

On the other hand, the eastern region has undergone more recent urban expansion, characterized by rapid population growth and the proliferation of housing developments with smaller plots and minimal tree cover. These urbanization patterns further intensify the risks associated with extreme weather events, exacerbating both environmental and social challenges (Leal et al., 2014).

3.2 Neighborhood scale

3.2.1 Centro and Rebouças neighborhoods

Based on the previously discussed data, two neighborhoods were selected as the focus of this study: Centro and the adjacent Rebouças (Figure 90). These areas represent key zones of urban centrality and are crossed by major structural axes in the city.

According to Leal (2012), these areas are classified as Microclimatic Units I and II (Table 08 and Figure 76), which are characterized by higher temperatures compared to other intra-urban zones. This thermal condition is further intensified by the low vegetation cover in both neighborhoods, as shown in the green space distribution map (Figure 77): Centro has only 4.15% vegetation cover, and Rebouças 3.78%, ranking them among the five least vegetated neighborhoods out of the city's 75 (Martinez et al., 2023). Additionally, as noted in the previous section, these areas are also designated as high-risk zones for flooding, inundation, and heat waves, reinforcing their environmental and urban vulnerability.

Based on the data from the 2010 Demographic Census (IPPUC, 2015), the Centro neighborhood encompasses a total area of 328 hectares and is home to a population of 37.283 residents, resulting in a population density of approximately 113.66 inhabitants per hectare. The demographic structure of the neighborhood is predominantly characterized by a majority of young individuals and adults within the economically active age group, reflecting its role as a vibrant urban area with significant social and economic activity.

As presented in Figure 91 and 92, the neighborhood comprises five different zones according to Curitiba's zoning legislation (Law No. 15.511, 2019). Among them, key areas characterized by their unique functions and features include the city's Historical zone, characterized by narrow streets and low-rise buildings of cultural and architectural value; the Central zone, marked by high density, intense urbanization, and a mix of commercial and service activities; and the Structural Axis zone, designated to accommodate high-density corridors and integrated transportation systems.

Adjacent to Centro, the Rebouças neighborhood occupies an area of 297 hectares and has a population of 14.888 residents, yielding a population density of approximately 50.12 inhabitants per hectare, according to the 2010 Demographic Census (IPPUC, 2015). In line with Centro's demographic profile, the population of Rebouças is predominantly composed of young individuals and adults within the economically active age bracket, indicating a similarly dynamic and labor-active community. As illustrated in Figure 91 and 92, the district is constituted by five zoning areas (Law No. 15.511, 2019). In addition to sharing the same structural axis as Centro, another notable zone in the region is the Marechal Floriano Axis, a key mobility corridor characterized by mixed-use development. Rebouças also includes large residential areas of medium to low density, as well as the Vale do Pinhão zone—formerly an industrial area, now designated for urban redevelopment with mixed-use and flexible density.

An examination of vegetation cover across both districts (Figure 93) indicates that the majority of green spaces are predominantly concentrated in public squares—especially within the Centro area—and along select streets. However, it is also possible to observe an increase in vegetation presence within residential zoning areas.

Regarding peak traffic hours in the neighborhoods—based on weekday data collected at 6 p.m. (Figure 94)—it is evident that the highest traffic volumes are concentrated in the Centro area. In contrast, the Rebouças neighborhood experiences significant traffic primarily along a limited number of main corridors, indicating a more localized traffic flow pattern in comparison to the broader congestion observed in Centro.

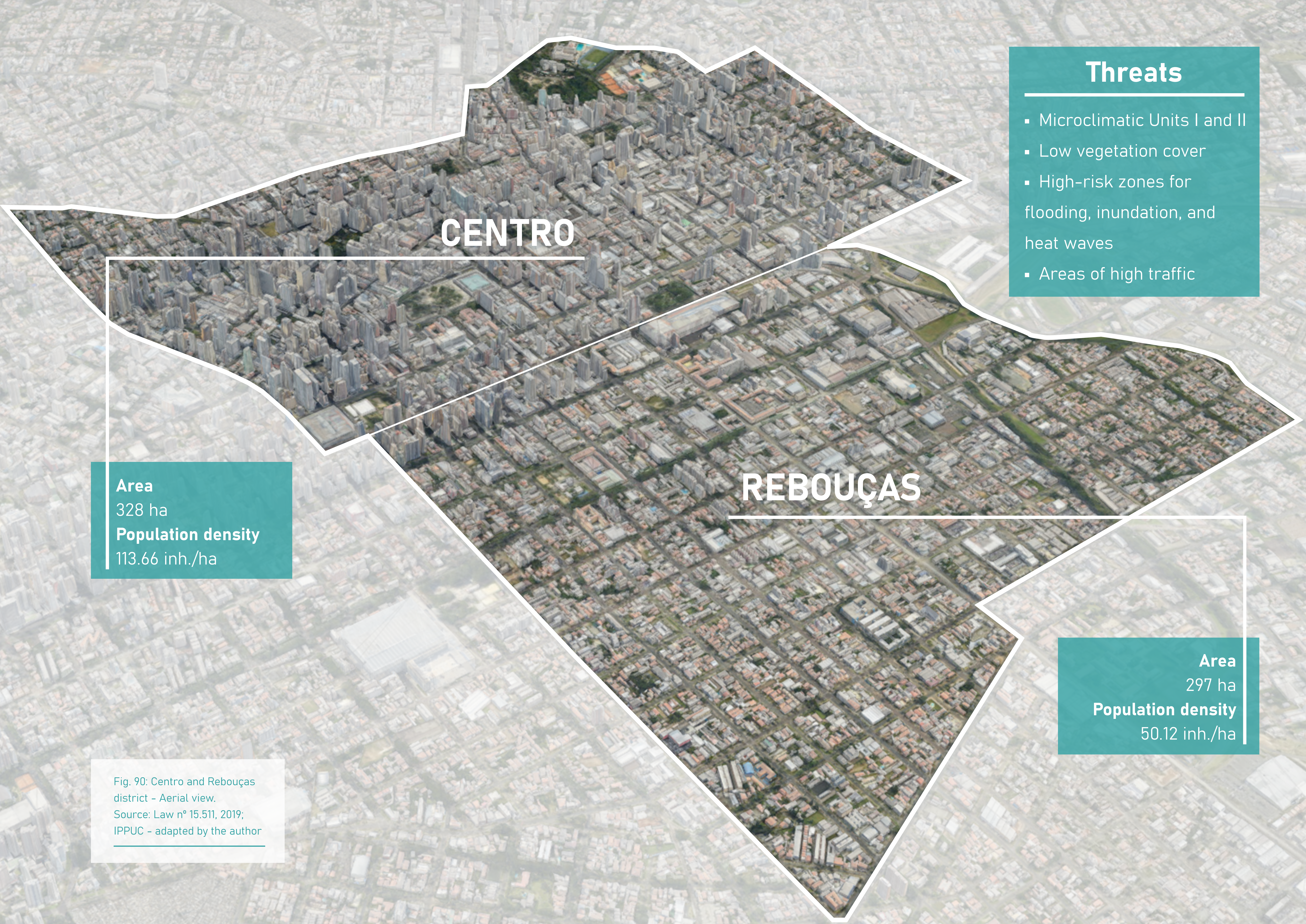


Fig. 90: Centro and Rebouças district - Aerial view.
Source: Law nº 15.511, 2019; IPPUC - adapted by the author

Fig. 91: Centro and Rebouças district - Zoning Aerial view. Source: Law nº 15.511, 2019; IPPUC - adapted by the author

Fig. 92: Centro and Rebouças district - Zoning map
Source: Law nº 15.511, 2019; IPPUC - adapted by the author

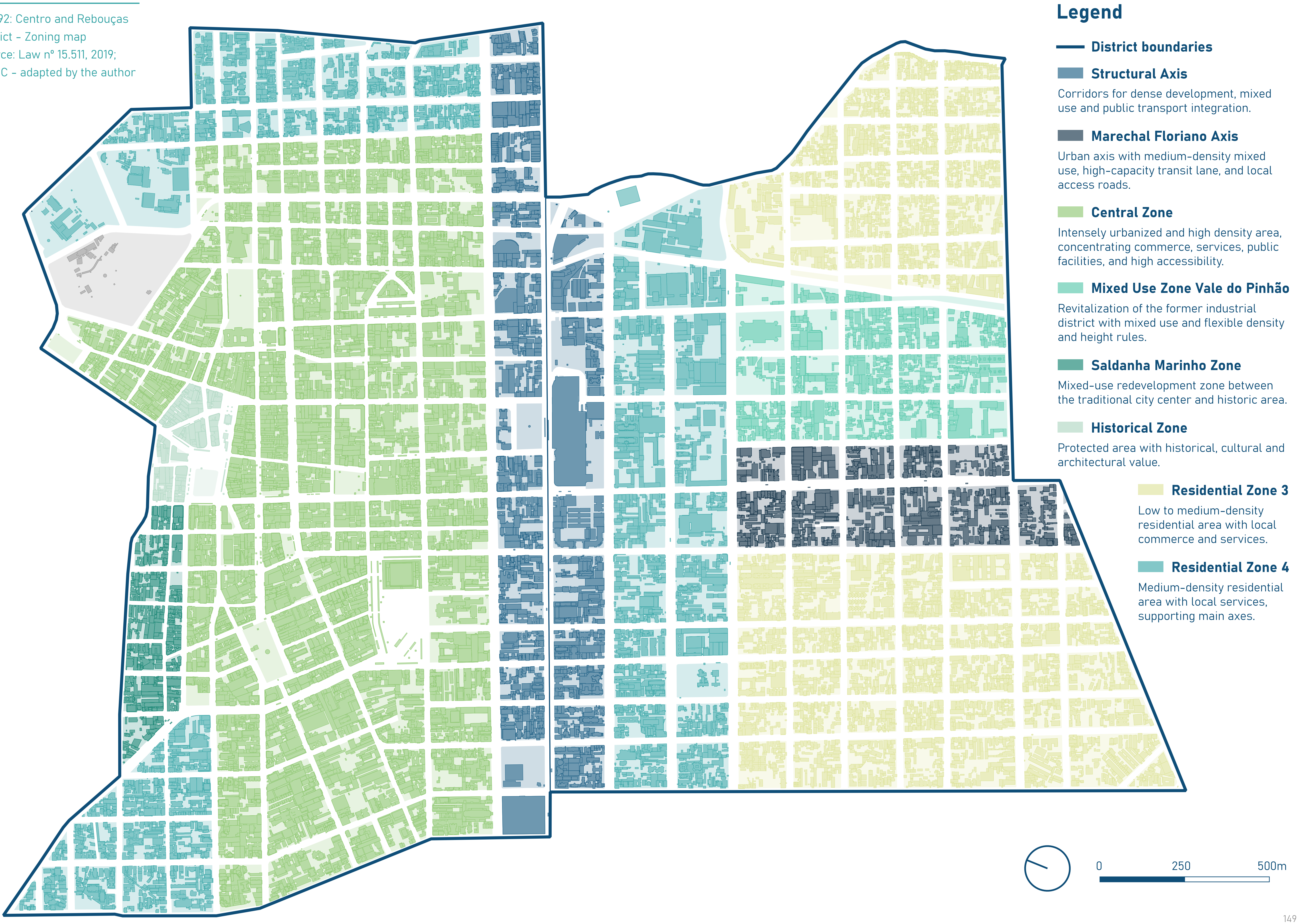


Fig. 93: Centro and Rebouças district - Green areas
Source: IPPUC - adapted by the author

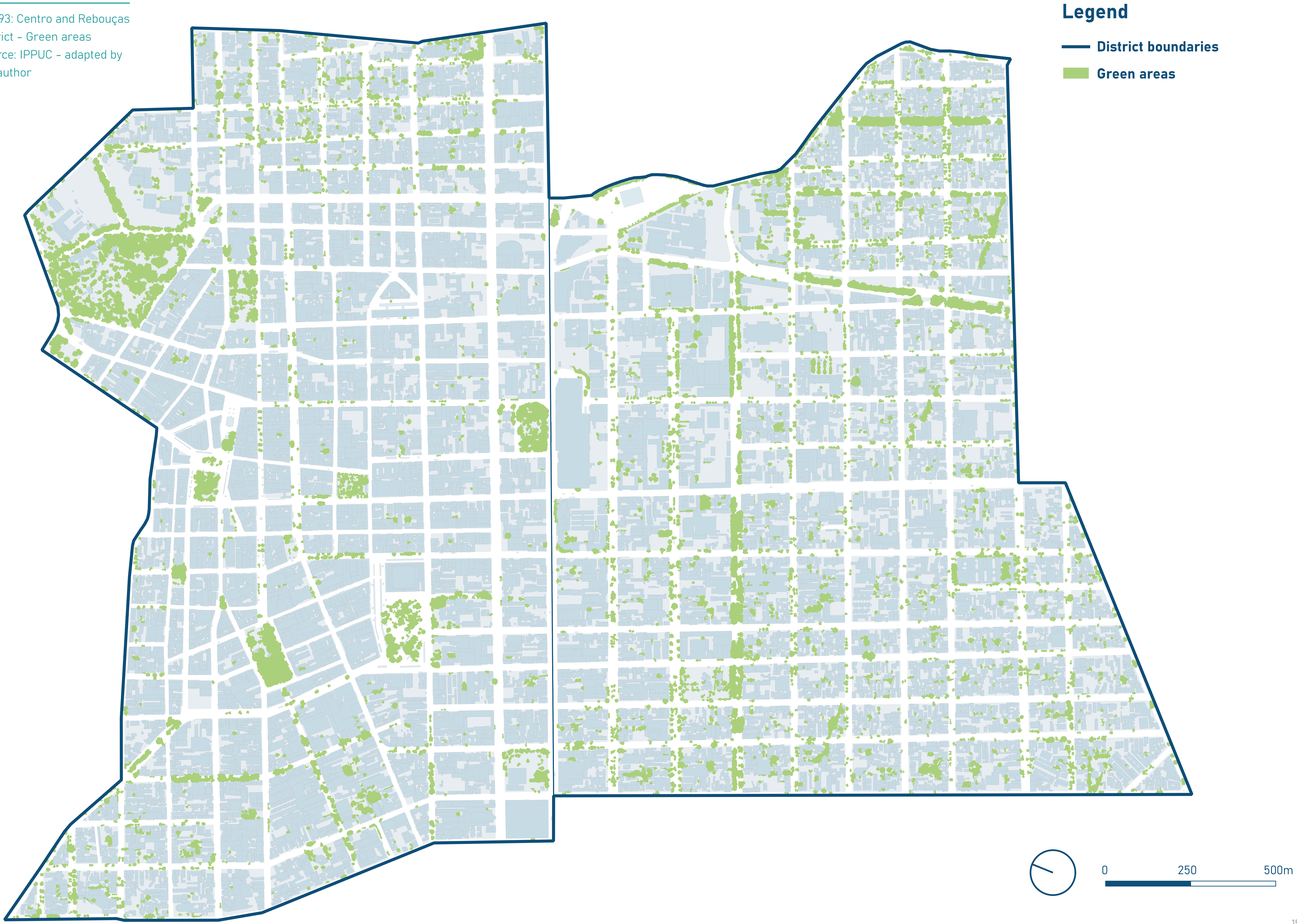


Fig. 94: Centro and Rebouças district - Average traffic on weekdays (6 p.m.). Source: Google maps - adapted by the author

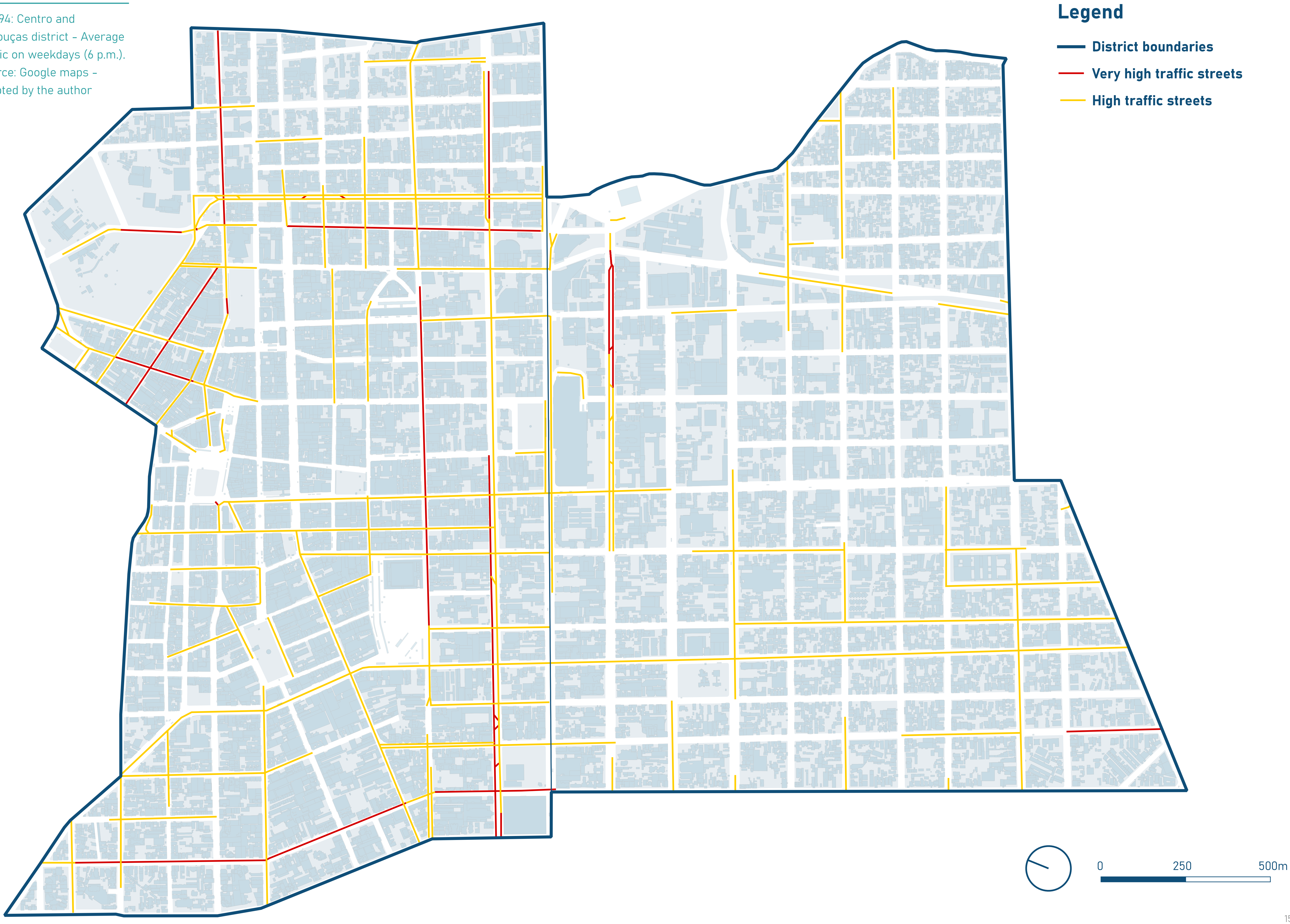
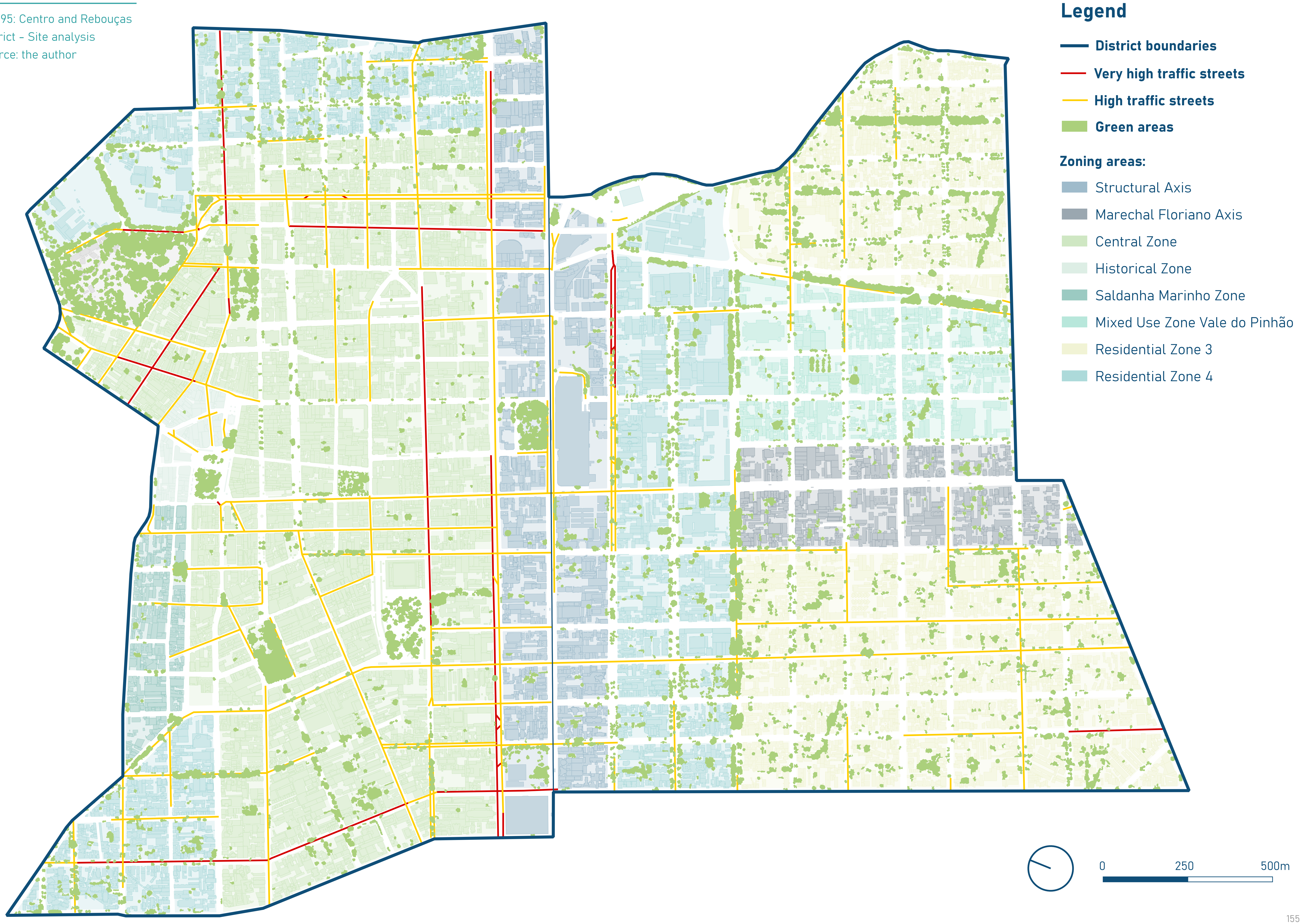


Fig. 95: Centro and Rebouças district - Site analysis
Source: the author



An analysis of the complete map (Figure 95) highlights several locations where high traffic, low vegetation cover, and intense urban activity converge. This observation indicates that the most critical and intervention-worthy areas are primarily concentrated along urban streets. While existing public squares possess substantial vegetation and effectively serve their environmental and social roles, the streets are characterized by high impermeability, heavy vehicular flow, and either excessive shading or excessive sun exposure.

Moreover, the urban morphology in these zones restricts the development of large-scale infrastructure, rendering street-level interventions—such as increased tree planting, permeable pavements, and the enhancement of public spaces—both more feasible and essential for mitigating environmental impacts and enhancing urban quality.

3.2.2 Potential urban acupuncture points

Based on the analyzed data, 24 specific locations, characterized by street segments along urban blocks, were identified as potential sites for urban acupuncture interventions (Figure 96, 97 and 98). A detailed evaluation of these sites was undertaken, encompassing variables such as land use patterns, pedestrian flow, vegetation cover and its qualitative description, pavement typology, height-to-width ratios of the urban canyon, solar exposure, and traffic volume within each segment (Table 09).

From this broader selection, the following chapter of this thesis concentrates on four sites, highlighted in Figure 99, with distinct characteristics, selected for a detailed analysis of their urban microclimates. The aim is to determine the most suitable intervention strategies to mitigate environmental stressors and enhance social functionality within each specific context. These case studies are intended to serve as a reference framework for guiding interventions in other areas with comparable conditions.

The first site, designated as point 6, consists of a street segment with high volumes of both vehicular and pedestrian traffic, largely influenced by its proximity to a major public transportation terminal. The area is marked by extensive impermeable surfaces and minimal vegetation cover. Additionally, the combination of street width, building height, and orientation contributes to a heightened level of solar exposure throughout the day.

The second site, identified as number 13, is a predominantly pedestrian-oriented street, lined with commercial and service establishments at ground level and characterized by minimal vehicular traffic. The street's narrow width in relation to the average height of surrounding buildings results in a high height-to-width ratio; however, its orientation facilitates significant solar exposure. Furthermore, the entire street surface is impermeable, and vegetation cover is entirely absent.

The third location, corresponding to site number 16, differs significantly from the previous cases by exhibiting low solar exposure, resulting from a height-to-width ratio (H/W ratio) of 1.26, which characterizes a deep urban canyon. This segment also experiences intense vehicular traffic and has very limited vegetation cover. Although recently planted trees are present, they are still in the early stages of growth. A comprehensive analysis of the local microclimate would be valuable in determining whether this intervention constitutes the most effective response to the environmental challenges imposed by the site's urban morphology.

Finally, site number 20 exhibits the lowest height-to-width ratio (H/W ratio) among the analyzed cases, which contributes to elevated solar exposure. Despite presenting low pedestrian traffic, the segment is distinguished by a dedicated public transportation lane, underscoring its functional significance within the urban mobility network. Small landscaped planting beds are present along the street; however, the predominance of impermeable surfaces restricts infiltration capacity and compromises thermal comfort.

Fig. 01: Centro and Rebouças district - Site analysis: potential points for urban acupucture
Source: the author

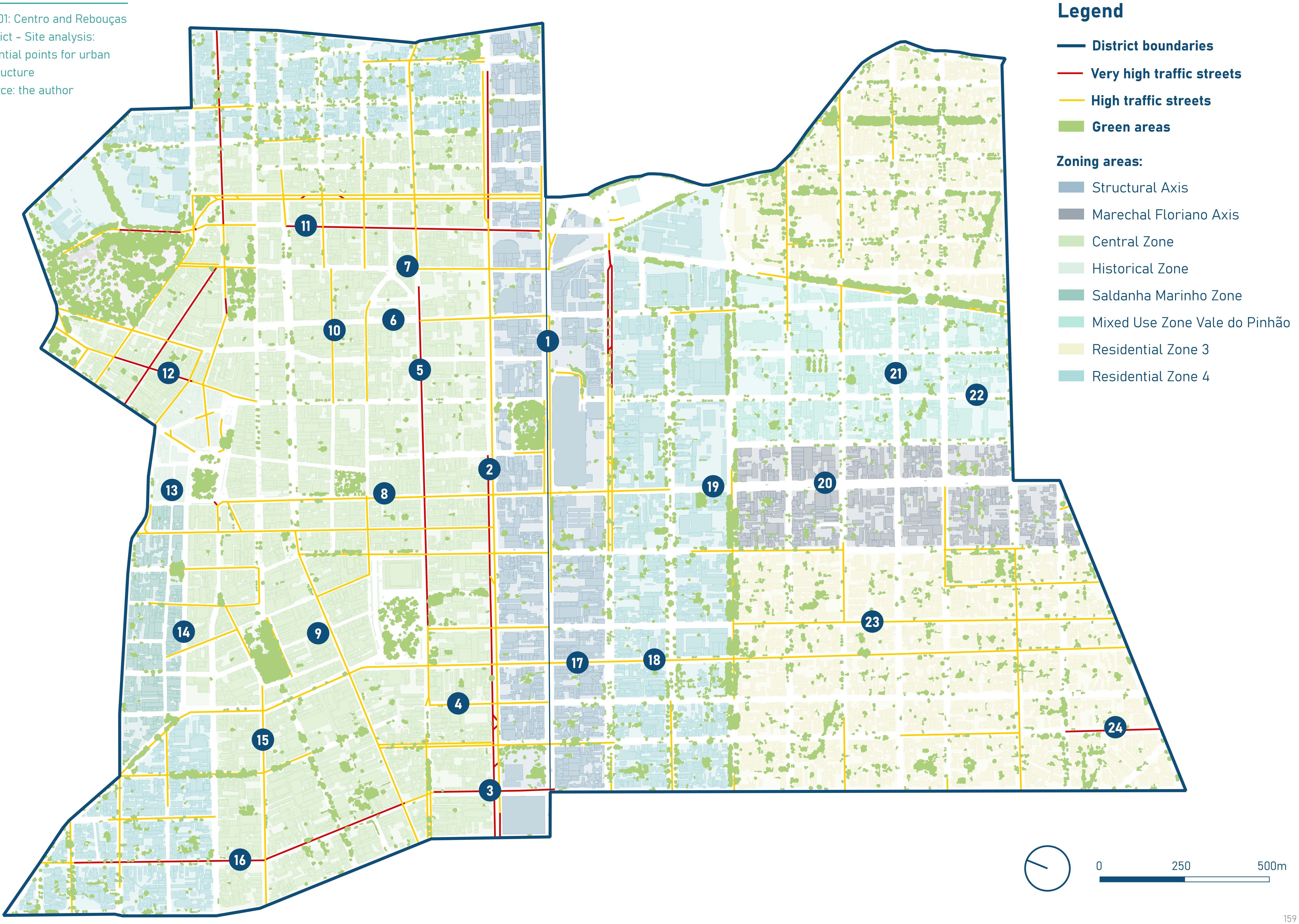


Fig. 01: Centro and Rebouças district - Site analysis: Potential points for urban acupucture
Source: the author

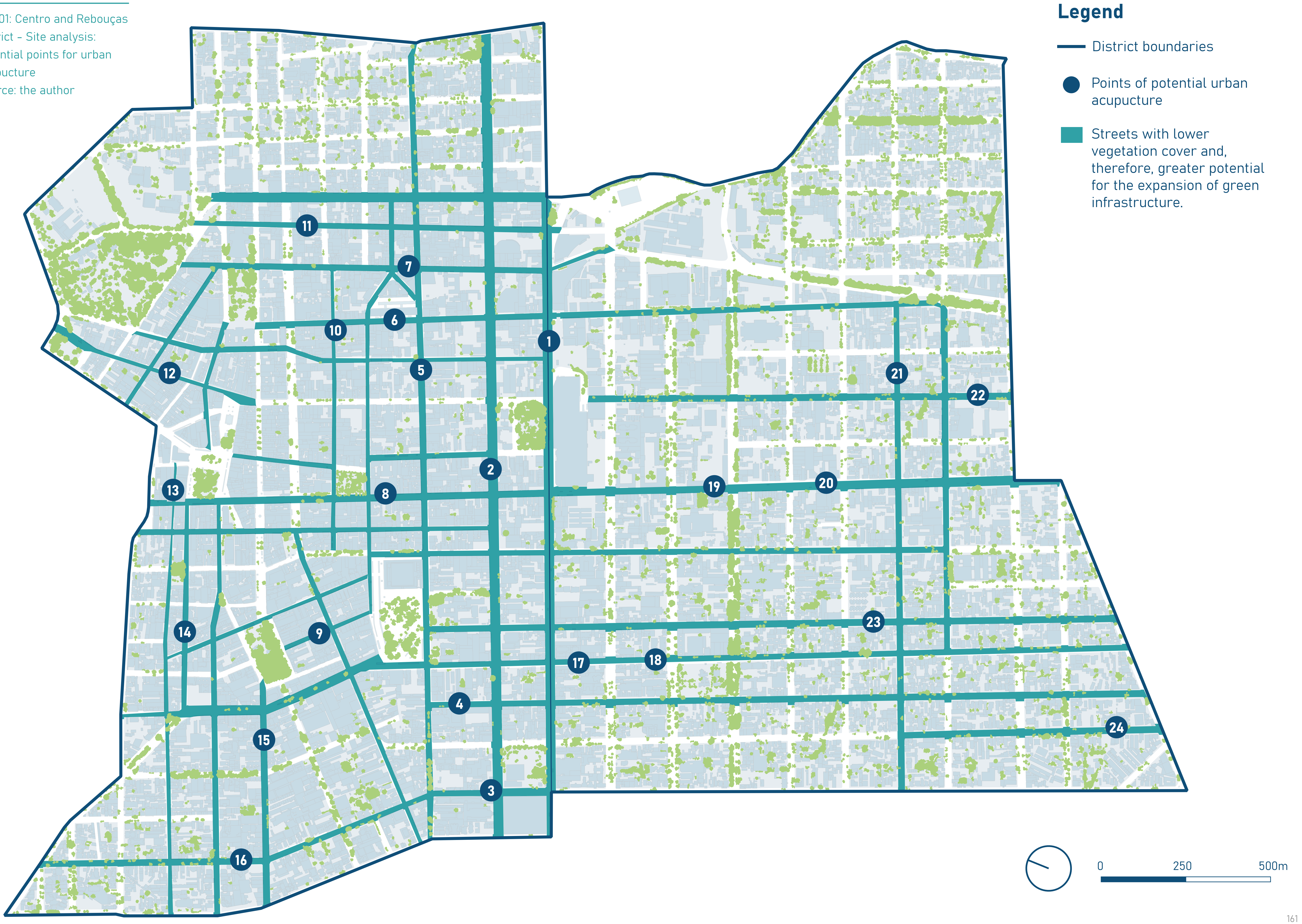


Fig. 01: Centro and Rebouças district - Potential urban acupuncture points.
Source: Google maps - the author

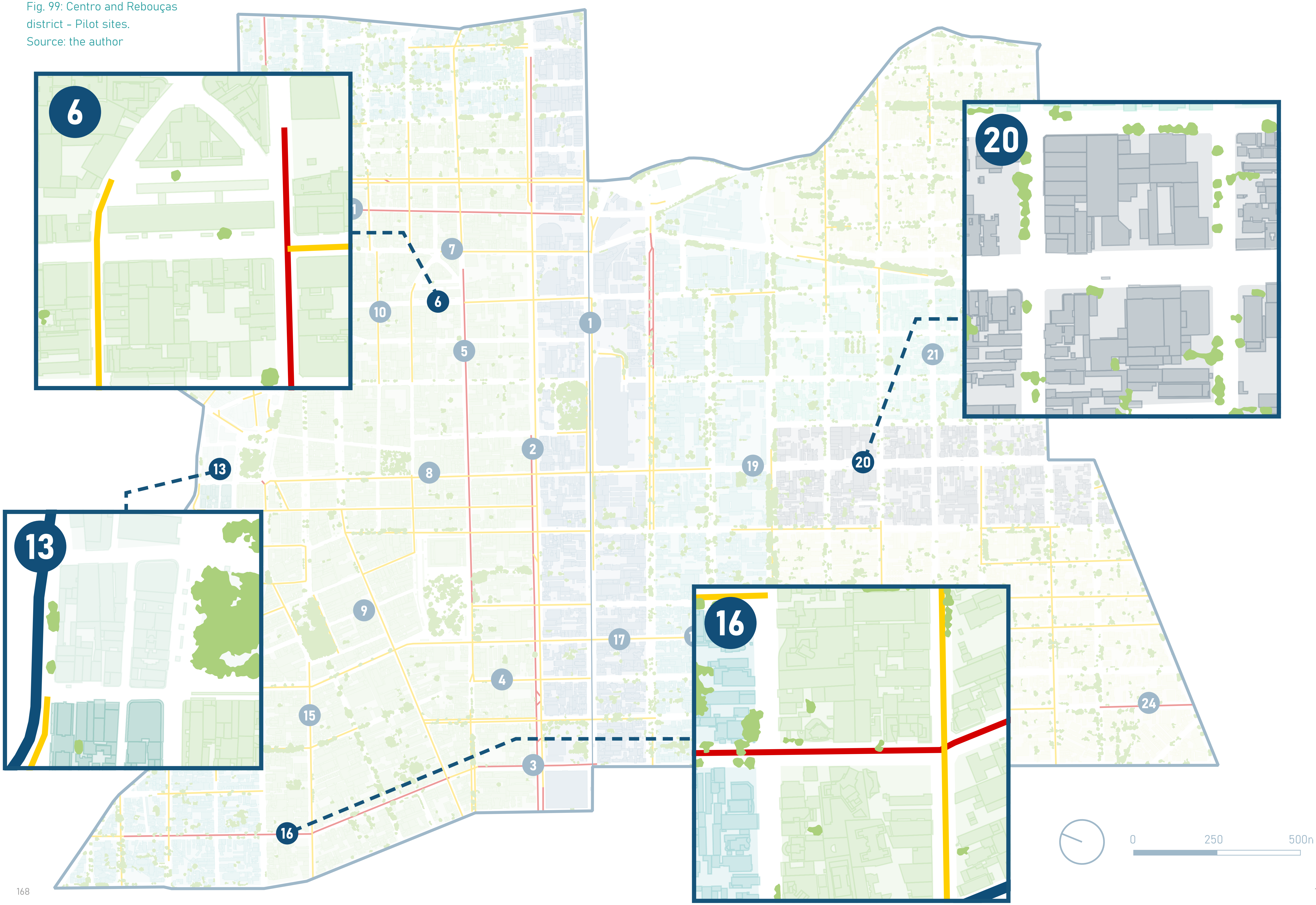
N°	Address	Use description	Pedestrian flux	Vehicular Traffic	Pavement Type	Vegetation cover	Vegetation description	Height/Width Ratio	Sun exposure
1	Av. Sete de Setembro (between Tv. da Lapa and R. João Negrão)	Segment with a special lane for public transport. Main land use is commercial and services.	Medium	High	Asphalt and paving blocks.	Low	Sparse vegetation, restricted to private lots. Recently planted tree saplings along the section.	0,25	High
2	Av. Visc. de Guarapuava (between R. Lourenço Pinto and Av. Mal. Floriano Peixoto)	Main land use is commercial and services.	Medium	Very high	Asphalt, paving blocks and grass.	Low	Street with central planting bed with limited presence of green elements in the section.	0,58	High
3	R. Brig. Franco (between R. Dr. Pedrosa and Av. Visc. de Guarapuava)	Mixed land use with commercial and services on the groundfloor.	Medium	Very high	Asphalt and paving blocks.	Low	Sparse vegetation, both in private lots and public space. Recently planted tree saplings along the section.	1,22	Low
4	R. Prefeito Moreira Garcez with R. Barão do Serro Azul	Main land use is commercial and services.	Medium	High	Asphalt and paving blocks.	Low	Modest planting bed with limited presence of green elements in the section.	0,90	Medium
5	R. André de Barros (between R. Barão do Rio Branco and Tv. da Lapa)	Mixed land use with commercial and services on the groundfloor.	Medium	Very high	Asphalt and paving blocks.	Low	No vegetation.	0,72	High
6	R. João Negrão (between R. Pedro Ivo and R. André de Barros)	Street adjacent to a public transport terminal. Main land use is commercial and services.	High	High	Asphalt and white Portuguese stone.	Low	Small planting bed with a medium-sized tree.	0,57	High
7	R. Conselheiro Laurindo (between Tv. Itararé and R. Nilo Cairo)	Mixed land use with commercial and services on the groundfloor.	High	High	Asphalt and black/grey cobblestones .	Low	Virtually no vegetation is present, with only a single small tree observed in the section.	0,58	High
8	Av. Mal. Floriano Peixoto (between R. Pedro Ivo and R. André de Barros)	Segment with a special lane for public transport. Main land use is commercial and services.	High	High	Asphalt and paving blocks.	Low	Modest planting bed with limited presence of green elements in the section.	0,78	High
9	R. Sen. Alencar Guimarães (between Praça Gen. Osório and R. Emiliano Perneta)	Mixed land use with commercial and services on the groundfloor.	High	Low	Black and white Portuguese stone.	Medium	Scattered, small-scale planters in limited quantity.	1,31	Medium
10	R. José Loureiro (between Tv. da Lapa and R. João Negrão)	Mixed land use with commercial and services on the groundfloor.	High	High	Asphalt and white Portuguese stone.	Low	No vegetation.	1,32	Medium
11	R. Tibagi (between R. Mal. Deodoro and R. Benjamin Constant)	Mixed land use with commercial and services on the groundfloor.	Medium	Very high	Asphalt and white Portuguese stone.	Low	Sparse vegetation, restricted to private lots.	1,22	Low
12	R. Riachuelo (between R. Treze de Maio and R. São Francisco)	Main land use is commercial and services.	High	Very high	Asphalt and paving blocks.	Low	Scattered, small-scale planters in limited quantity.	1,21	Medium

Table 09: Centro and Rebouças district - Potential urban acupuncture points.
Source: Google maps - the author

13	R. Saldanha Marinho (between R. do Rosário and R. José Bonifácio)	Mixed land use with commercial and services on the groundfloor.	High	Low	Asphalt and white Portuguese stone.	Low	No vegetation.	1,83	High
14	R. Cruz Machado (between R. Voluntários da Pátria and R. Des. Ermelino de Leão	Mixed land use with commercial and services on the groundfloor.	Medium	Medium	Asphalt and white Portuguese stone.	Low	No vegetation.	0,78	High
15	Av. Vicente Machado (between R. Visc. do Rio Branco and R. Visc. de Nácar)	Mixed land use with commercial and services on the groundfloor.	High	Medium	Asphalt and white Portuguese stone.	Low	Sparse vegetation with small-sized trees along the section.	1,28	Medium
16	R. Brig. Franco (between Al. Carlos de Carvalho and Av. Vicente Machado)	Mixed land use, residential and commercial.	Medium	Very high	Asphalt and paving blocks.	Low	Sparse vegetation, restricted to private lots. Recently planted tree saplings along the section.	1,26	Low
17	R. 24 de Maio (between Av. Sete de Setembro and Av. Silva Jardim)	Mixed land use with commercial and services on the groundfloor.	Medium	High	Asphalt and paving blocks.	Low	Sparse vegetation, restricted to private lots. Recently planted tree saplings along the section.	0,88	Medium
18	R. 24 de Maio (between Av. Silva Jardim and Av. Iguaçu)	Predominantly residential land use, with the presence few commercial establishments.	Medium	High	Asphalt, paving blocks and black/grey cobblestones.	Medium	Sparse vegetation, restricted to private lots. Recently planted tree saplings along the section.	0,32	High
19	Av. Mal. Floriano Peixoto (between Av. Iguaçu and Av. Pres. Getúlio Vargas)	Segment with a special lane for public transport. Main land use is commercial and services.	Low	Medium	Asphalt and paving blocks.	Low	Modest planting bed with limited presence of green elements in the section. Vegetation limited to private lots.	0,42	High
20	Av. Mal. Floriano Peixoto (between R. Eng. Rebouças and R. Brasílio Itiberê)	Segment with a special lane for public transport. Mixed land use with commercial and services on the groundfloor.	Low	Medium	Asphalt and grey cobblestones.	Low	Modest planting bed with limited presence of green elements in the section.	0,19	High
21	R. Alm. Gonçalves (between R. Rockefeller and R. Piquiri)	Mixed land use, residential and commercial.	Low	Low	Grey cobblestones.	Medium	Sparse vegetation, both in private lots and public space. Recently planted tree saplings along the street.	0,27	High
22	R. Rockefeller (between R. Baltazar Carrasco dos Reis and R. Chile)	Mixed land use, residential and commercial.	Low	Medium	Asphalt, black/grey cobblestones, and grass.	Medium	Grass plots with few small to medium-sized trees scattered along the section.	0,27	High
23	R. Alferes Poli (between R. Brasílio Itiberê and R. Alm. Gonçalves)	Main land use is commercial and services.	Low	High	Asphalt and grey cobblestones.	Low	Sparse vegetation with small-sized trees and recently planted tree saplings along the section.	0,31	High
24	R. Lamenha Lins (between R. Conselheiro Dantas and Av. Pres. Kennedy	Predominantly residential land use, with the presence of a school and a few commercial establishments.	Medium	Very high	Asphalt and black and grey cobblestones.	Medium	Small private gardens within private lots. Modest planting beds and small-sized trees, along the section.	0,28	High

Table 09: Centro and Rebouças district - Potential urban acupuncture points.
Source: Google maps - the author

Fig. 99: Centro and Rebouças district - Pilot sites.
Source: the author



3.2.3 Selection of NBS strategies

The strategy definition was based on the table provided by the Salute4ce project (Starzewska-Sikorska et al., 2022), which ranks the 30 Nature-Based Solutions (NBS) most compatible with the urban acupuncture methodology. The list was reviewed by prioritizing the top-ranking items—those offering the greatest number of benefits, as well as the highest efficiency and lowest technical demands relative to their lifespan (Table 10).

According to the table, the most viable strategies include interventions such as large shrubs, ground cover plants, urban wilderness areas, and urban meadows. These solutions stand out for requiring low initial investment and low labor intensity. In addition, they offer immediate effectiveness and, in most cases, a long lifespan, which reinforces their medium- and long-term viability. From an environmental perspective, they provide multiple benefits, such as thermal regulation, soil protection, water management, and air quality improvement, while also generating positive social impacts, such as enhanced well-being and quality of public spaces.

In a second group, with moderate feasibility, are strategies such as street trees, green pavements, linear hedges (hedgerows), rain gardens, and green façades. These solutions require somewhat more technical planning, labor, and financial resources, especially because they sometimes depend on interventions in already established urban infrastructure. However, they offer significant and lasting environmental benefits, such as improved air quality, shading, stormwater management, and enhancement of urban spaces. They are recommended for urban projects with greater capacity for ongoing management and maintenance.

Finally, the strategies considered less feasible appear at the bottom of the table and include solutions such as hydroponic mobile living walls, green covering shelters, compacted pollinator modules, ornamental vertical gardens, and technological vertical gardens. These alternatives have low environmental impact; however, they usually have a short lifespan and high installation costs, especially when involving technological systems or specialized maintenance. Their main benefit lies in social and aesthetic aspects.

Moreover, as this study focuses on urban road segments, it is still necessary to analyze practical limitations for applying these tools in contexts where space availability is limited and adaptations to the existing urban layout are required. Thus, priority is given to strategies that require less space and are more suitable for public areas.

As previously noted, incorporating green areas is an effective thermoregulation strategy in temperate climates. Implementation can take various forms, including the use of pavements, shrubs, and trees, as well as green walls and rooftops—although the latter often require private collaboration and investment (Schmitz, 2014; Kumar, 2024). The tree canopy also contributes to reducing thermal amplitude by providing shade and increasing the relative humidity of the air (Schmitz & Mendonça, 2011; Kumar, 2024), with greater microclimate efficiency in configurations of dense, interwoven canopies—tunnel-shaped—gradually decreasing towards isolated tree arrangements (Martini, 2013). Furthermore, Schmitz (2014) highlights the ability of incorporating permeable soils to enhance this increase in humidity, as well as to reduce surface runoff and promote water retention in the soil.

3.2.4 ENVI-met simulations

The analysis of the four pilot sites will be developed based on their morphological, functional, and social characteristics. Subsequently, both current conditions and proposed scenarios will be analyzed using ENVI-met, a software that simulates how buildings, vegetation, and other urban elements affect microclimate in small areas.

The simulation will examine Potential Air Temperature, Surface Temperature, Wind Speed, and Physiological Equivalent Temperature (PET) at four distinct times during the day (9:00, 12:00, 14:00, and 16:00) on January 8, 2024—the hottest day of the year—using atmospheric data provided by the National Institute of Meteorology (INMET) for Curitiba. As a result, critical points for micro-scale interventions will be identified, and the efficacy of strategies for each case will be evaluated.

	Technical/Economic aspects					Environmental aspects				
NBS strategy	Spatial disposition	Labour intensity	Expected efficacy	Approx. lifespan	Investment costs	Water management	Soil protection	Heat stress	Air quality	Social aspect
Large shrubs	Area	Low	Immediate	Long	Low	Yes	Yes	Yes	Yes	Yes
Ground cover plants	Area	Low	Immediate	Medium	Low	Yes	Yes	Yes	No	Yes
Urban wilderness/succession area	Area	Moderate	Immediate	Long	Low	Yes	Yes	Yes	Yes	No
Urban meadows	Area	Low	Immediate	Short	Low	Yes	Yes	Yes	No	Yes
Park trees	Area	Low	Long term	Long	High	Yes	Yes	Yes	Yes	Yes
Green pavements	Linear	Moderate	Immediate	Long	Moderate	Yes	Yes	Yes	No	Yes
Street trees	Linear	Moderate	Medium term	Long	Moderate	Yes	Yes	Yes	Yes	Yes
Fruit trees/shrubs	Area	Moderate	Medium term	Long	High	Yes	Yes	Yes	Yes	Yes
Hedge/hedgerow	Linear	Moderate	Medium term	Medium	Moderate	Yes	Yes	Yes	Yes	Yes
VRSS* slopes with green fences	Point	Low	Immediate	Medium	Moderate	No	Yes	No	Yes	Yes
Lawn	Area	High	Immediate	Medium	Moderate	Yes	Yes	Yes	No	Yes
Rain gardens (under-drained)	Point	Low	Immediate	Short	Moderate	Yes	No	Yes	No	Yes
Hanging wall planters (as green street furniture)	Point	Low	Immediate	Short	Low	No	No	No	Yes	Yes
Herb spiral	Point	Low	Immediate	Medium	Low	No	No	No	No	Yes
Verges/flower beds with native perennials	Point	Low	Immediate	Long	Moderate	No	No	No	No	Yes
Green facades with climbing plants	Area	Low	Long term	Long	Moderate	No	No	No	Yes	Yes
Rain gardens in planter (self-contained)	Point	Low	Immediate	Short	Moderate	Yes	No	No	No	Yes
Street planters (as green street furniture)	Point	Low	Immediate	Short	High	No	No	No	Yes	Yes
Road-side swales for retention and infiltration	Linear	Moderate	Immediate	Long	Moderate	Yes	No	No	No	No
Vertical vegetable/herb gardens	Point	High	Immediate	Short	Moderate	No	No	No	Yes	Yes
Green pergolas/green arbours	Point	Moderate	Medium term	Long	High	No	No	No	Yes	Yes
Green roof/roof terrace	Area	Moderate	Immediate	Medium	High	Yes	No	No	No	Yes
Ground crops of vegetables/herbs	Area	Moderate	Immediate	Short	Low	No	No	No	No	Yes
Green covering shelters	Area	Low	Immediate	Short	Moderate	No	No	No	No	Yes
Hydroponic mobile living walls/ vertical gardens	Point	Low	Immediate	Short	Moderate	No	No	No	No	Yes
Linear wetlands stormwater filtration	Linear	Moderate	Long term	Short	High	Yes	No	Yes	No	Yes
Wall-mounted living walls	Area	High	Immediate	Short	High	No	No	No	Yes	Yes
Rockery	Linear	High	Immediate	Medium	High	No	No	No	No	Yes
Compacted pollinators‘ module	Point	Moderate	Long term	Short	Moderate	No	No	No	No	Yes
Natural pollinators‘ modules	Point	Moderate	Long term	Short	Moderate	No	No	No	No	Yes

Expected efficacy:
Immediate (0-1 year)
Medium term (< 5 years)
Long term (> 5 years)

Approximate lifespan:
Short (< 10 years)
Medium (11-30 years)
Long (> 30 years)

* Vegetated reinforced soil slope

Fig. 10: Nature-Based Solutions (NBS) adapted to urban acupuncture and their characteristics.
Source: Starzewska-Sikorska et al.(2022) - adapted by the author

3.3 Pilot sites

3.3.1 Site 06: R. João Negrão (between R. Pedro Ivo and R. André de Barros)

Site number 06 is located on João Negrão Street, in the segment between Pedro Ivo and André de Barros streets, in the Centro neighborhood (Figure 100 and 101). The area is characterized by urban dynamism and intense pedestrian and bus traffic, largely influenced by the presence of the Guadalupe Public Transport Terminal and the homonymous Church/Sanctuary on one side of the street. On the opposite side, the streetscape is dominated by predominantly mixed-use buildings, featuring commercial and service establishments on the ground floor and varying in height from two to six stories, with the exception of one notable building that rises to 11 floors.

The vegetation cover along the segment is quite limited, with punctual small to medium-sized trees, providing minimal shade. The lack of greenery further contributes to the predominance of impermeable surfaces, as the street is paved with asphalt and the sidewalks are surfaced with a mix of materials, including paver blocks and, in some areas, white Portuguese stone.

Segment length **160.00m**

Average segment width **24.50m**

Soil permeability **0.29%**

Vegetation cover **2.29%**

Height/Width Ratio **0.57**

Fig. 100 and 101: Street view Site 06 - R. João Negrão.
Source: Google maps

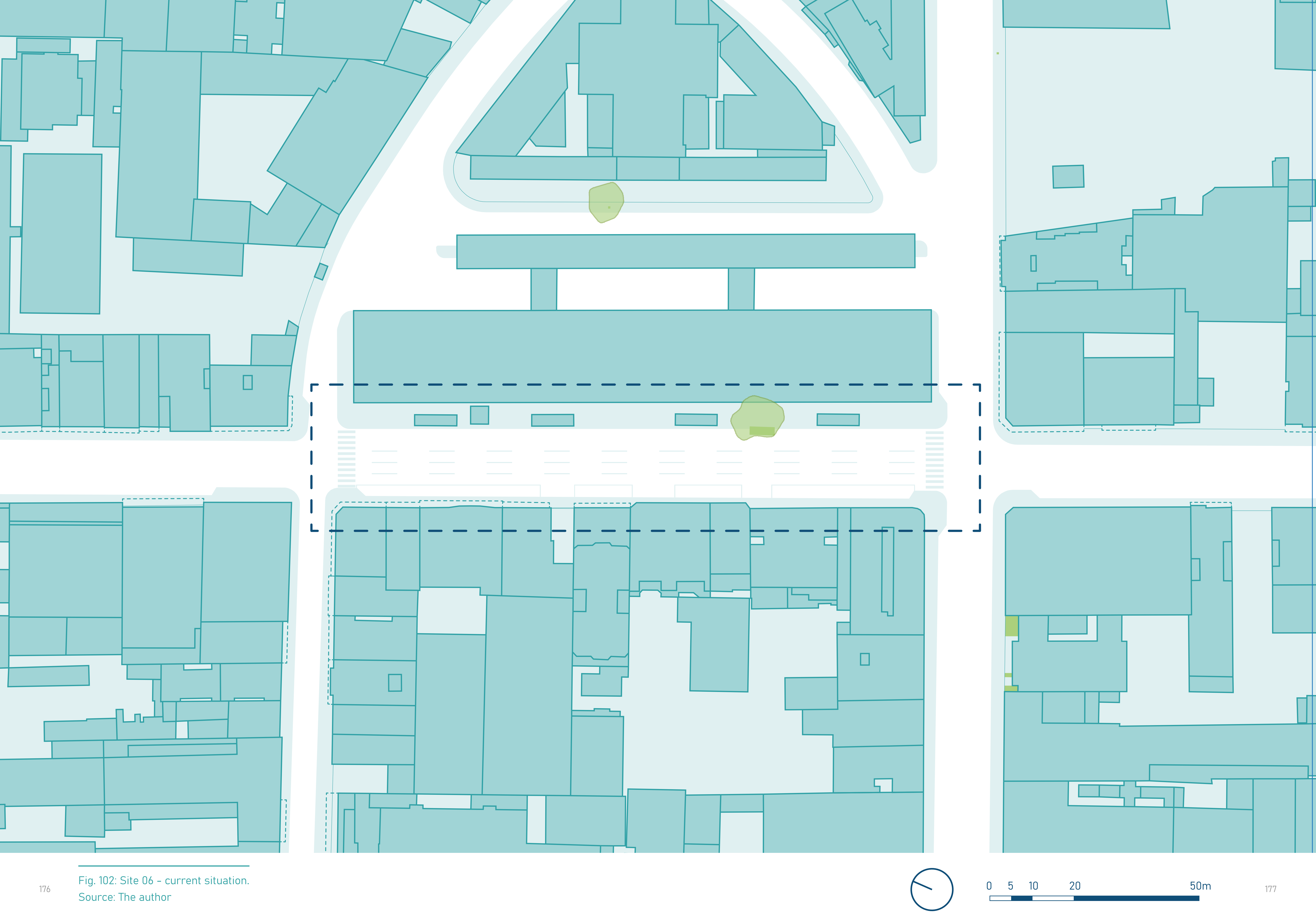


Fig. 102: Site 06 - current situation.
Source: The author

Fig. 103: Site 06 - Current scenario - Potential Air Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Potential Air Temperature

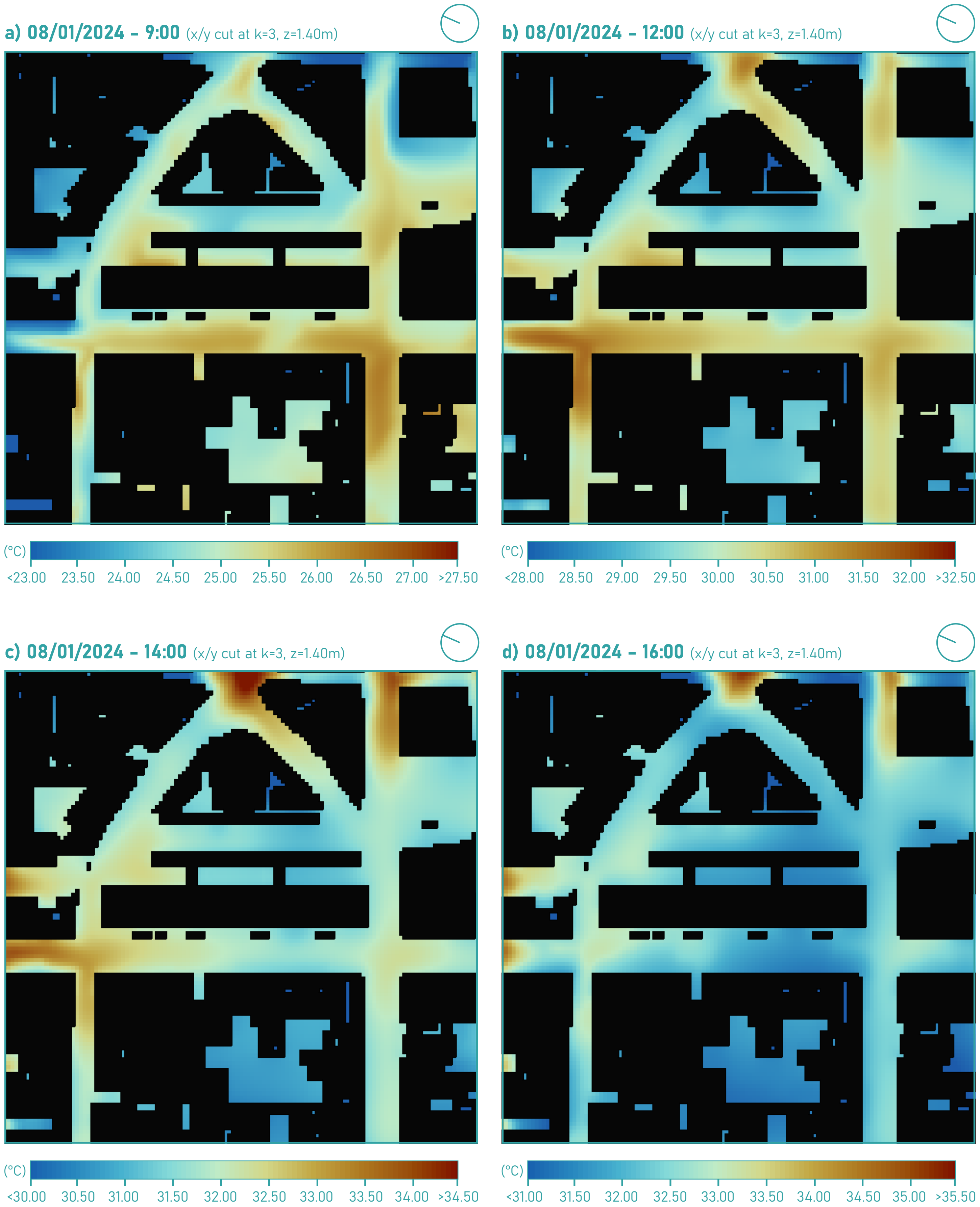


Fig. 104: Site 06 - Current scenario - Surface Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Surface Temperature

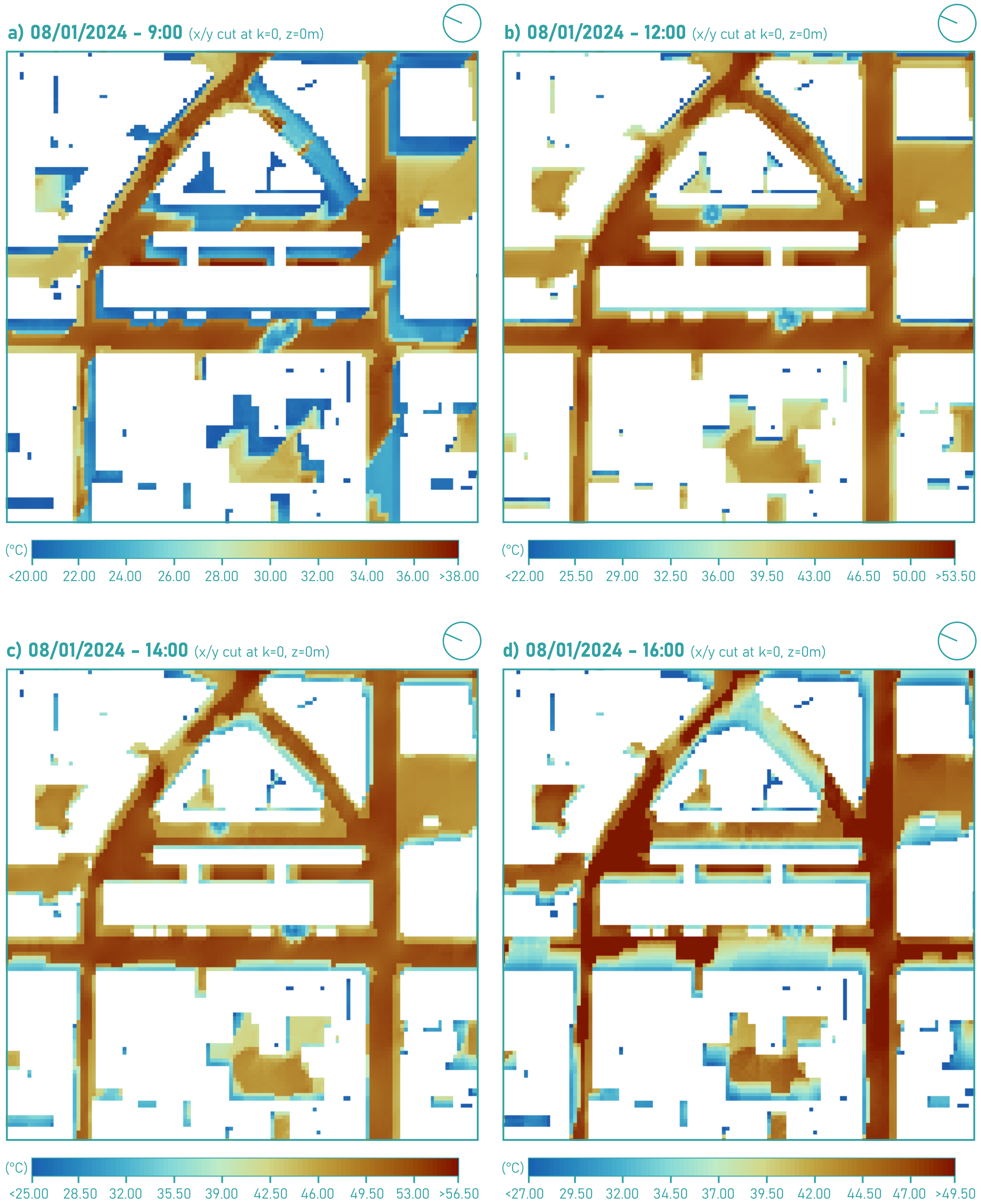


Fig. 105: Site 06 - Current scenario - Wind speed maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Wind speed

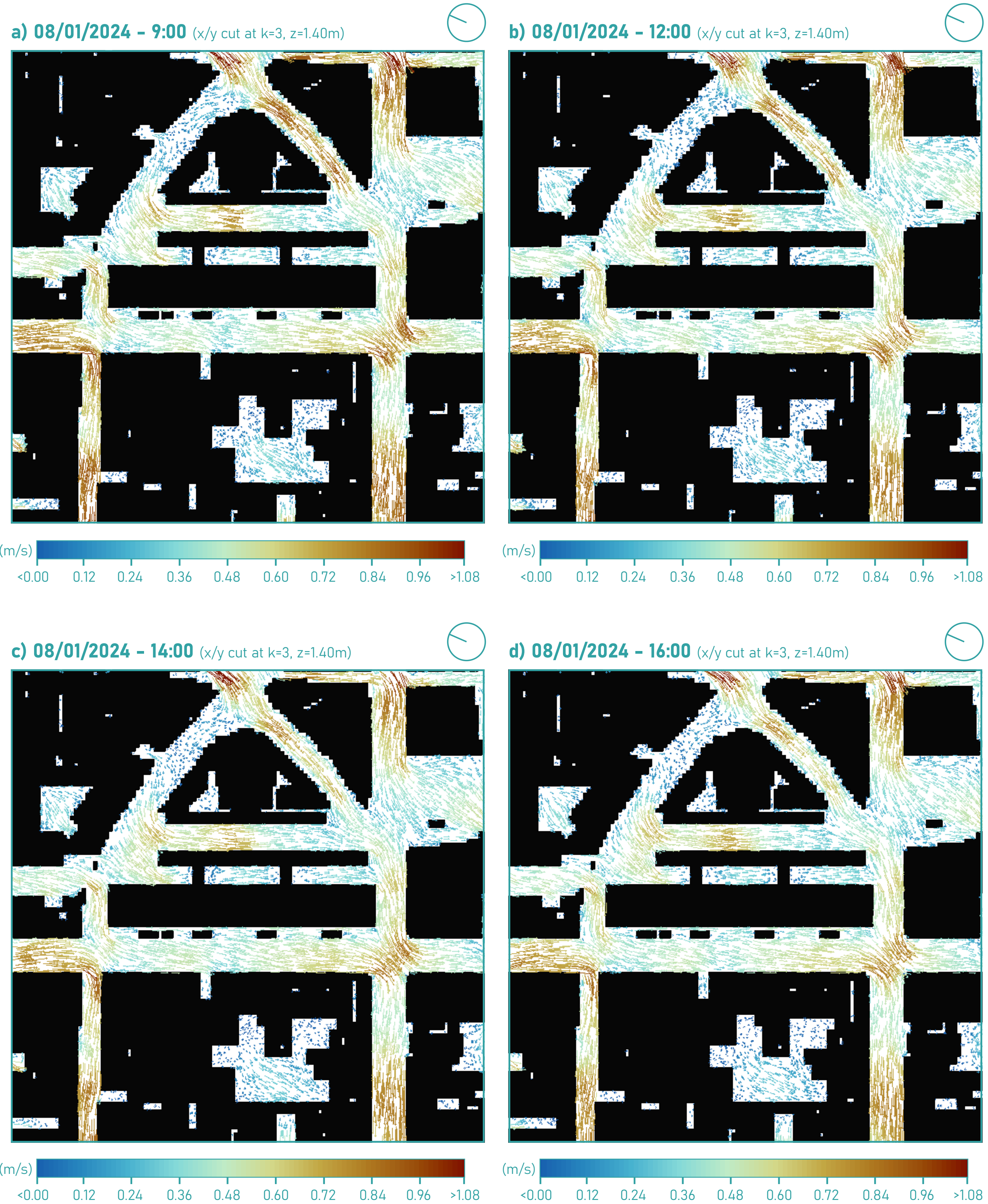
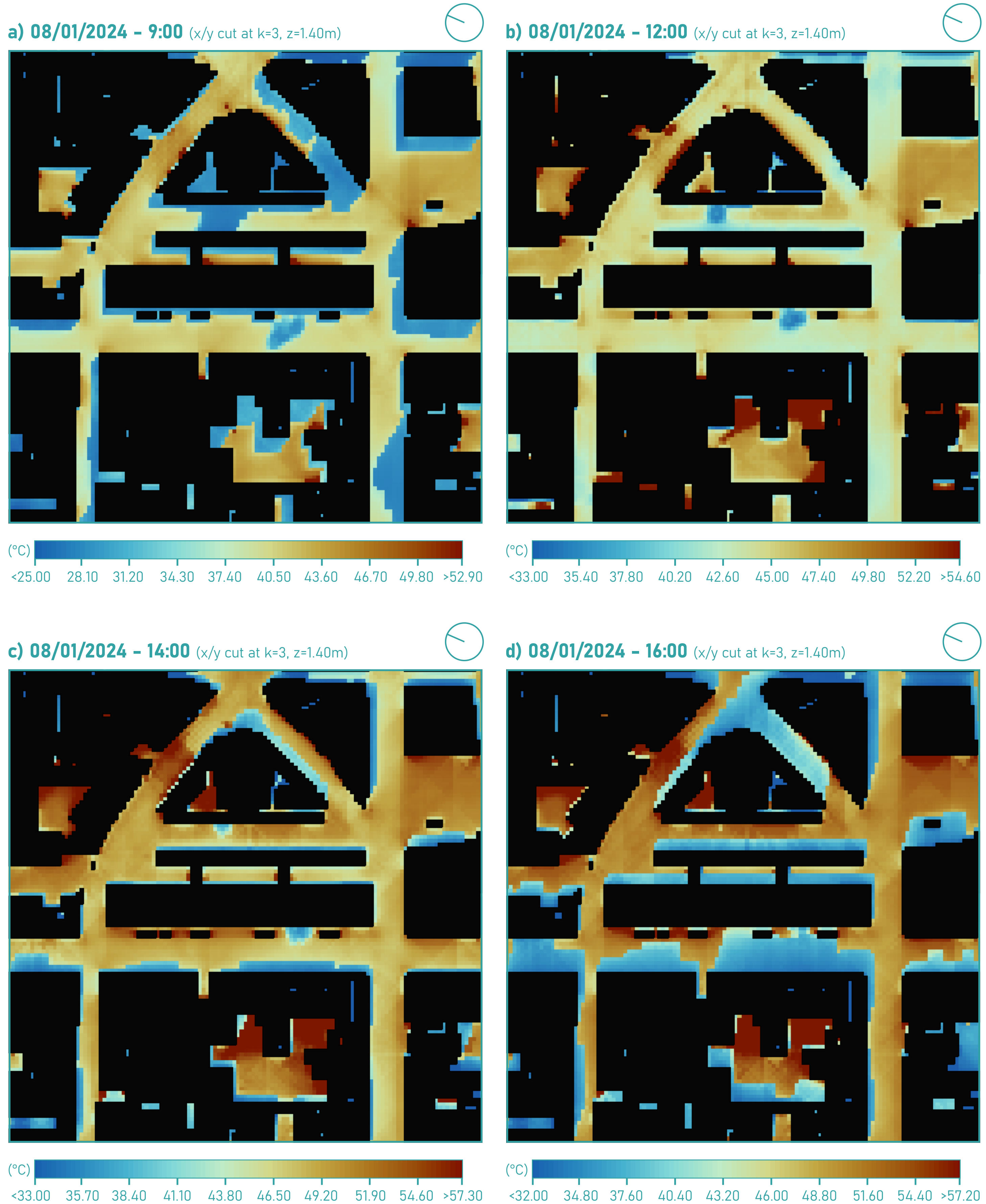


Fig. 106: Site 06 - Current scenario - Physiologically Equivalent Temp. (PET) maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Physiologically Equivalent Temperature - PET



According to the analysis of the current scenario, main strengths points include the dynamic commerce and services in the region, the high pedestrian flow, and the well-developed public transportation infrastructure. Additionally, ENVI-met simulations highlight the north-south orientation as an advantage, providing greater thermal comfort in the late afternoon due to building shadows (Figure 106d).

However, the extensive impervious surfaces and near absence of vegetation limit water infiltration and contribute significantly to heat retention in the area. This is intensified by the low Height-to-Width Ratio, which results in prolonged sun exposure throughout the day. Surface temperature maps show paved asphalt areas exceeding 50°C in early afternoon (Figures 104b and c). Additionally, although variations in wind speed are detectable within the segment, overall, the values remain low, not surpassing 1 m/s (Figure 105). These factors help explain the PET data results, which indicate a predominance of temperatures exceeding the "slight heat stress" threshold, as previously mentioned, defined as up to 37°C (Figure 106).

For the implementation of the strategies, several opportunities can be highlighted, including the availability of sidewalk space and the presence of wide streets, which are suitable for urban interventions, as well as the long stretch of parking space that could be reduced. Furthermore, the presence of the public bus terminal building provides greater flexibility for adopting strategies that also involve architectural aspects. However, interventions must avoid compromising visibility, obstructing circulation, or reducing airflow.

Based on the NBS table, implementing urban meadows that serve as rain gardens (under-drained) can be suggested to improve soil permeability and increase attractiveness. These solutions offer immediate effectiveness while requiring low to moderate investment. Additionally, to provide greater shading, the planting of street trees in a continuous line along one side of the street is proposed. Finally, exceptionally in this area, the installation of an extensive green roof on the bus terminal can also be implemented — a strategy that, although involving higher investment, can help alleviate pressure on the city's water management system.

Table 11: Site 06 - SWOT analysis. Source: The author

Site 06 - SWOT analysis	
Strengths	▪ High pedestrian flow and active ground-floor commerce, enhancing urban vitality. ▪ Connectivity to the public transport system, facilitating access and mobility. ▪ Shading provided by buildings in the late afternoon due to east-west orientation.
Weaknesses	▪ Extensive presence of impermeable surfaces, limiting rainwater infiltration. ▪ Predominance of asphalt and pavement, contributing to heat retention. ▪ Significant lack of vegetation, reducing shading and environmental comfort. ▪ High afternoon temperatures, intensifying thermal discomfort. ▪ High solar radiation incidence during the morning and early afternoon. ▪ Low wind circulation in the segment.
Opportunities	▪ Available sidewalk space, enabling urban and landscape interventions. ▪ Extra lane for parking can be repurposed for more sustainable uses. ▪ Presence of a bus terminal, a public building, allows for flexibility and integration of urban renewal proposals.
Threats	▪ Installation of elements that reduce wind speed, affecting natural ventilation. ▪ Possible visual obstruction of strategic points, such as the bus terminal and commercial establishments. ▪ Interference with pedestrian circulation, hindering accessibility and urban flow.

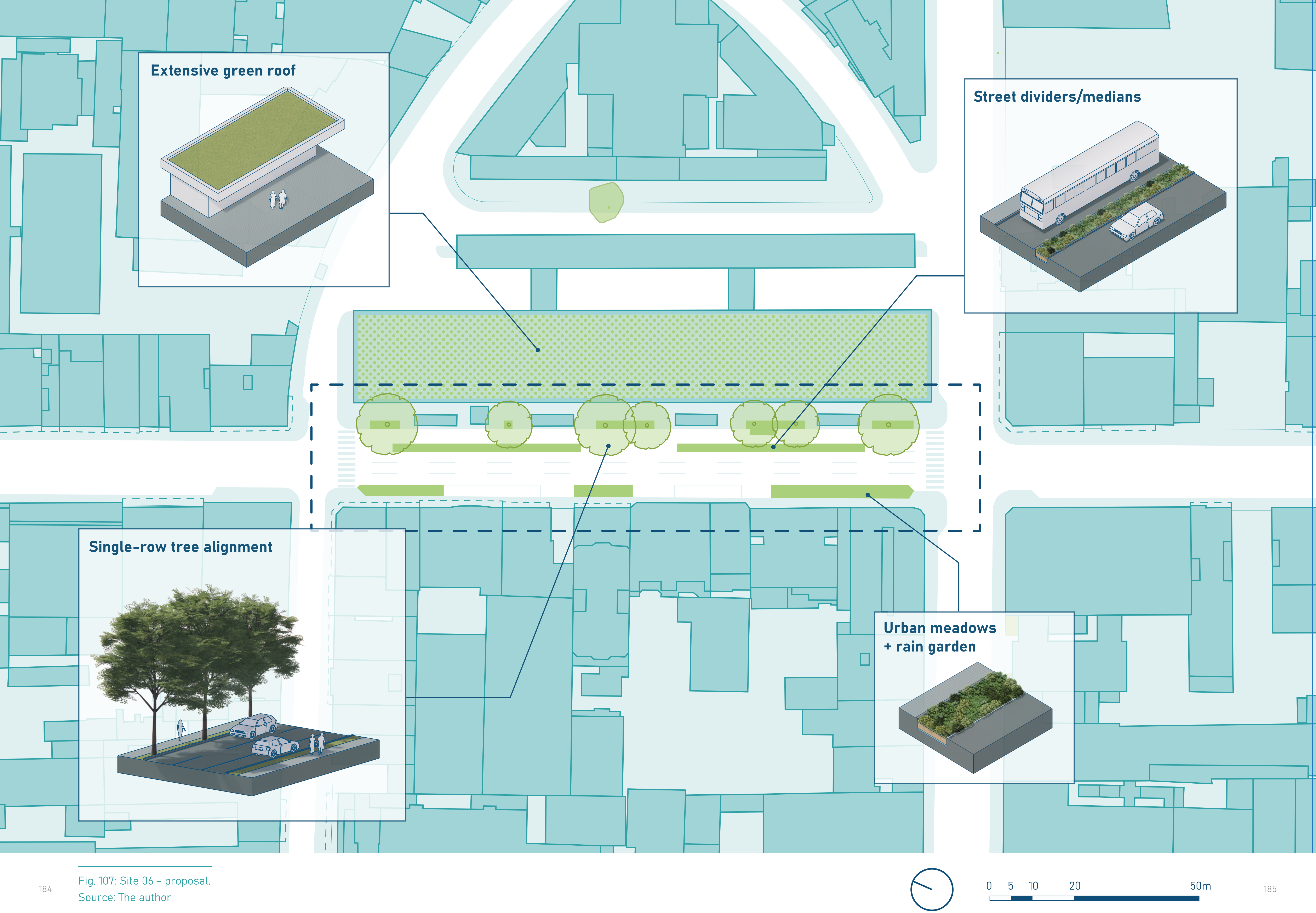


Fig. 107: Site 06 - proposal.
Source: The author

Fig. 108: Site 06 - proposal.
Source: AI-generated image (OpenAI) based on personal project - adapted by the author

Fig. 109: Site 06 - Proposal - Potential Air Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Potential Air Temperature

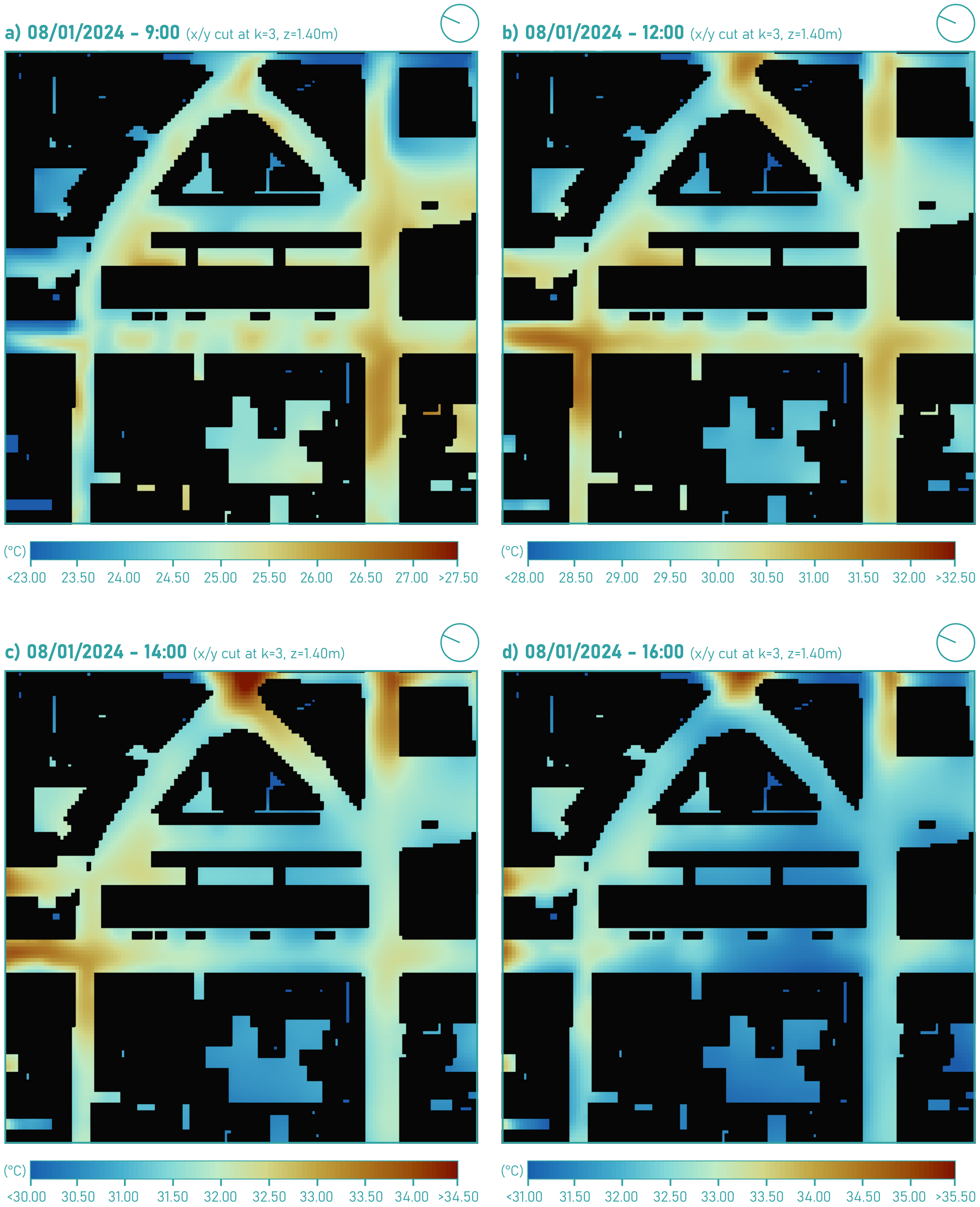


Fig. 110: Site 06 - Proposal - Surface Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Surface Temperature

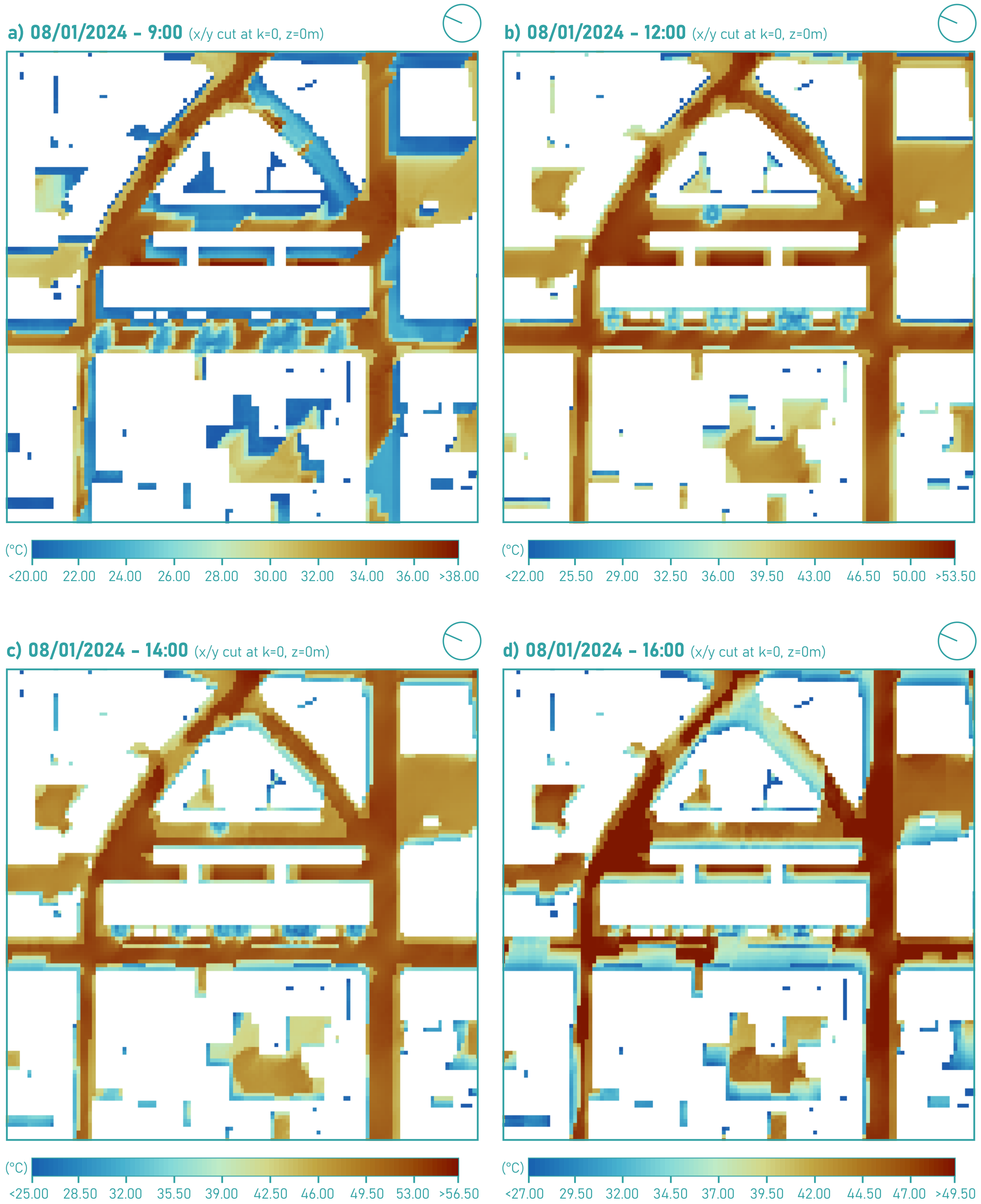
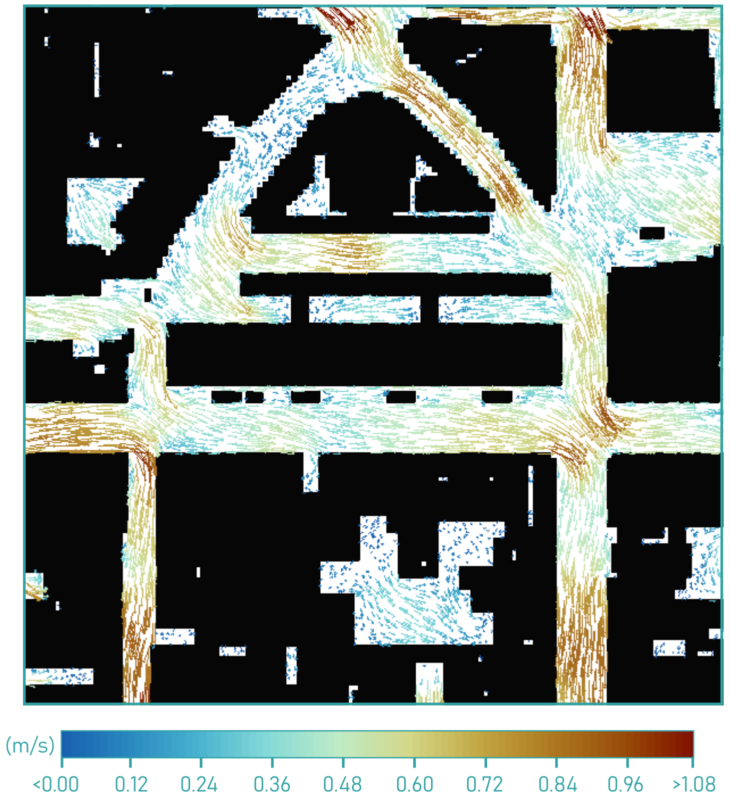


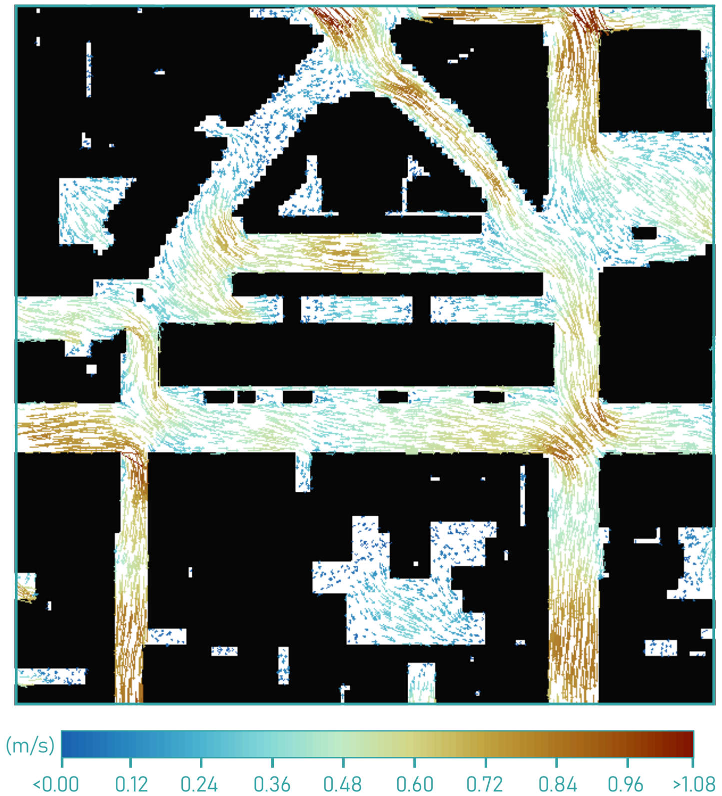
Fig. 111: Site 06 - Proposal - Wind speed maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Wind speed

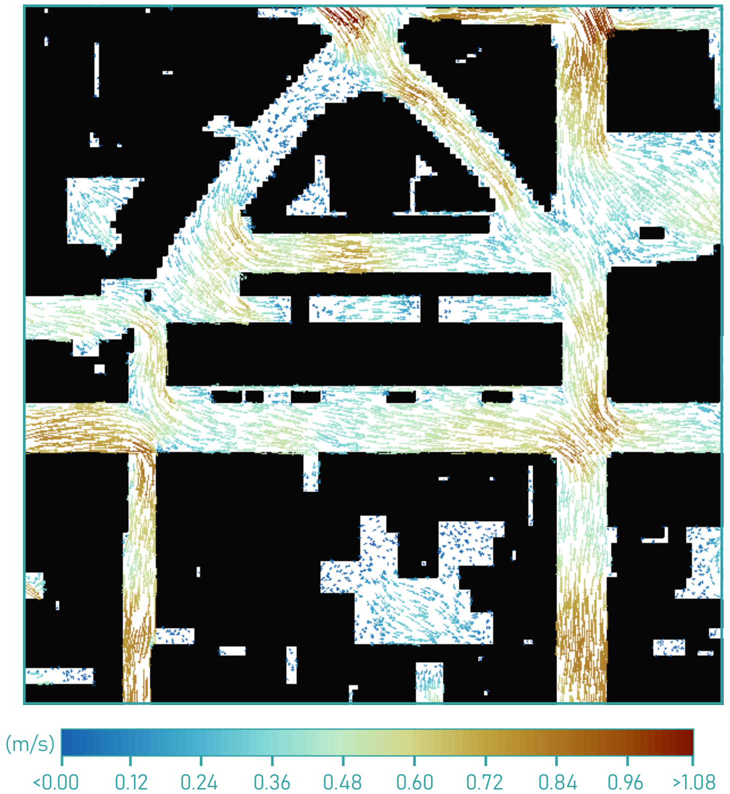
a) 08/01/2024 - 9:00 (x/y cut at k=3, z=1.40m)



b) 08/01/2024 - 12:00 (x/y cut at k=3, z=1.40m)



c) 08/01/2024 - 14:00 (x/y cut at k=3, z=1.40m)



d) 08/01/2024 - 16:00 (x/y cut at k=3, z=1.40m)

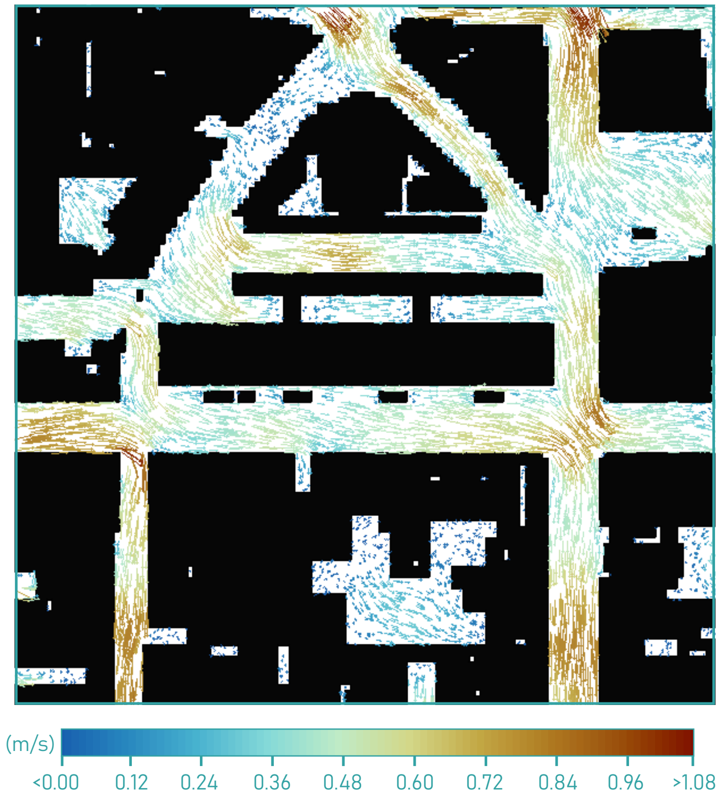
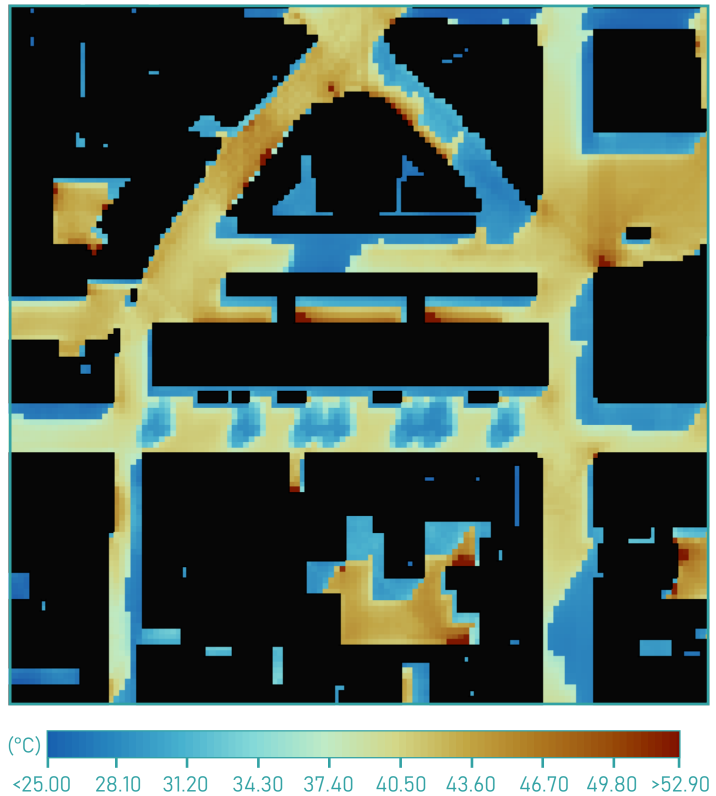


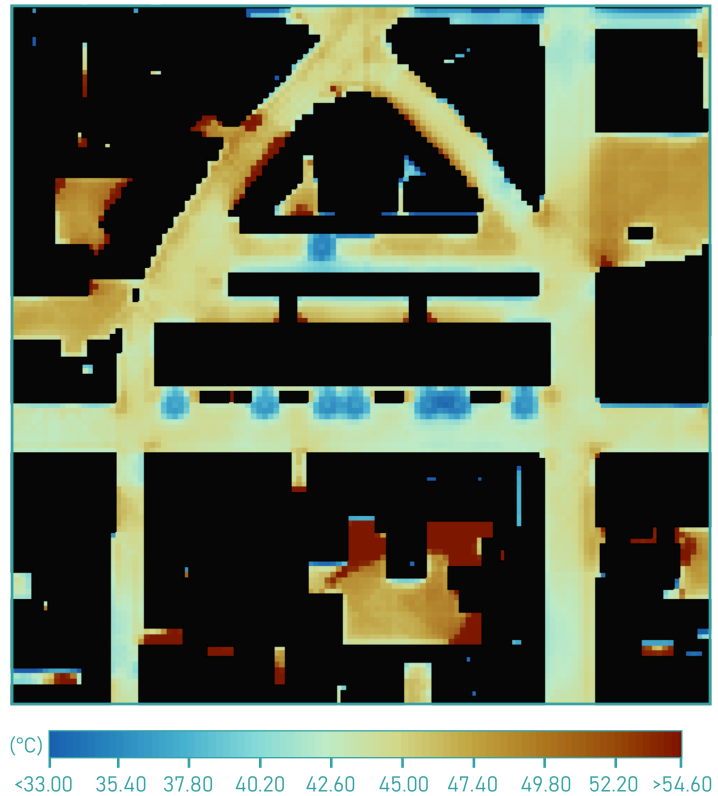
Fig. 112: Site 06 - Proposal - Physiologically Equivalent Temperature (PET) maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Physiologically Equivalent Temperature - PET

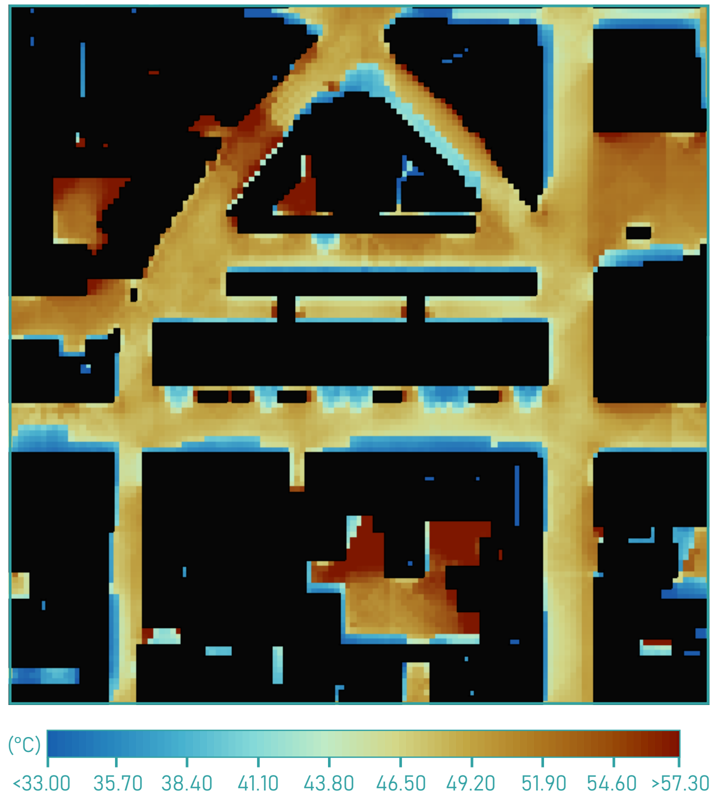
a) 08/01/2024 - 9:00 (x/y cut at k=3, z=1.40m)



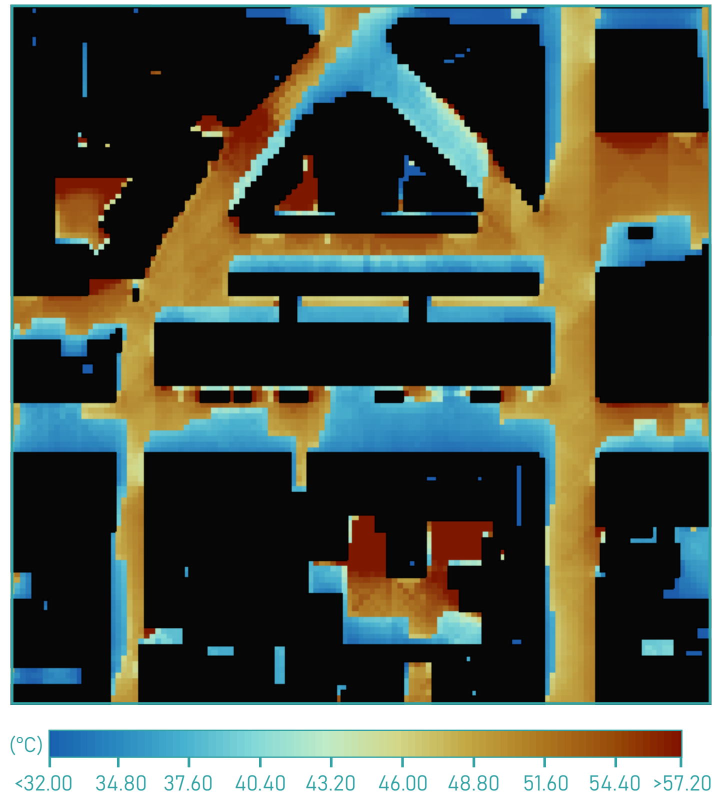
b) 08/01/2024 - 12:00 (x/y cut at k=3, z=1.40m)



c) 08/01/2024 - 14:00 (x/y cut at k=3, z=1.40m)



d) 08/01/2024 - 16:00 (x/y cut at k=3, z=1.40m)



The analysis of the Potential Air Temperature maps before and after the intervention reveals that the most significant temperature reductions occur between 12:00 and 14:00 (Figure 109b and c), reaching up to 1°C. Tree shading emerges as the primary contributing factor. In contrast, areas featuring urban meadows exhibit only minimal changes in temperature.

Conversely, both trees and low vegetation show a pronounced effect on Surface Temperature maps (Figure 110), particularly during periods of intense solar exposure (before 16:00). Temperature differences of approximately 11°C in shaded areas and 8°C in green surfaces are observed in the morning; 19°C and 14°C at noon; and 16°C and 17°C at 14:00. A clear trend of rapid temperature increase is evident on asphalt surfaces throughout the day, while vegetated areas maintain more stable thermal conditions.

The Wind Speed maps (Figure 111) show no notable changes following the implementation of the interventions. Lastly, the PET map analysis (Figure 112), consistent with the Potential Air Temperature data, confirms that shading strategies are the most effective, with potential temperature reductions of up to 15°C. Figures 113 and 114 highlight the point with the greatest variation in PET within the study area, presenting its values throughout the day and comparing the current situation with the proposed intervention.

In terms of surface absorption capacity, the implementation of Nature-Based Solutions (NBS) increases the site's permeable surface coverage from 0.29% to 9%, helping to reduce the burden on the municipal stormwater management system.

b) 08/01/2024 – 12:00 (x/y cut at k=3, z=1.40m)

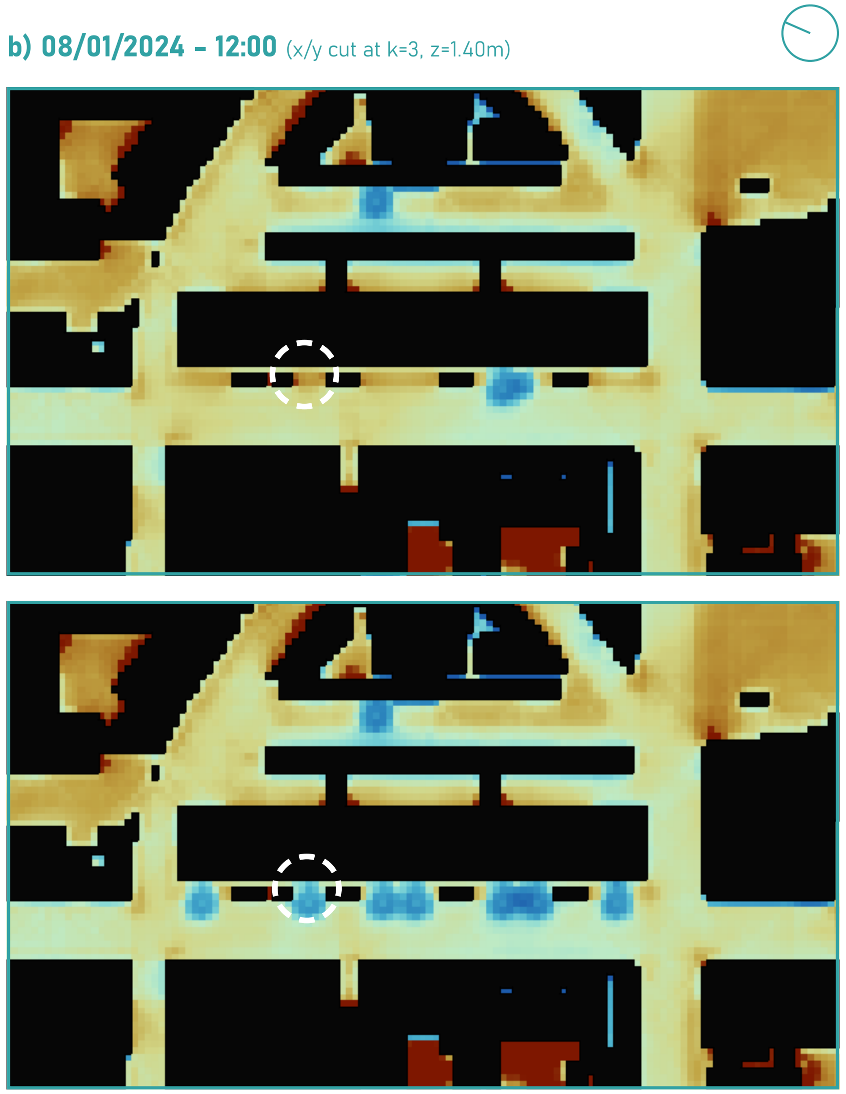


Fig. 113: Site 06 – PET peak variation point.
Source: The author

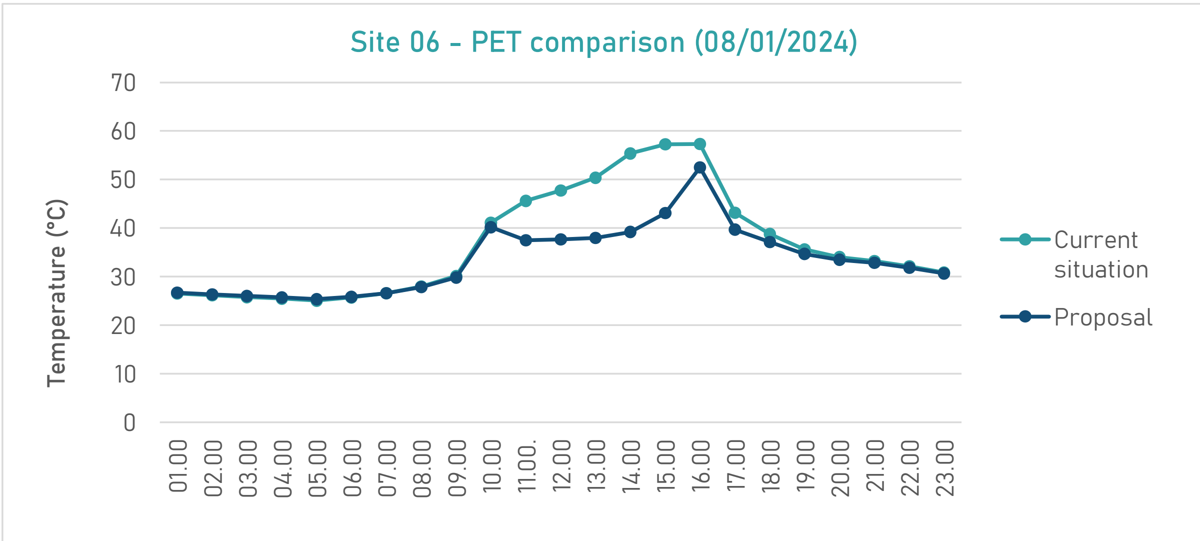


Fig. 114: Site 06 – PET peak variation point comparison before and after intervention.
Source: The author

3.3.2 Site 13: R. Saldanha Marinho (between R. do Rosário and R. José Bonifácio)

Site number 13 is located on Saldanha Marinho Street, in the segment between Street of Rosário and José Bonifácio street, in the Centro neighborhood (Figure 115 and 116). Characterized as a street exclusively for pedestrian use, the segment features mixed-use buildings ranging from 3 to 15 meters in height. The ground floors, predominantly occupied by commerce and services, add dynamism and vitality to the space, while reinforcing a human-scale environment. Located in the historic heart of Curitiba and adjacent to Tiradentes Square, the area also holds significant symbolic and cultural value for the city.

There are no permeable surfaces in the segment, as it is entirely paved with white Portuguese stone. Moreover, vegetation is noticeably absent, both in public and private areas. Another prominent feature is that, despite its high Height-to-Width Ratio of 1.83, the street's east-west orientation results in considerable solar exposure throughout the day.

Segment length **120m**

Average segment width **7.70m**

Soil permeability **0%**

Vegetation cover **0%**

Height/Width Ratio **1.83**

Fig. 115 and 116: Street view Site 13 - R. Saldanha Marinho.
Source: Google maps

Fig. 117: Site 13 - current situation.
Source: The author

Fig. 118: Site 13 - Current scenario - Potential Air Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Potential Air Temperature

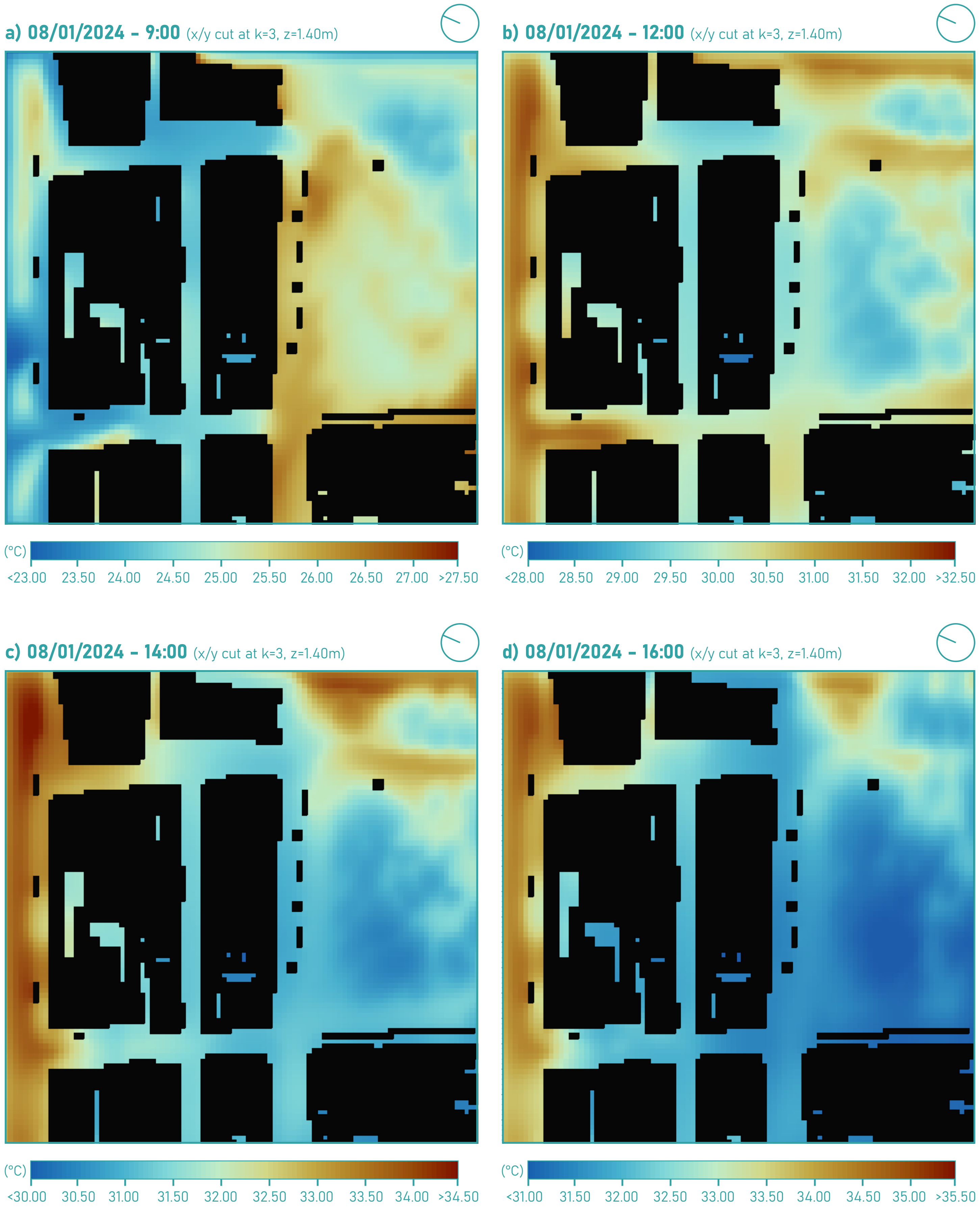


Fig. 119: Site 13 - Current scenario - Surface Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Surface Temperature

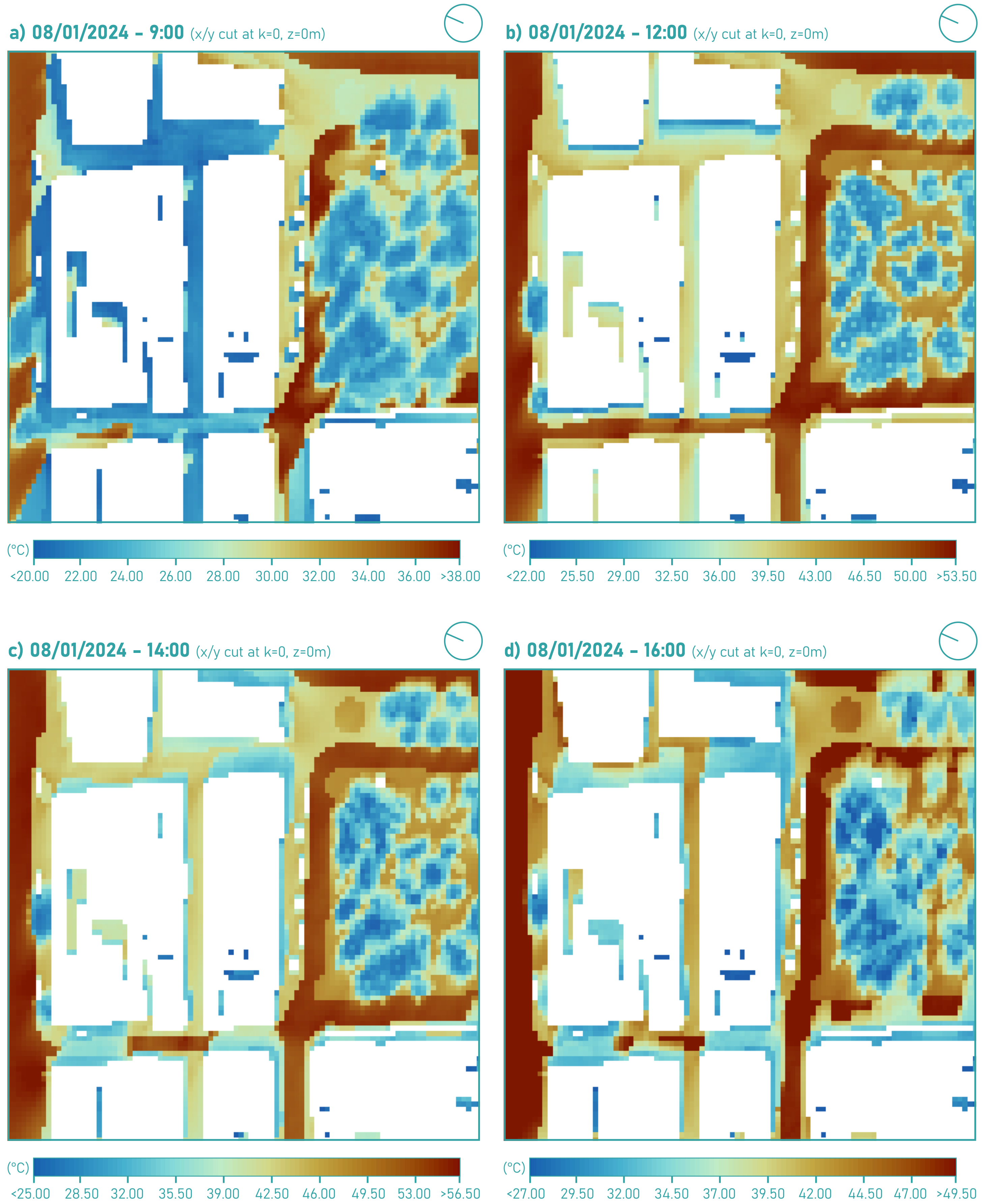


Fig. 120: Site 13 - Current scenario - Wind speed maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00. Source: The author

Wind speed

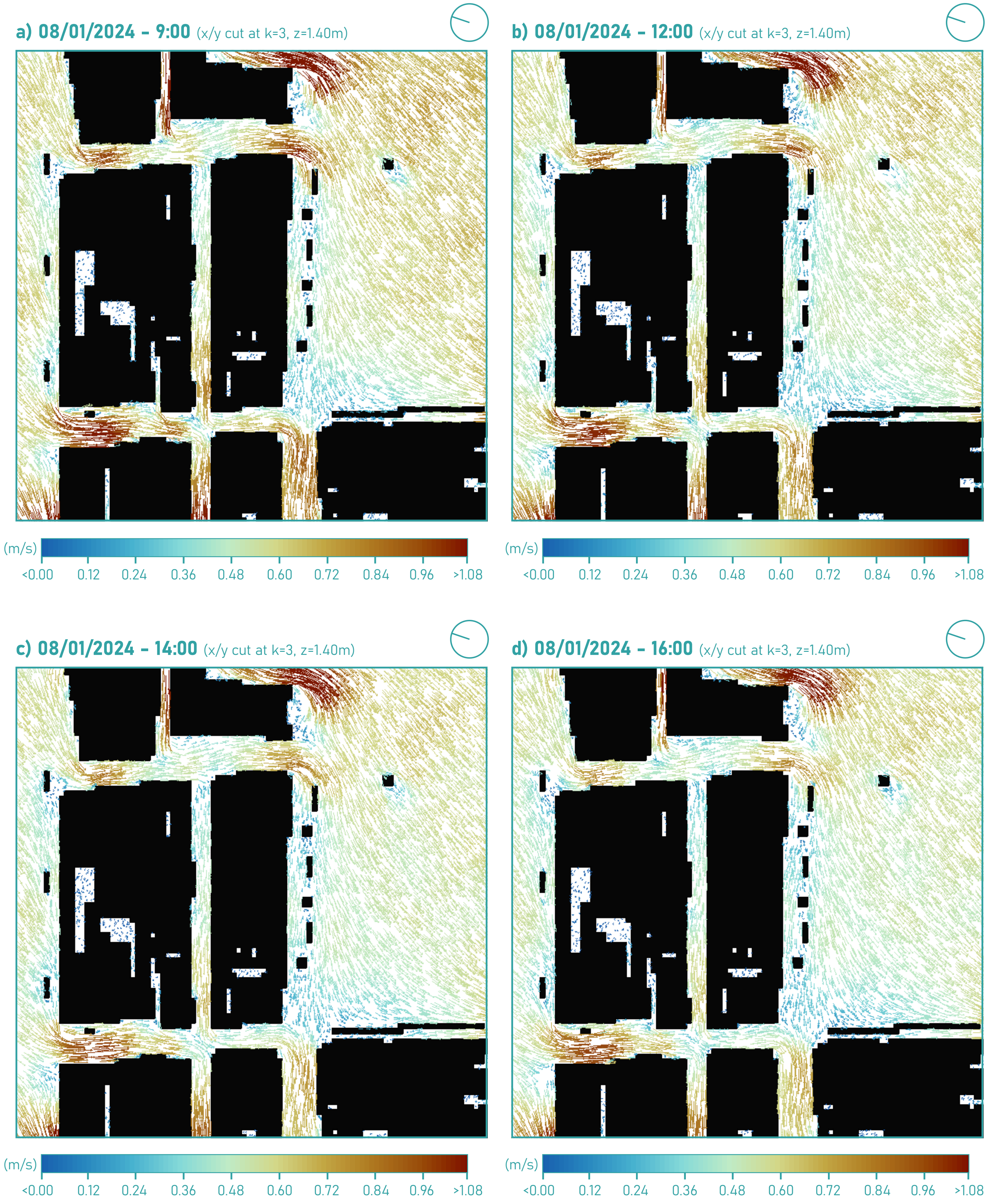
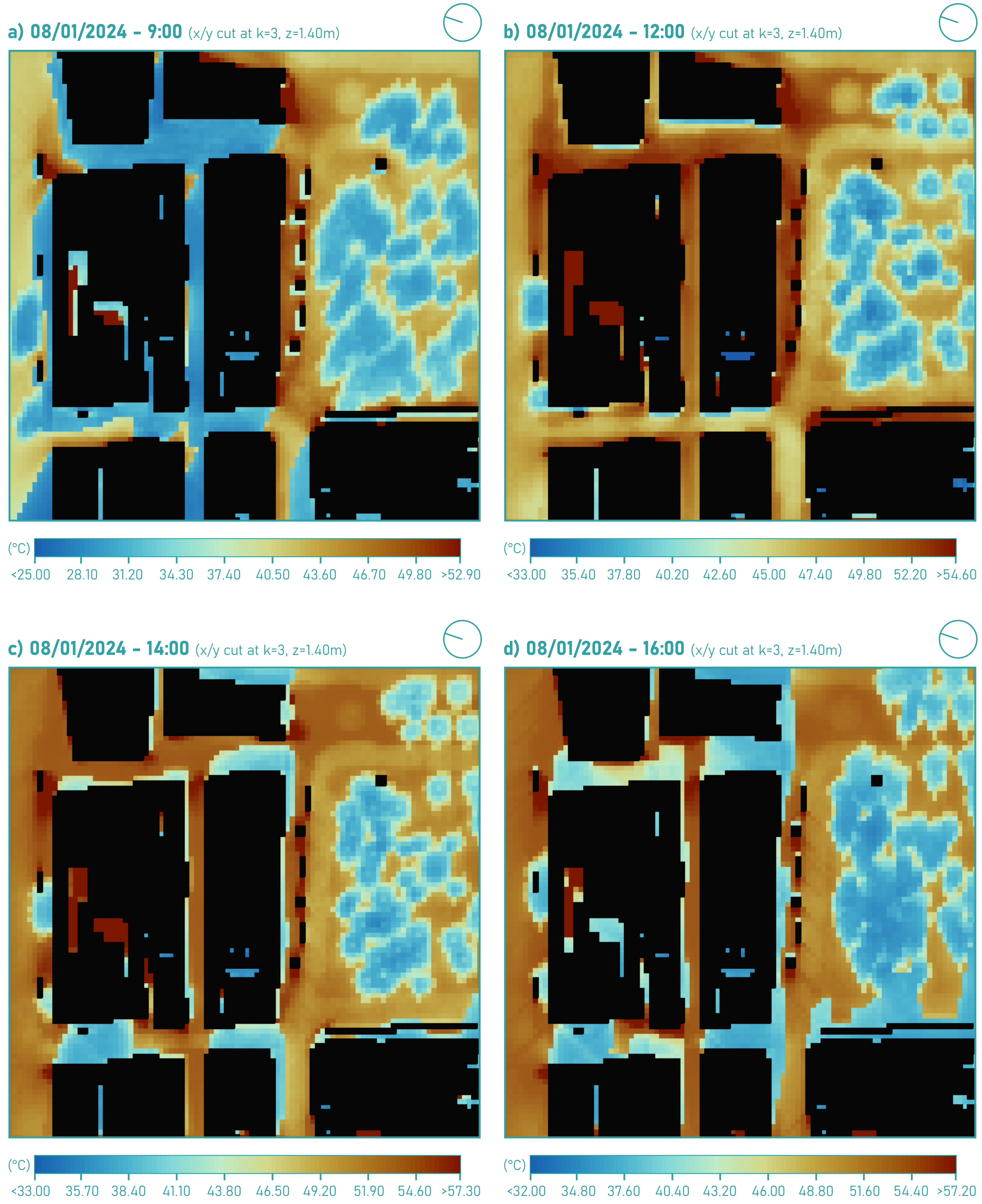


Fig. 121: Site 13 - Current scenario - Physiologically Equivalent Temp. (PET) maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00. Source: The author

Physiologically Equivalent Temperature - PET



The analysis of the current scenario highlights several positive aspects of the segment, including its designation as a pedestrian-only street and its significant cultural and symbolic value for the city. These characteristics give the space an active and vibrant atmosphere, with potential to further enhance its appeal and to establish a green network connected to the adjacent Tiradentes Square.

Additionally, it is worth noting that, due to the shading provided by the buildings, the area experiences milder temperatures and greater thermal comfort in the morning compared to the surrounding regions (Figure 121a). However, because of its east-west orientation, the segment receives high solar exposure throughout the rest of the day, which, combined with the fully impervious surface and lack of vegetation, contributes to a significant temperature increase. These factors are evident in the simulation results, which indicate PET values above 47 °C (Figure 121) and surface temperatures (Figure 119) around 40 °C from 12 p.m. onwards. Moreover, as also observed in the previous segment, the area presents very low wind speed (Figure 120) values across all analyzed times, further reinforcing this scenario.

Given the narrow width of the street, strategies that allow for small-scale and space-efficient implementation are more appropriate. Special care should be taken to avoid obstructing pedestrian flow or impeding access for emergency vehicles. Ensuring adequate artificial lighting at night is also crucial to maintain safety for passersby. Additionally, it is essential to preserve the historical character of the area, which is defined by its traditional façades and Portuguese stone pavement. In this context, the implementation of urban meadows and under-drained rain garden strips is proposed, complemented by large shrubs and small-scale trees.

Table 12: Site 13 - SWOT analysis. Source: The author

Site 13 - SWOT analysis	
Strengths	▪ Exclusively pedestrian street with active ground-floor commerce. ▪ Significant cultural and historical importance. ▪ Proximity to green areas of Tiradentes Square. ▪ Lower morning temperatures due to building shading.
Weaknesses	▪ Limited space for interventions due to the narrow street width. ▪ High solar exposure throughout the day, leading to elevated temperatures. ▪ Fully impervious surface with no presence of vegetation. ▪ Low wind circulation within the segment.
Opportunities	▪ Potential to enhance pedestrian appeal. ▪ Opportunity for the inclusion of small-scale structures. ▪ Potential to establish a connection with the green infrastructure of the adjacent square.
Threats	▪ Possible obstruction of pedestrian and emergency vehicle circulation. ▪ Limitation of artificial lighting during nighttime hours. ▪ Risk of adding structures incompatible with the narrow width of the street. ▪ Potential loss of the area's historical and cultural character.

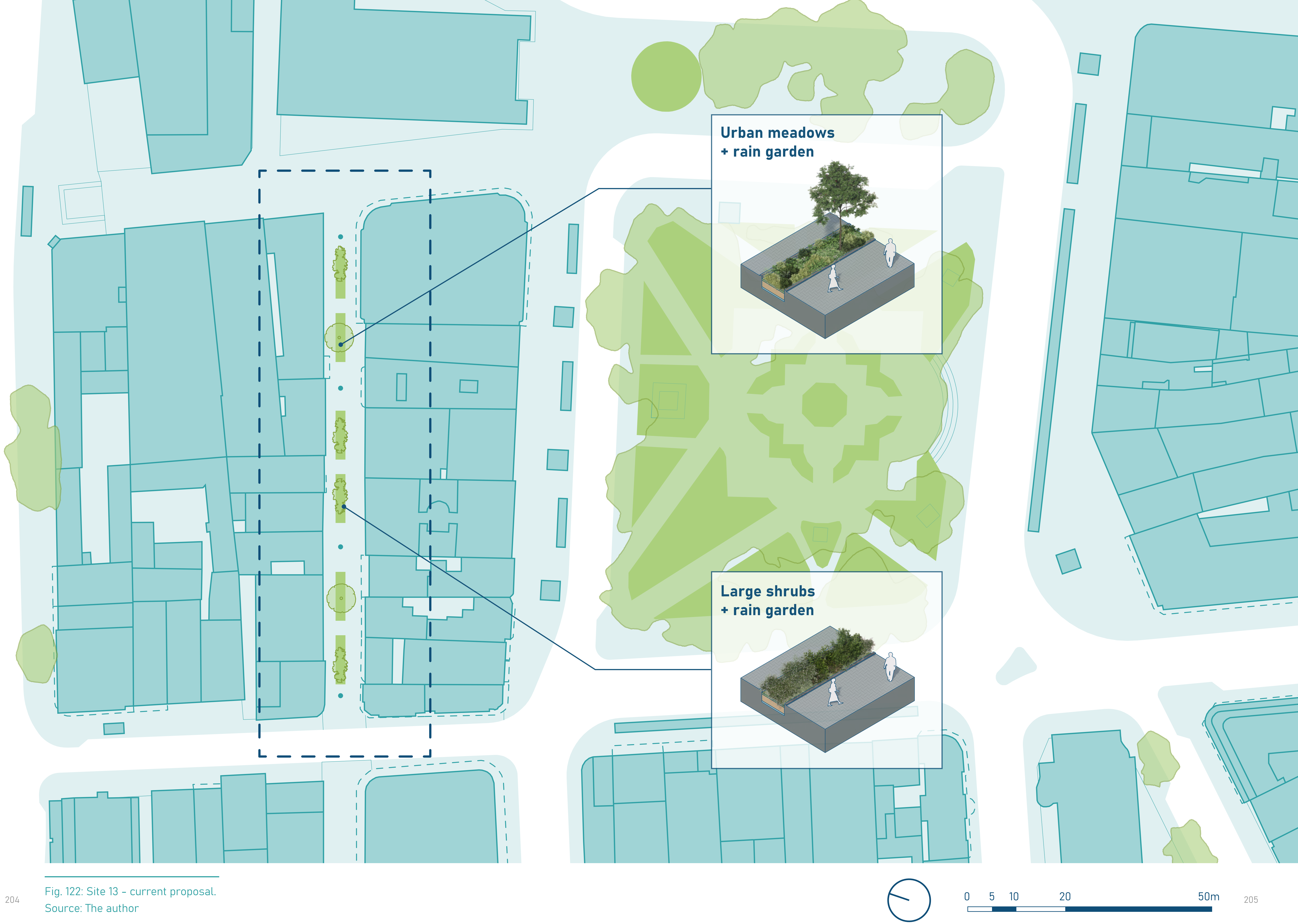


Fig. 122: Site 13 - current proposal.
Source: The author

Fig. 123: Site 13 - proposal.
Source: AI-generated image (OpenAI) based on personal project - adapted by the author

Fig. 124: Site 13 - Proposal - Potential Air Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Potential Air Temperature

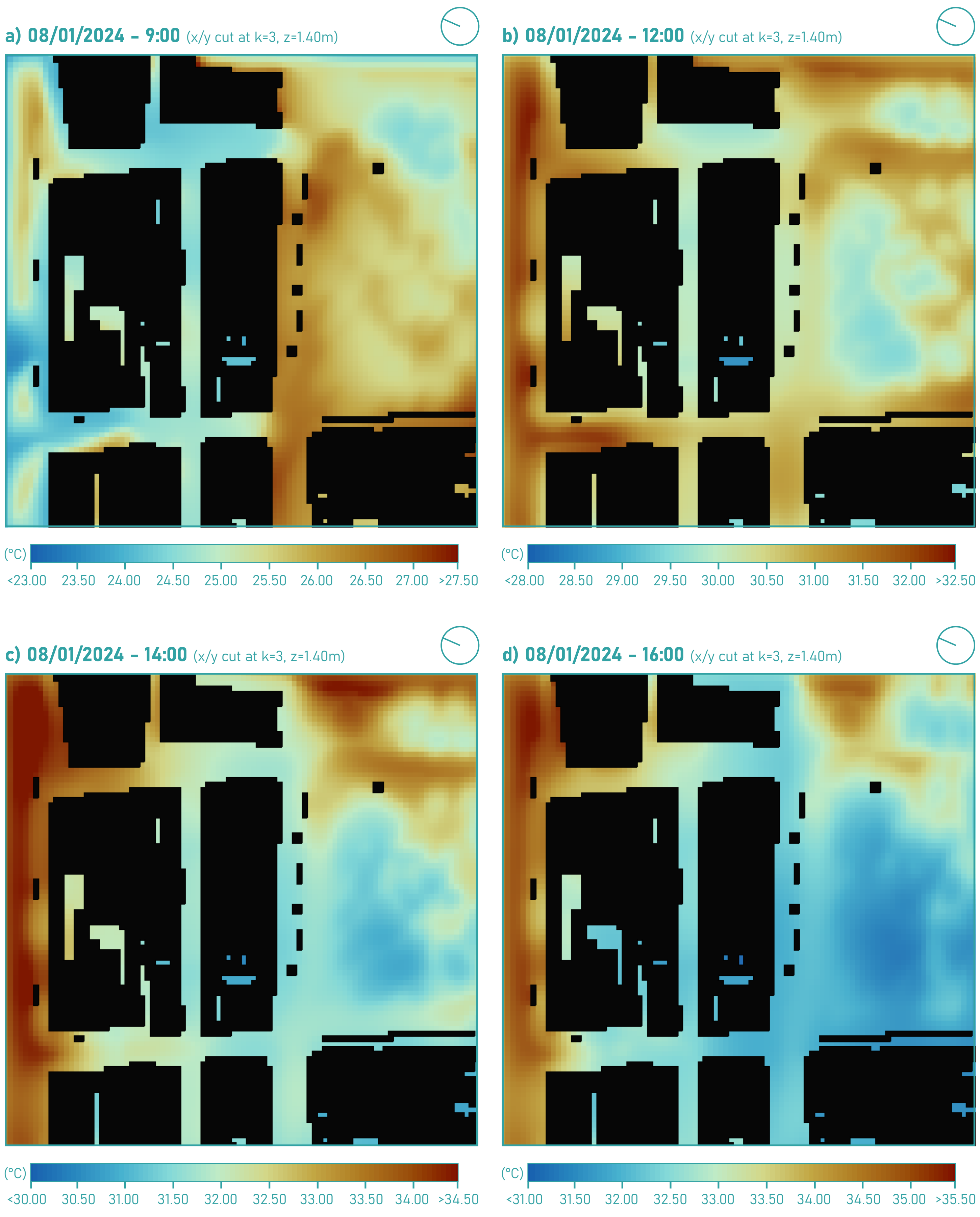
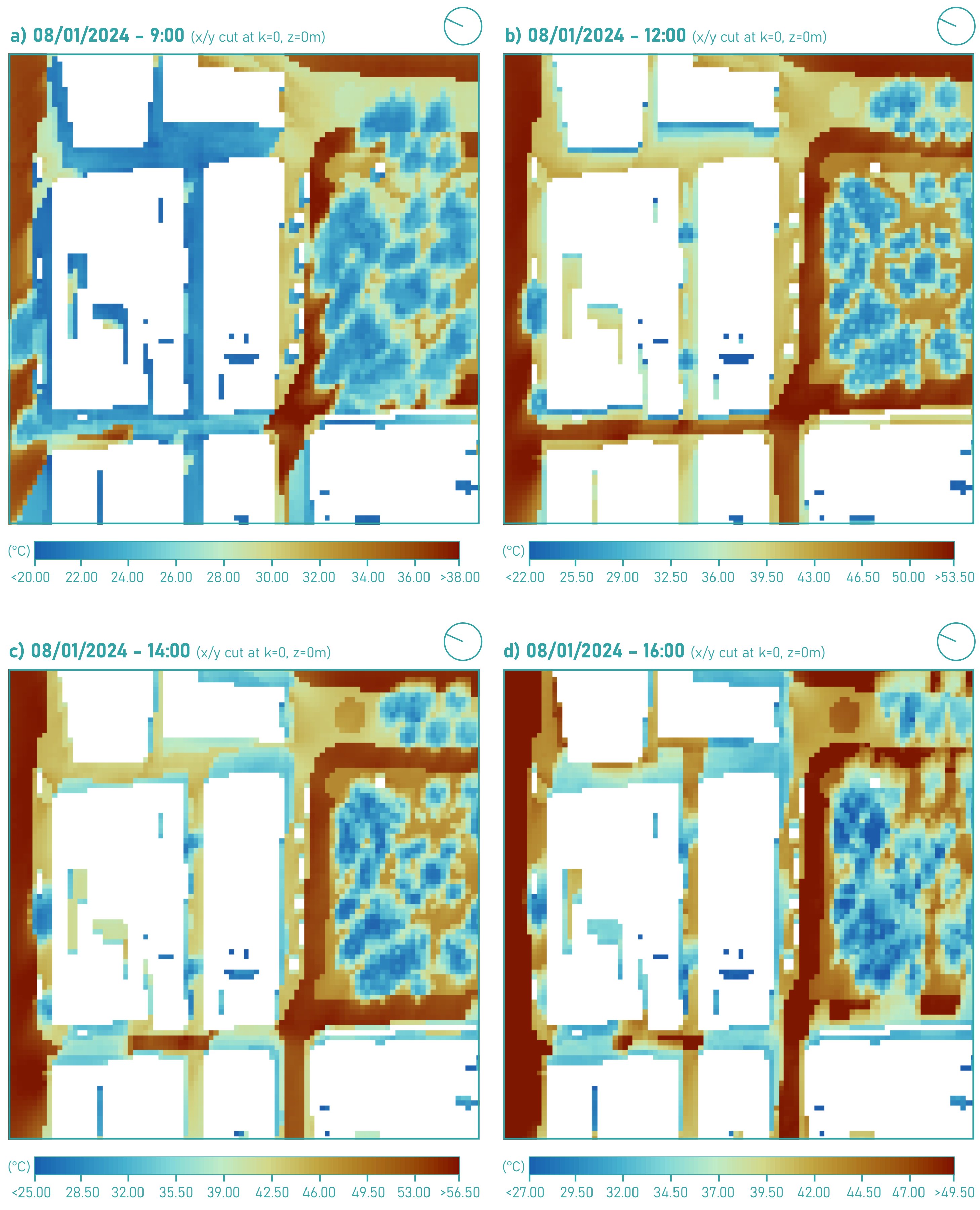


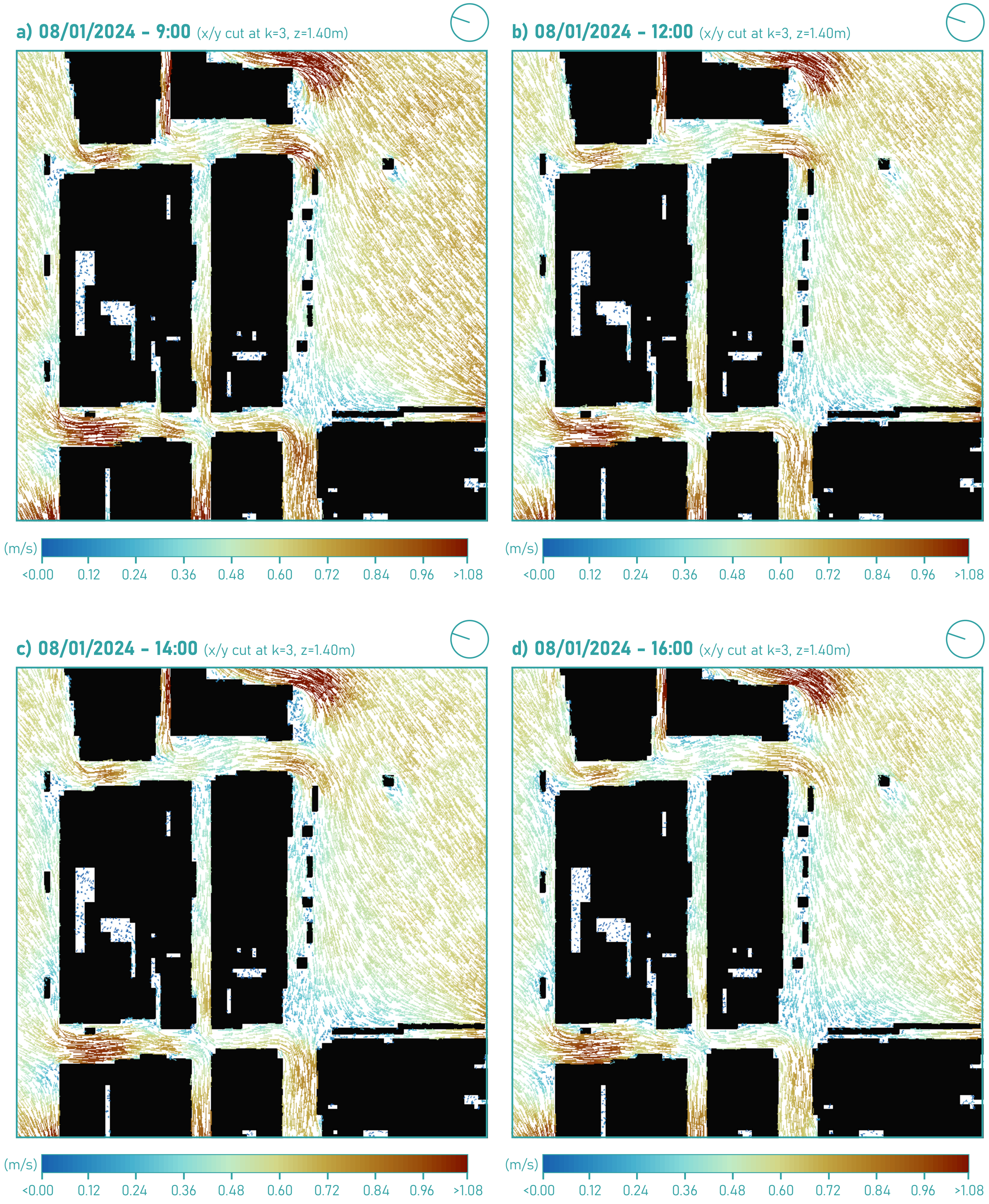
Fig. 125: Site 13 - Proposal - Surface Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Surface Temperature



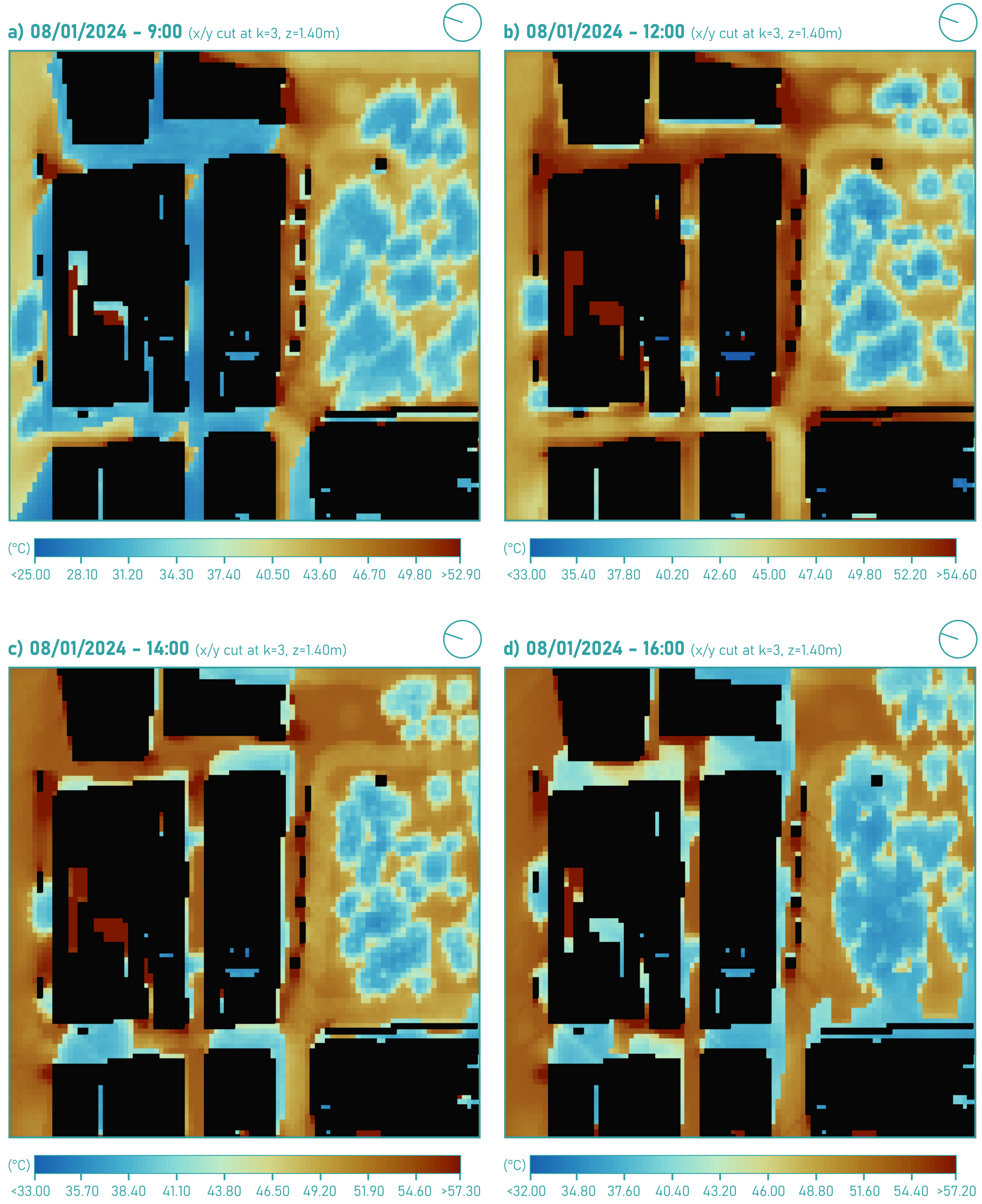
Wind speed

Fig. 126: Site 13 - Proposal - Wind speed maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author



Physiologically Equivalent Temperature - PET

Fig. 127: Site 13 - Proposal - Physiologically Equivalent Temp. (PET) maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author



When analyzing the Potential Air Temperature maps for site 13 (Figure 124), few changes are observed compared to the current situation, indicating a limited effect of the implemented strategies in this regard. On the other hand, the Surface Temperature results show small variations in areas where Nature-Based Solutions (NBS) were applied, with reductions of up to 4 °C at 2:00 p.m. (Fig 125c) and reaching 6 °C at 4:00 p.m (Figure 125d). As in the first site, the implementation of trees, even of small size, proved to be the most effective measure.

Regarding the wind speed maps (Figure 126), a slight variation can be observed at one end of the street; however, overall, values remain below 1 m/s and are nearly zero at the other end.

Regarding Physiological Equivalent Temperature (PET) values (Figure 127), the shading effect on reducing thermal stress is clearly evident. In the area, small trees led to significant variations in results before and after the intervention. As shown in Figure 128 and 129, which compares PET values at the point of greatest NBS impact, reductions from 53.66 °C to 40.64 °C at 2:00 p.m. and from 44.20 °C to 40.74 °C at 4:00 p.m. can be observed — both times corresponding to peak solar exposure.

Although large shrubs and urban meadows show only modest effects on temperature reduction, these strategies proved effective as soil unsealing measures, resulting in a total of 8% of permeable surface in the section. Moreover, since these structures require little space for implementation, they preserve the unique historical character of the site.

08/01/2024 - 12:00 (x/y cut at k=3, z=1.40m)

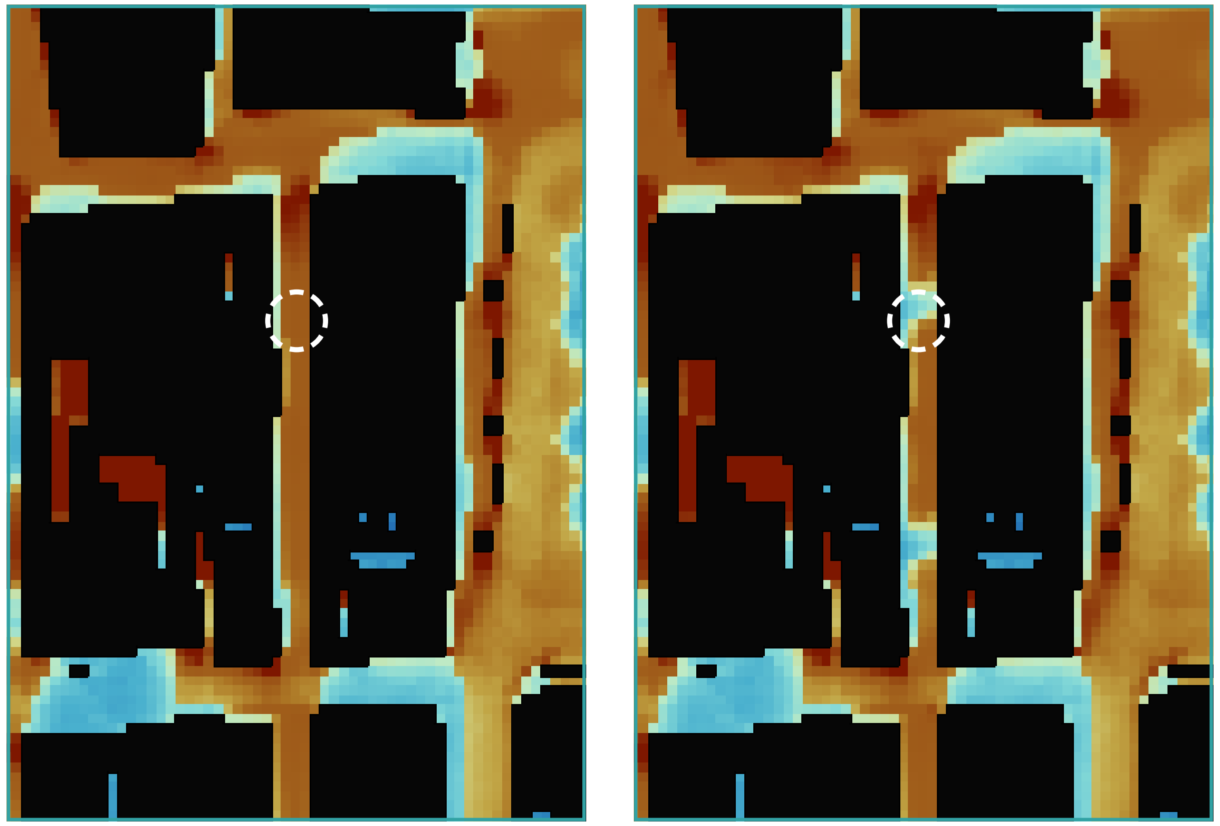


Fig. 128: Site 13 - PET peak variation point.
Source: The author

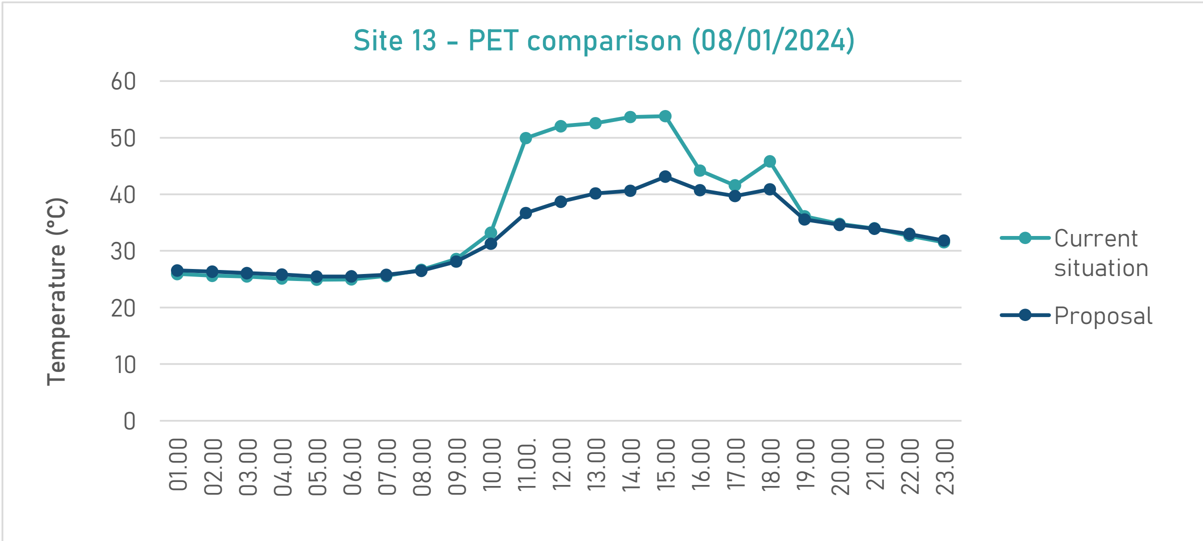


Fig. 129: Site 13 - PET peak variation point comparison before and after intervention.
Source: The author

3.3.3 Site 16: R. Brig. Franco (between Al. Carlos de Carvalho and Av. Vicente Machado)

Site number 16 is located on Brigadeiro Franco Street, in the segment between Carlos de Carvalho Avenue and Vicente Machado Avenue, in the Centro neighborhood (Figure 130 and 131). The area is characterized by high built density, with an aspect ratio of 1.26 and buildings reaching heights of up to 102 meters. This results in limited sunlight exposure throughout the day.

The site's region is characterized by a high concentration of tertiary-sector activities, with a diverse offering of restaurants, shops, and specialized services, as well as proximity to commercial centers and public squares. However, in the segment under analysis, vehicular circulation prevails, supported by wide road infrastructure, inactive frontages, and sidewalks that are essentially impermeable and sparsely vegetated, resulting in a pedestrian-hostile environment. It is worth noting, however, the recent planting of trees along the street, which are currently still in the seedling stage.

Segment length **145m**

Average segment width **25.10m**

Soil permeability **2.00%**

Vegetation cover **4,22%**

Height/Width Ratio **1.26**

Fig. 130 and 131: Street view Site 16 - R. Brig. Franco.
Source: Google maps

Fig. 132: Site 16 - current situation.
Source: The author

Fig. 133: Site 16 - Current scenario - Potential Air Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Potential Air Temperature

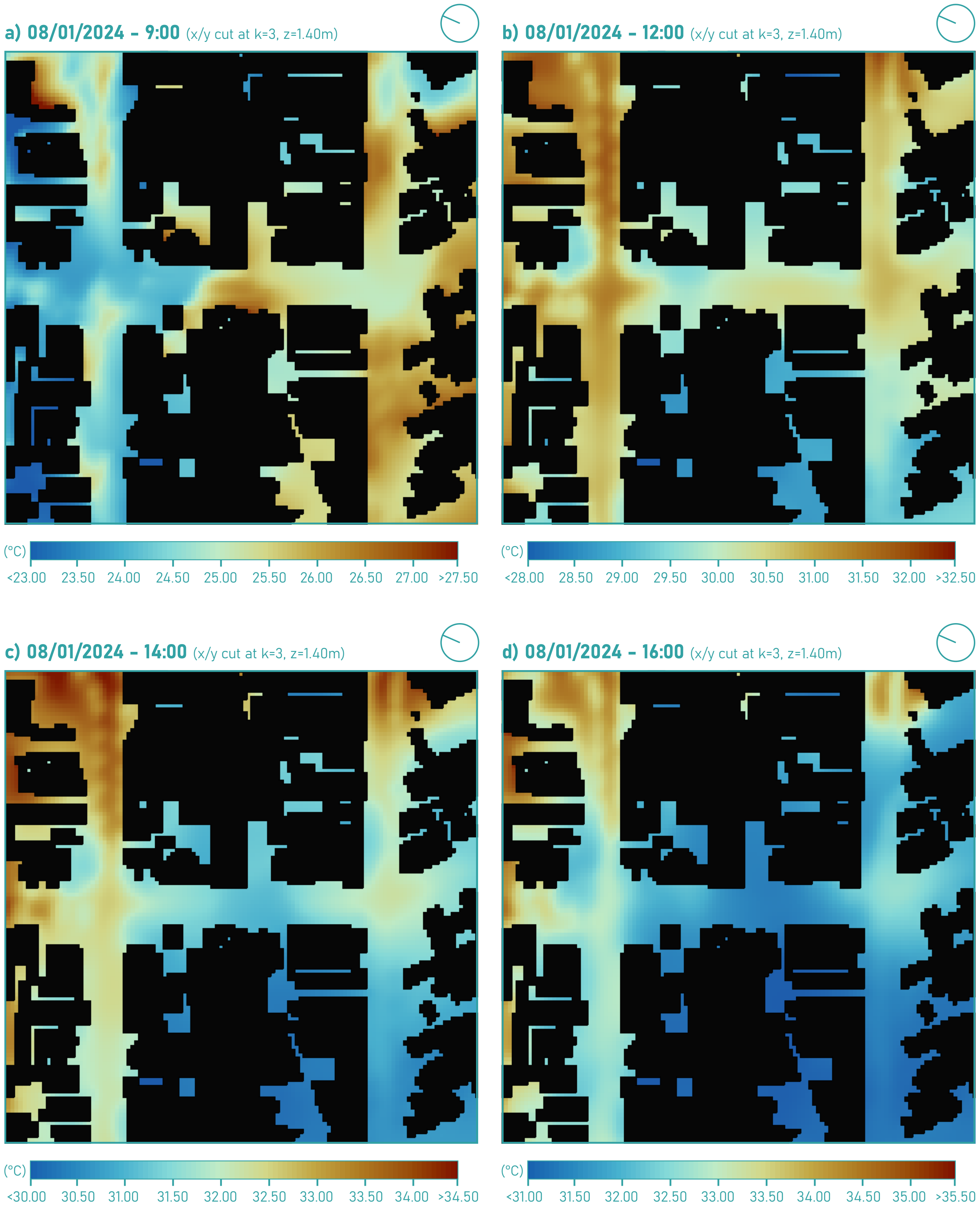


Fig. 134: Site 16 - Current scenario - Surface Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Surface Temperature

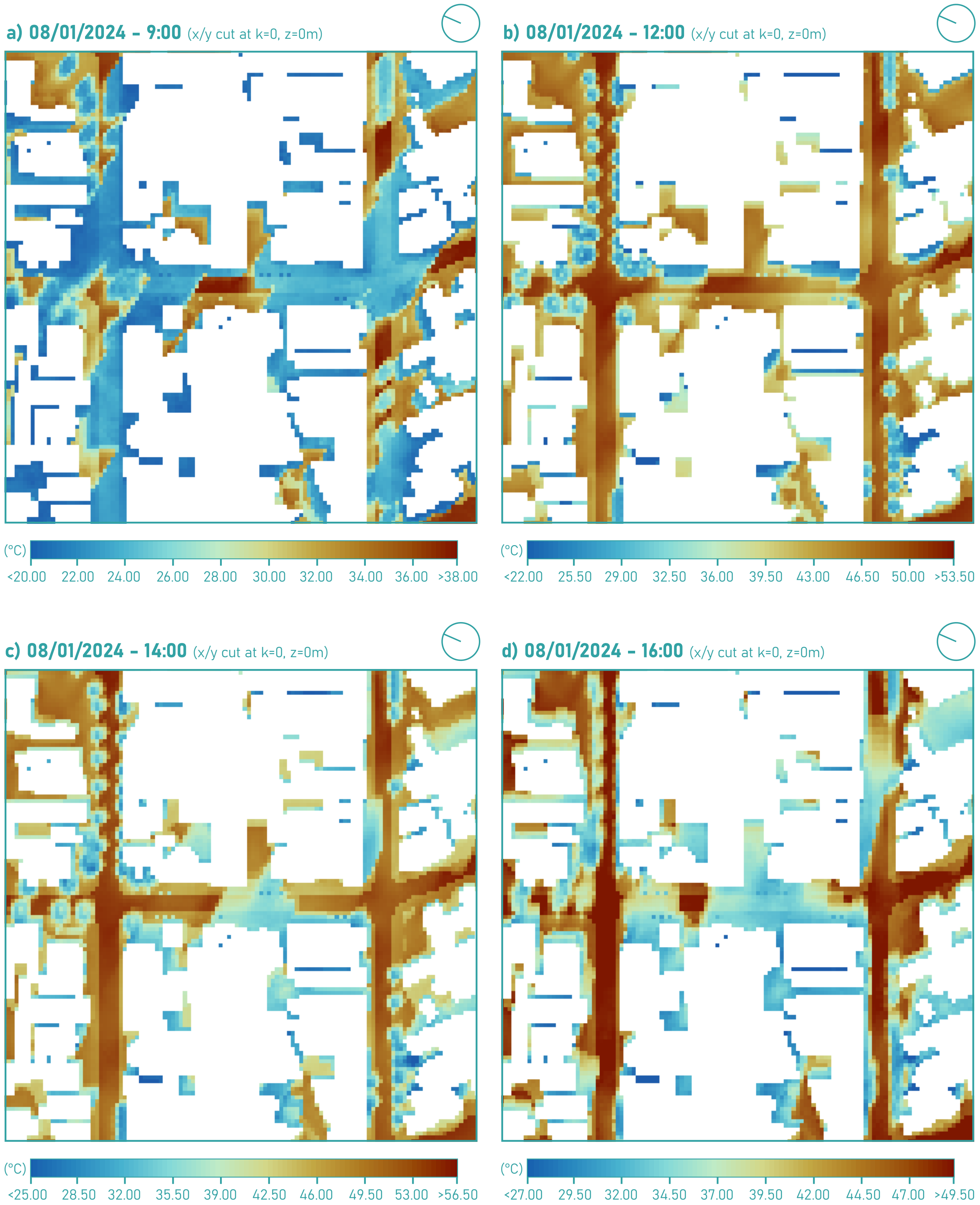
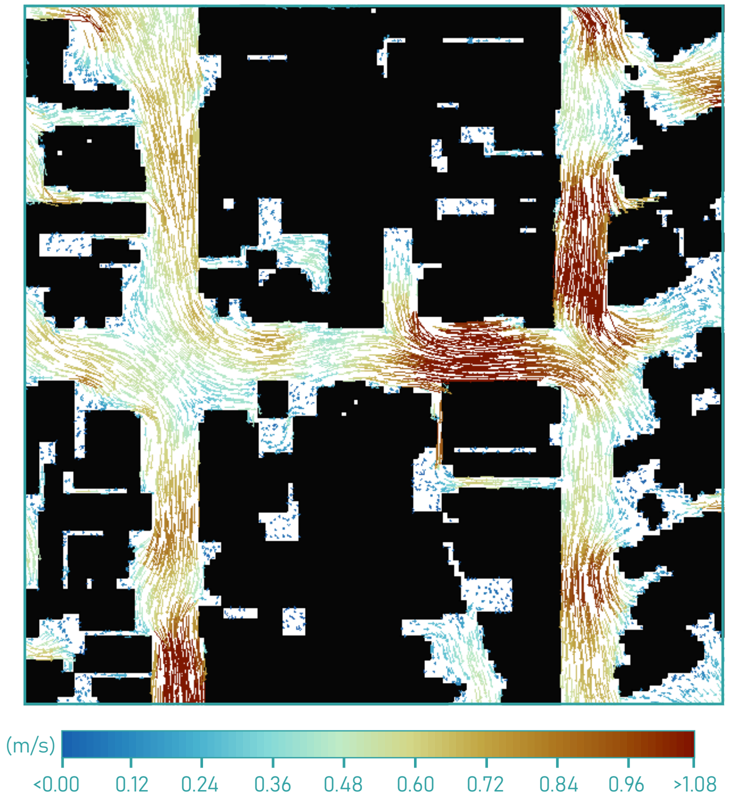


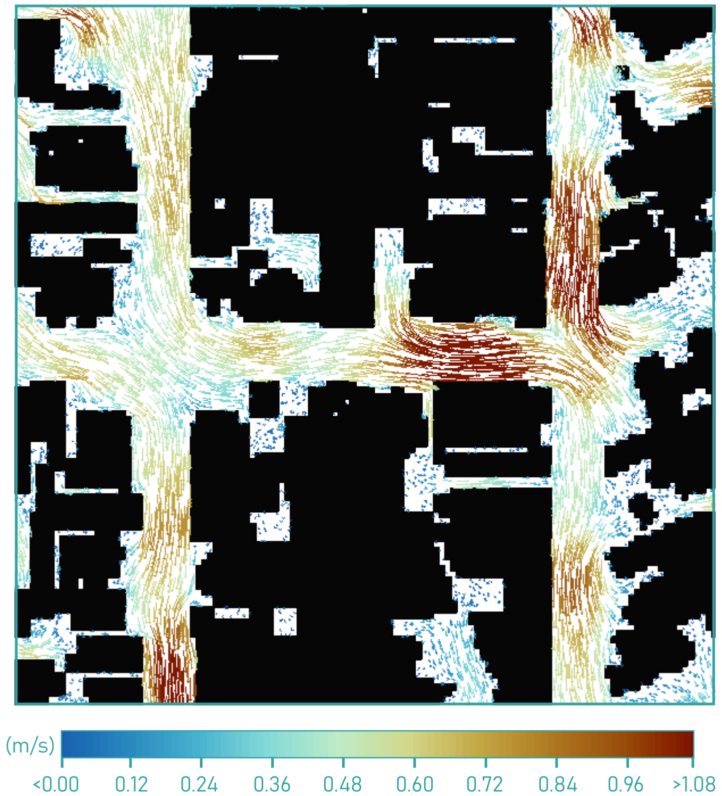
Fig. 135: Site 16 - Current scenario - Wind speed maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Wind speed

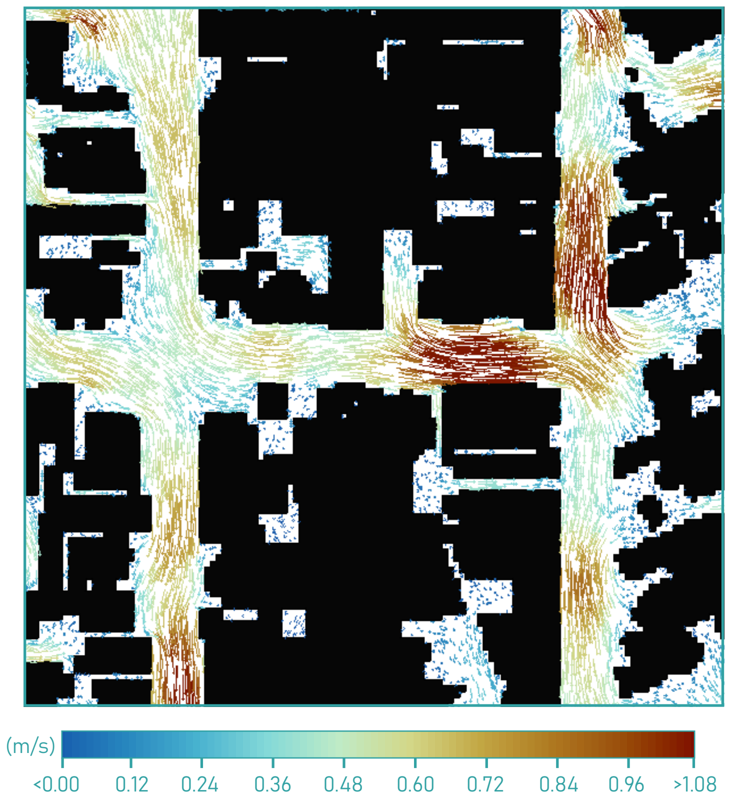
a) 08/01/2024 - 9:00 (x/y cut at k=3, z=1.40m)



b) 08/01/2024 - 12:00 (x/y cut at k=3, z=1.40m)



c) 08/01/2024 - 14:00 (x/y cut at k=3, z=1.40m)



d) 08/01/2024 - 16:00 (x/y cut at k=3, z=1.40m)

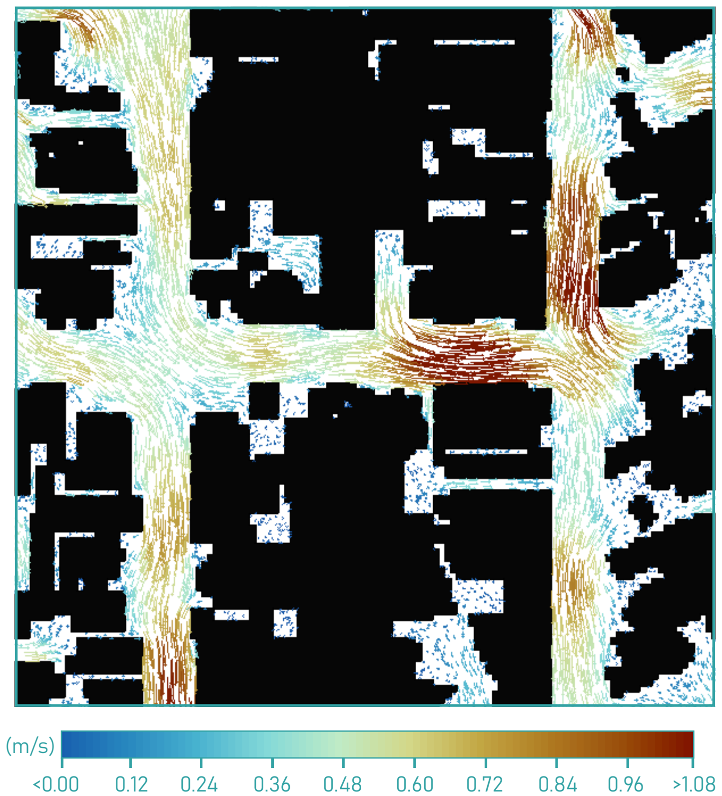
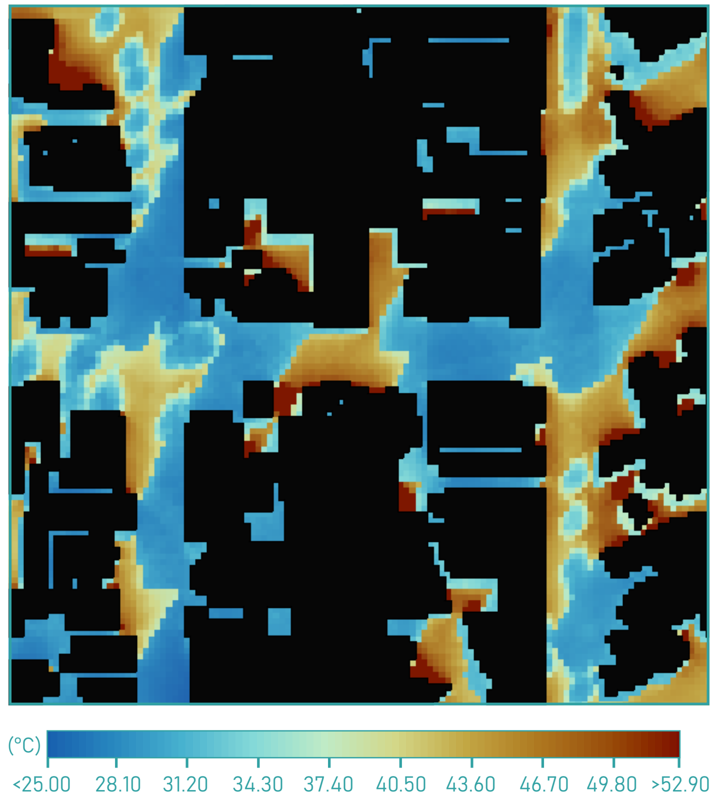


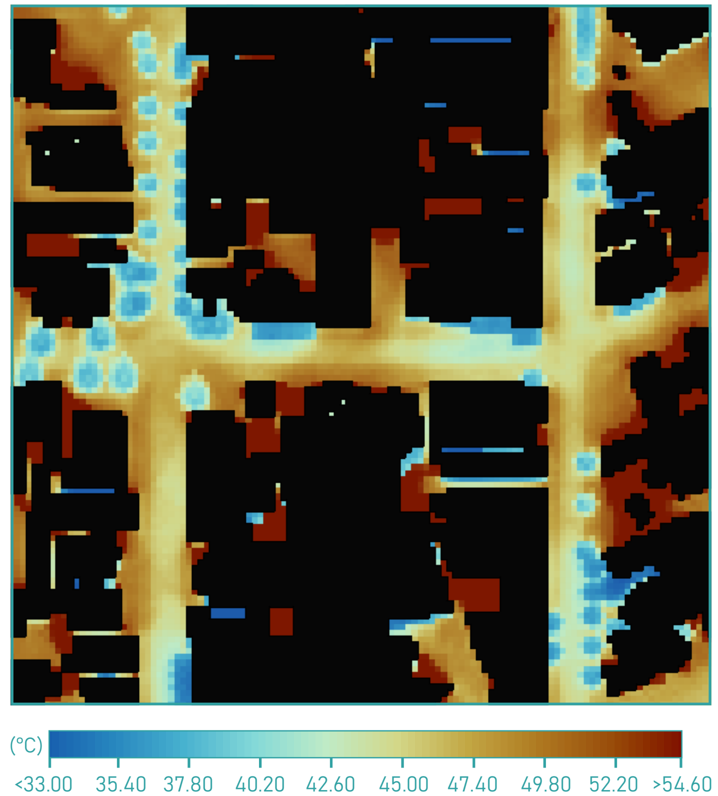
Fig. 136: Site 16 - Current scenario - Physiologically Equivalent Temp. (PET) maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Physiologically Equivalent Temperature - PET

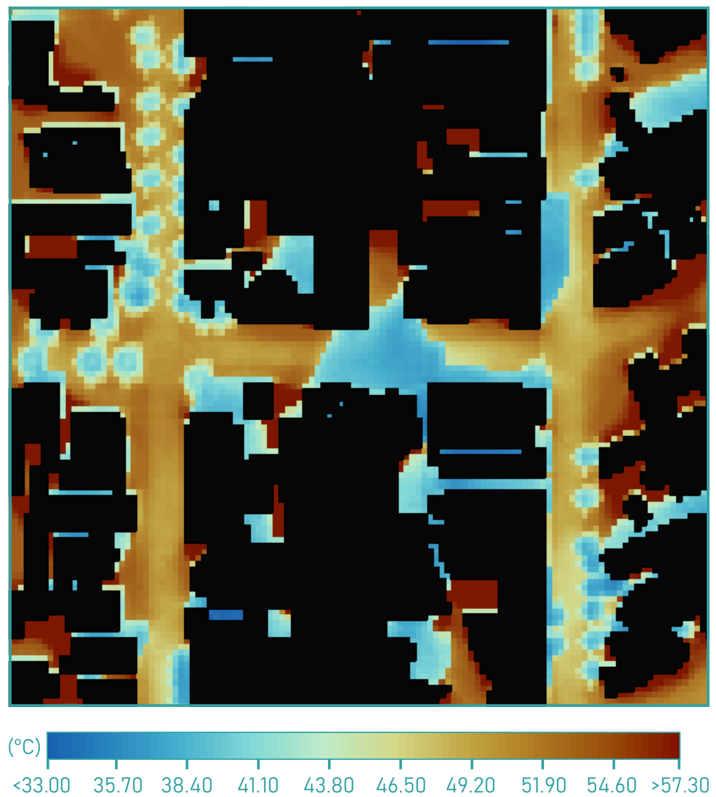
a) 08/01/2024 - 9:00 (x/y cut at k=3, z=1.40m)



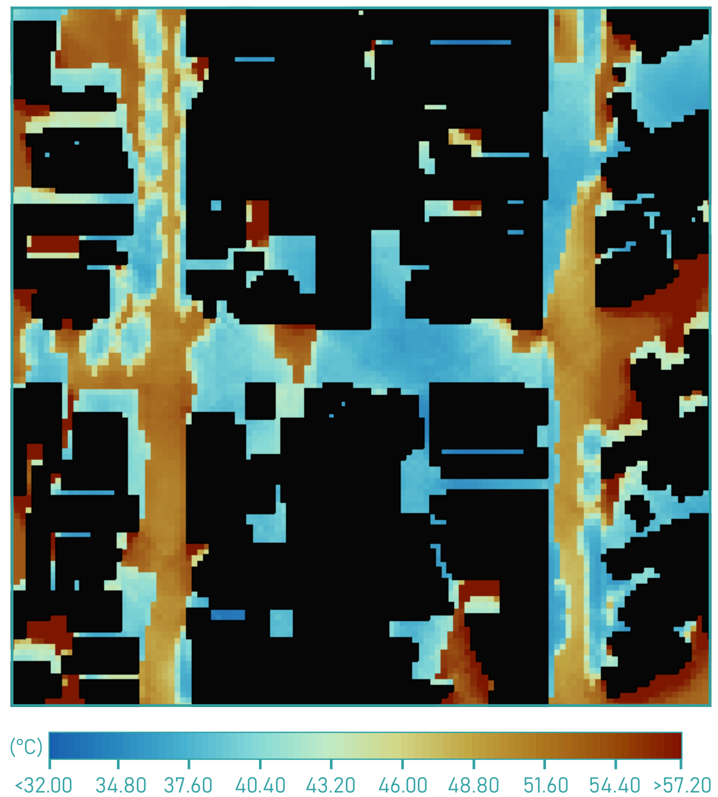
b) 08/01/2024 - 12:00 (x/y cut at k=3, z=1.40m)



c) 08/01/2024 - 14:00 (x/y cut at k=3, z=1.40m)



d) 08/01/2024 - 16:00 (x/y cut at k=3, z=1.40m)



One of the main strengths of the analyzed site is its strategic location within an area offering a diverse range of commercial and service establishments, along with close proximity to recreational spaces. This context presents a valuable opportunity to integrate the site into the surrounding urban fabric.

In terms of climatic conditions, the layout and considerable height of the surrounding buildings result in slightly milder local temperatures compared to adjacent areas that are exposed to direct solar radiation for longer periods. This effect is evident in the potential air temperature map (Figure 133) and the PET map (Figure 136). The site also experiences higher wind speeds than its immediate surroundings (Figure 135), contributing to this microclimatic condition. However, except during the morning hours, the area consistently exhibits levels of thermal stress for pedestrians — ranging from slight (above 25 °C) to high (above 37 °C) — as indicated by the PET maps (Figure 136).

Among the segment's main weaknesses is the prioritization of vehicle traffic over pedestrians, as evidenced by wide roadways, predominantly inactive façades, and sparse vegetation, which is confined for the most part to private lots, all contributing to significant soil impermeabilization. While future benefits are anticipated from the recent tree planting efforts, these measures have yet to deliver immediate pedestrian comfort and could be more effective if combined with rapid-impact interventions.

It is therefore proposed to implement large shrubs combined with rain gardens to buffer pedestrian and vehicle flows. These strategies also significantly improve soil permeability and air quality, enhance walkability, and increase the area's overall attractiveness. However, it is essential that these measures do not impede existing airflow, obstruct pedestrian circulation or building access, and that they ensure nighttime safety through adequate street lighting.

Table 13: Site 16 - SWOT analysis. Source: The author

Site 16 - SWOT analysis	
Strengths	▪ An area well served by commerce and services, and located near recreational spaces. ▪ Enhanced wind flow relative to surrounding areas. ▪ Shading from buildings contributes to moderately reduced daytime temperatures relative to adjacent areas. ▪ Recent planting of tree saplings along the roadway.
Weaknesses	▪ The segment prioritizes high vehicle flow over pedestrian circulation, featuring wide roadways and predominantly inactive building façades. ▪ High soil impermeability throughout the entire segment. ▪ Although lower than in neighboring areas, temperatures remain high, with PET values predominantly indicating thermal stress. ▪ Vegetation is limited and mostly private, with recent saplings not yet benefiting pedestrian comfort.
Opportunities	▪ Potential for green infrastructure additions on sidewalks. ▪ Increase attractiveness for pedestrians by integrating the area with commercial and leisure zones. ▪ Potential to buffer pedestrian and vehicle flows through vegetative barriers, improving air quality and walkability.
Threats	▪ Blockage of the current airflow in the segment. ▪ Obstruction of pedestrian flow and building entrances. ▪ Compromise of pedestrian safety during nighttime hours.

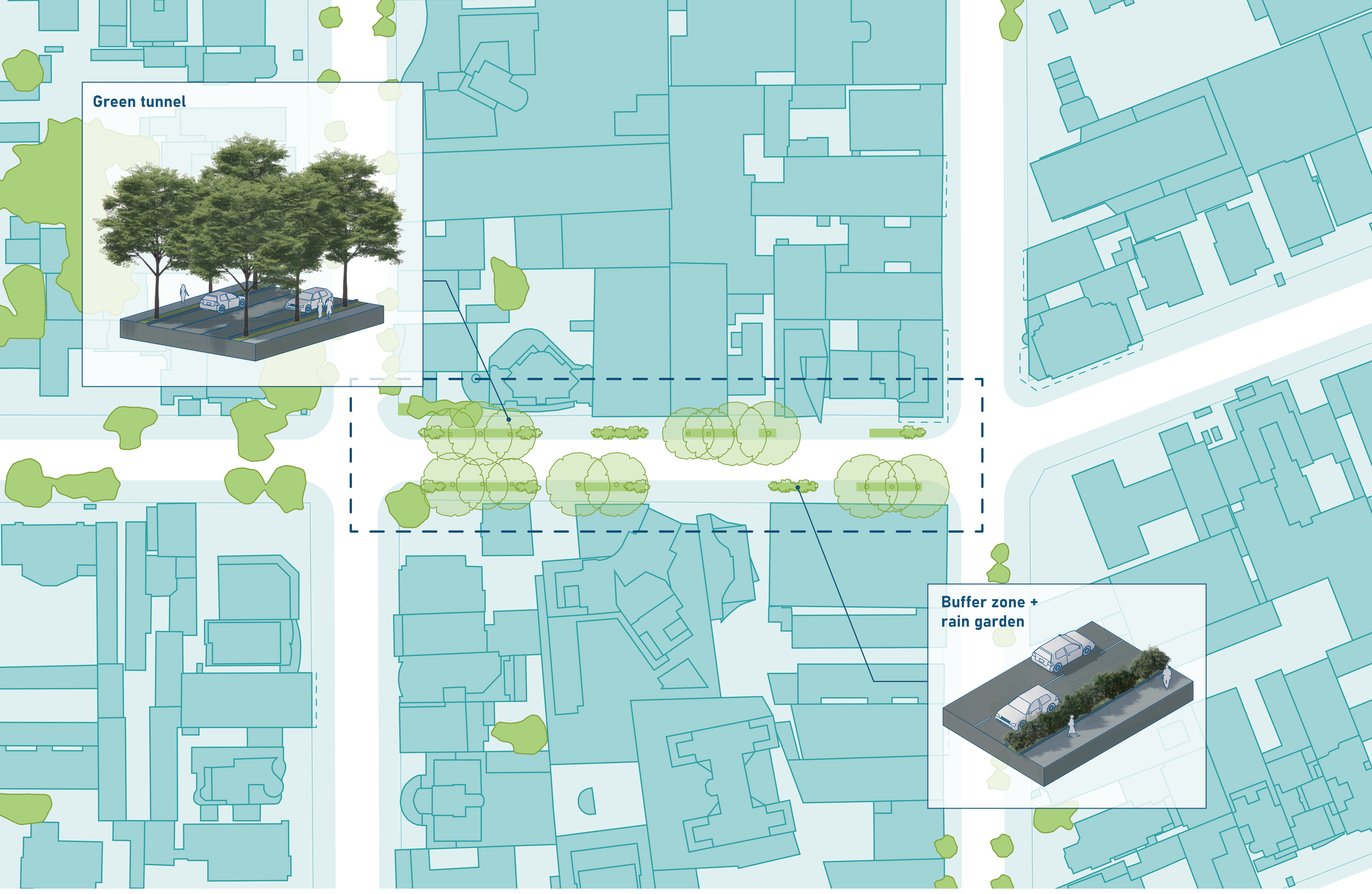


Fig. 137: Site 16 - proposal.
Source: The author

Fig. 138: Site 16 - proposal.
Source: AI-generated image (OpenAI) based on personal project - adapted by the author

Fig. 139: Site 16 - Proposal - Potential Air Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Potential Air Temperature

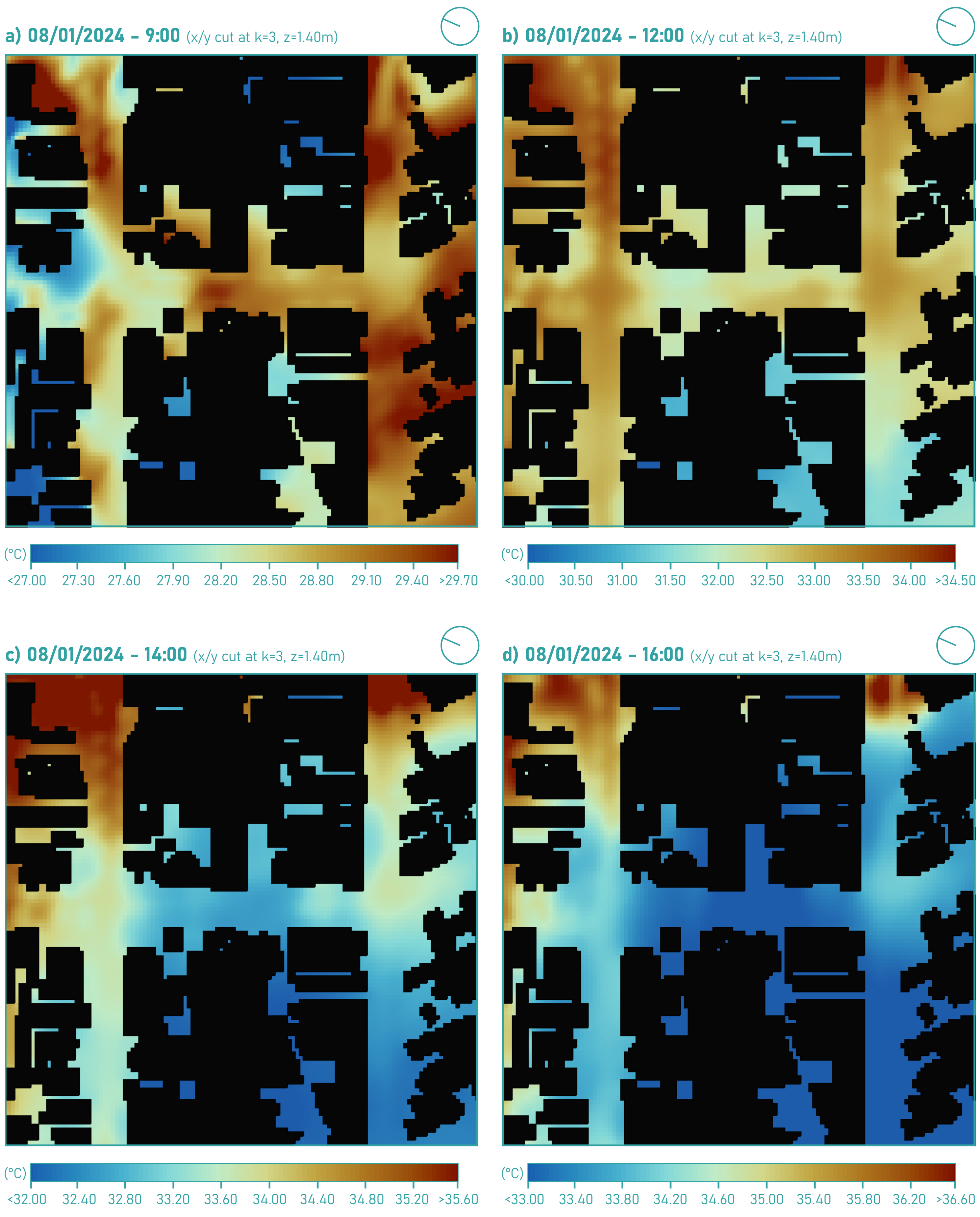


Fig. 140: Site 16 - Proposal - Surface Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Surface Temperature

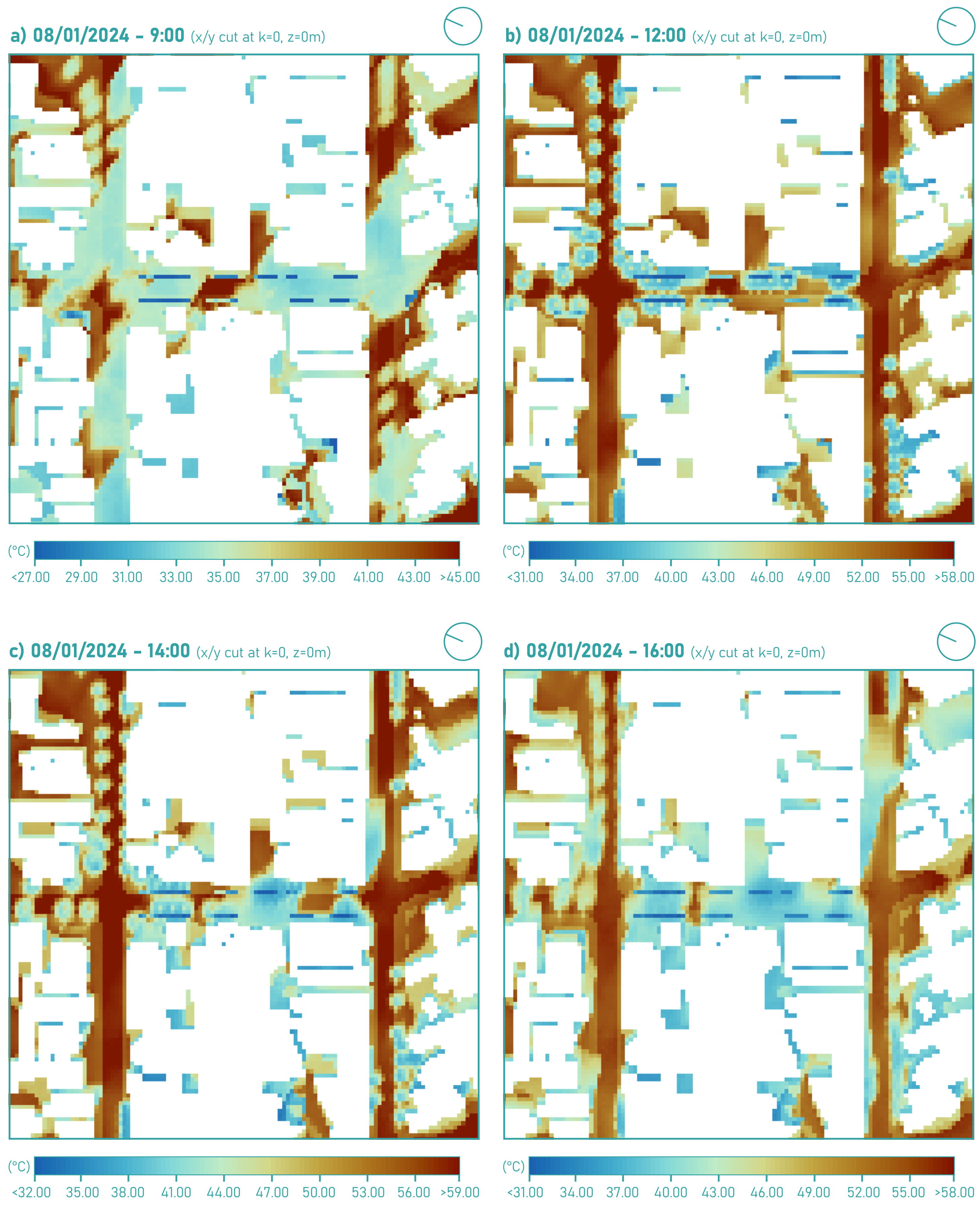


Fig. 141: Site 16 - Proposal - Wind speed maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Wind speed

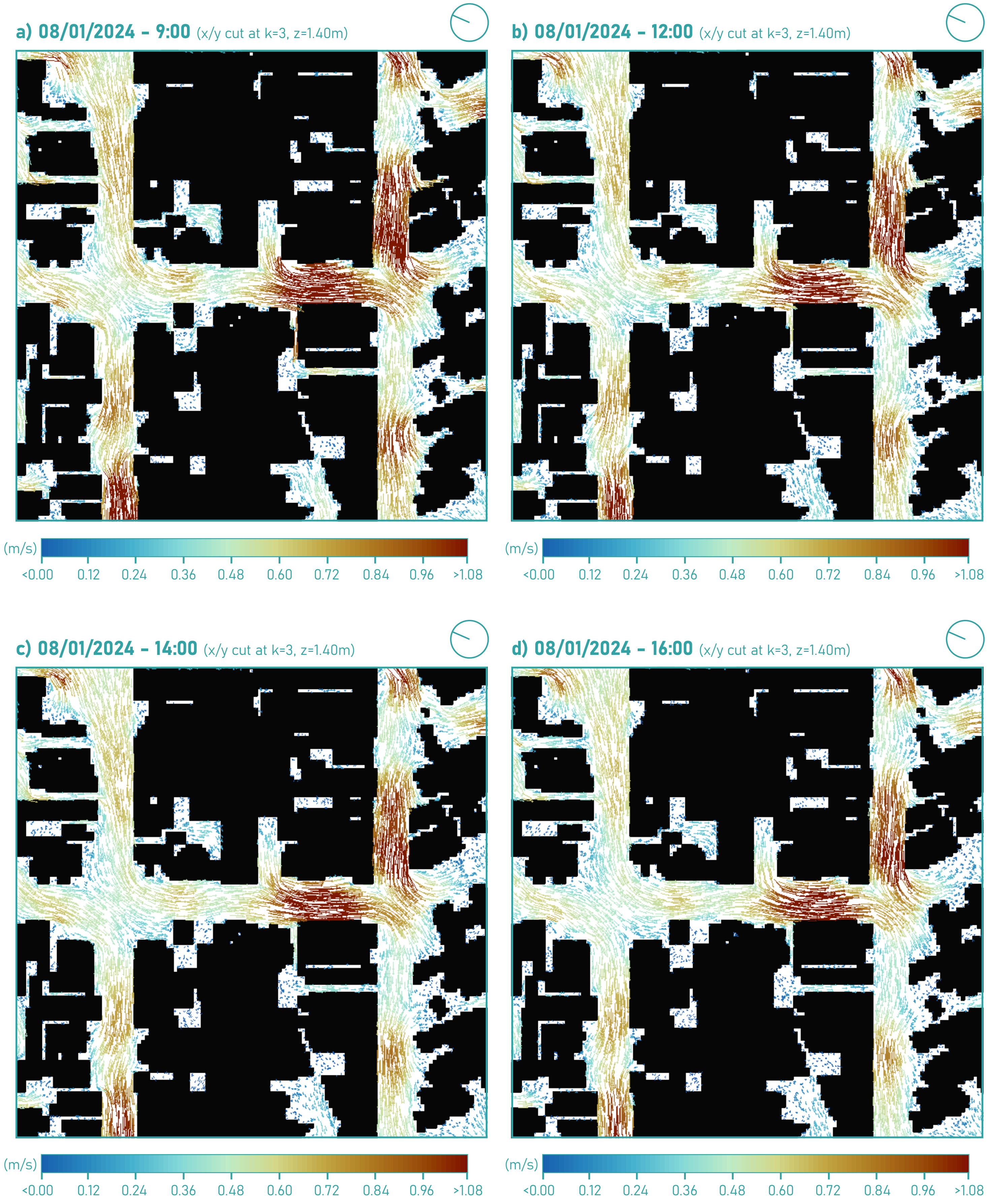
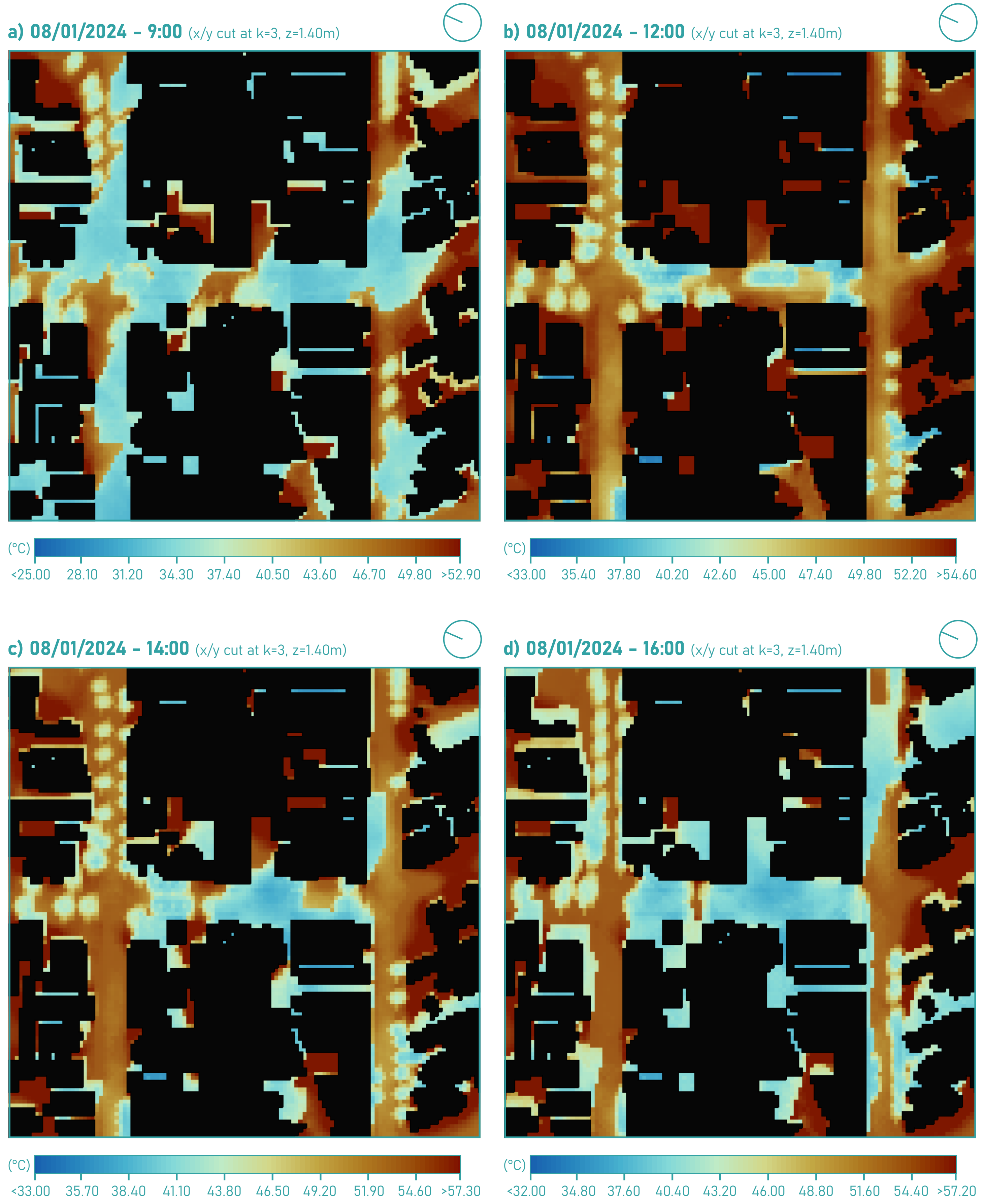


Fig. 142: Site 16 - Proposal - Physiologically Equivalent Temp. (PET) maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Physiologically Equivalent Temperature - PET



In analyzing the results of the strategies applied to site 16, it is essential to account for certain limitations inherent to the ENVI-met software. Methodological discrepancies arising from recent system updates affected the calculation of microclimatic variables, leading to significant variations in baseline temperature between the current and proposed scenarios. Consequently, the evaluation will be based solely on the maps generated for the intervention scenario, with comparisons drawn against the immediate surroundings to ensure greater interpretative consistency of the simulated data.

Although the area already experiences limited solar exposure, the presence of tree canopies significantly expands shaded zones. As a result, differences of up to 3 °C in Potential Air Temperature can be observed when compared to adjacent sun-exposed areas, as shown in Figure 139.

This cooling effect, resulting from increased shading, is also evident in the Physiological Equivalent Temperature (PET) maps, particularly at 12:00 (Figure 142b), further reinforcing the role of vegetation in microclimate regulation. Consequently, a significant reduction in local thermal stress is observed, as illustrated in Figure 143 and 144, which highlights spatial variations between areas with and without tree canopy coverage.

In terms of wind speed, the presence of large-scale vegetation does not result in a significant reduction, thereby preserving natural ventilation within the area and maintaining favorable conditions for heat dissipation and air exchange.

The Surface Temperature maps further demonstrate the effectiveness of planted beds and large shrubs in reducing ground surface temperatures. Substantial differences are observed throughout the simulation period (Figure 140), with temperature gaps exceeding 25 °C between asphalt-covered areas and natural ground cover, particularly at 12:00 and 14:00 (Figure 140b and c).

Additionally, the intervention resulted in a notable increase in ground permeability, with permeable surface coverage rising from 2% to 8.2%. This change contributes not only to improved stormwater infiltration and reduced surface runoff but also supports microclimatic regulation by enhancing soil moisture retention and evapotranspiration capacity in vegetated zones.

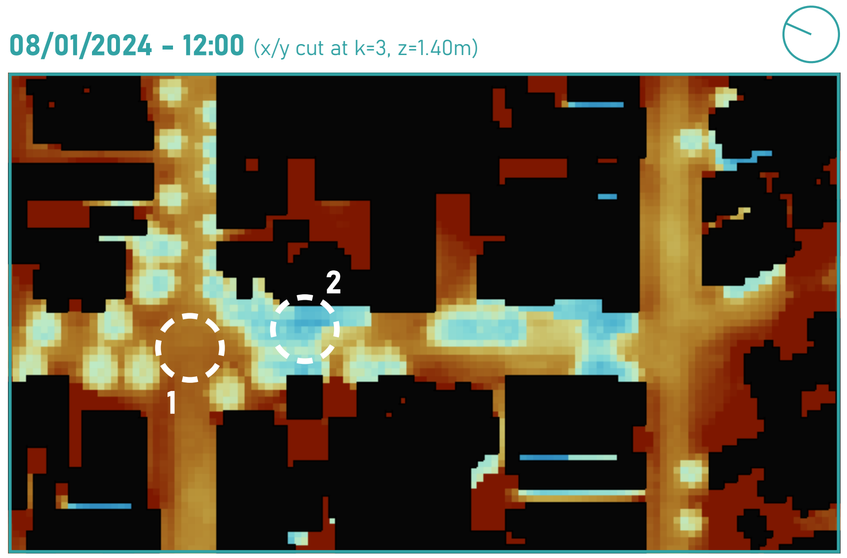


Fig. 143: Site 16 - PET peak variation point.
Source: The author

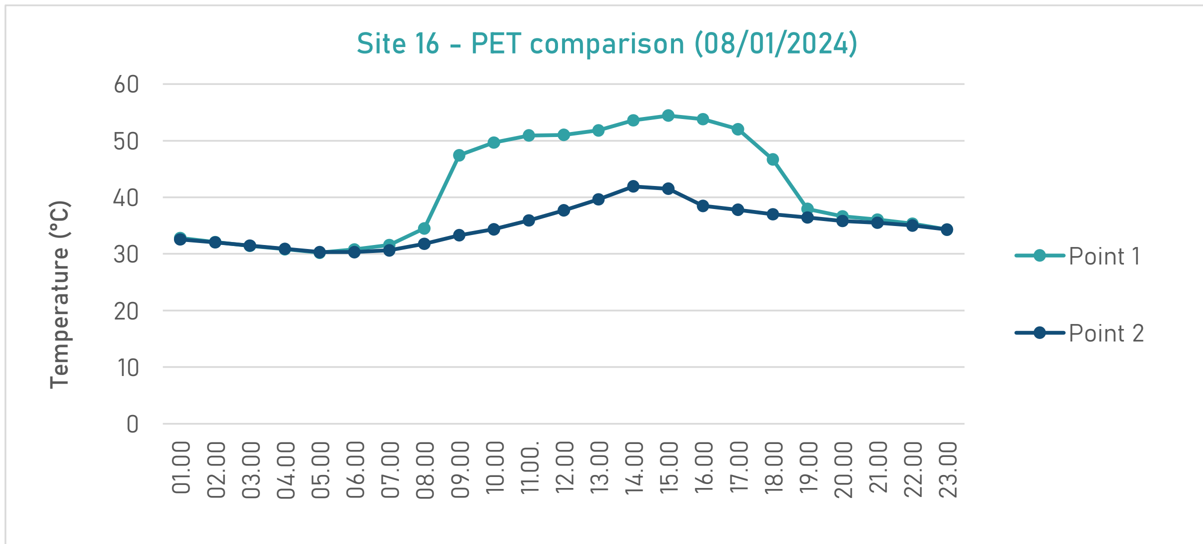


Fig. 144: Site 16 - PET peak variation point comparison with and without tree shading.
Source: The author

3.3.4 Site 20: Av. Mal. Floriano Peixoto (between R. Eng. Rebouças and R. Brasílio Itiberê)

Located in the Rebouças neighborhood, on Marechal Floriano Peixoto Avenue, between Eng. Rebouças Street and Brasílio Itiberê Street, Site 20 is primarily defined by its road infrastructure, with a central lane dedicated exclusively to public transportation, making it one of Curitiba's key accessibility corridors (Figure 145 and 146).

The area presents the lowest aspect ratio among the analyzed sites, with a value of just 0.19. It is composed of low-rise buildings, up to 15 meters in height, and a large roadway area, which contributes to a high incidence of solar radiation. Although a small planted median is present, the area is predominantly paved with asphalt and gray cobblestones, and vegetation is largely absent throughout the segment. Still, as observed at the previous site, it is possible to notice recent planting of tree saplings along the street.

Despite its high accessibility and a built environment with mixed residential and commercial uses, the area experiences limited pedestrian activity. Nevertheless, it demonstrates clear potential to become more attractive, especially considering its proximity to points of interest such as universities, churches, and commercial centers.

Segment length **160m**

Average segment width **37.85m**

Soil permeability **5.00%**

Vegetation cover **1.98%**

Height/Width Ratio **0.19**

Fig. 145 and 146: Street view Site 20 - Av. Mal. Floriano Peixoto.
Source: Google maps

Fig. 147: Site 20 – current situation.
Source: The author

Fig. 148: Site 20 - Current scenario - Potential Air Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00. Source: The author

Potential Air Temperature

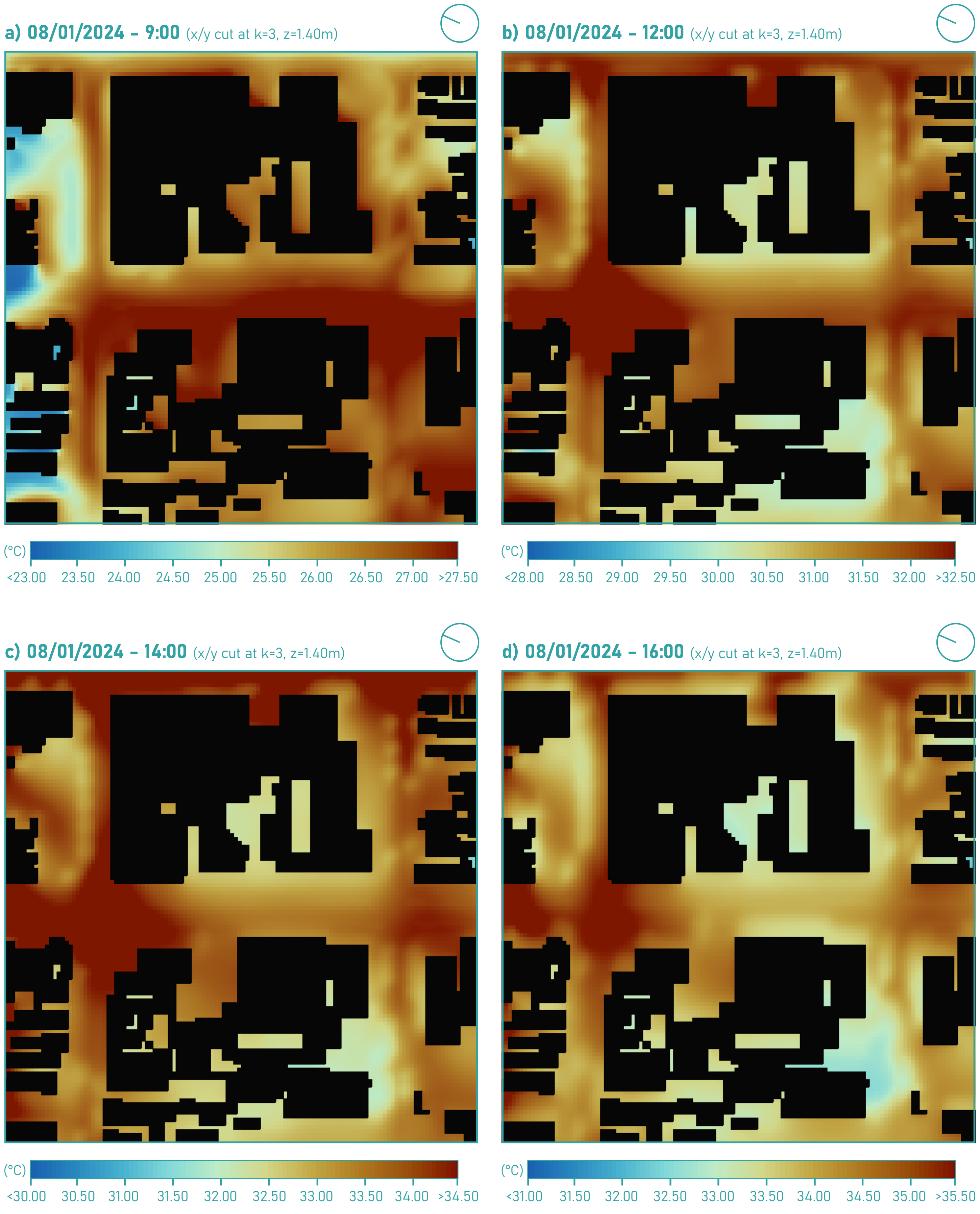


Fig. 149: Site 20 - Current scenario - Surface Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00. Source: The author

Surface Temperature

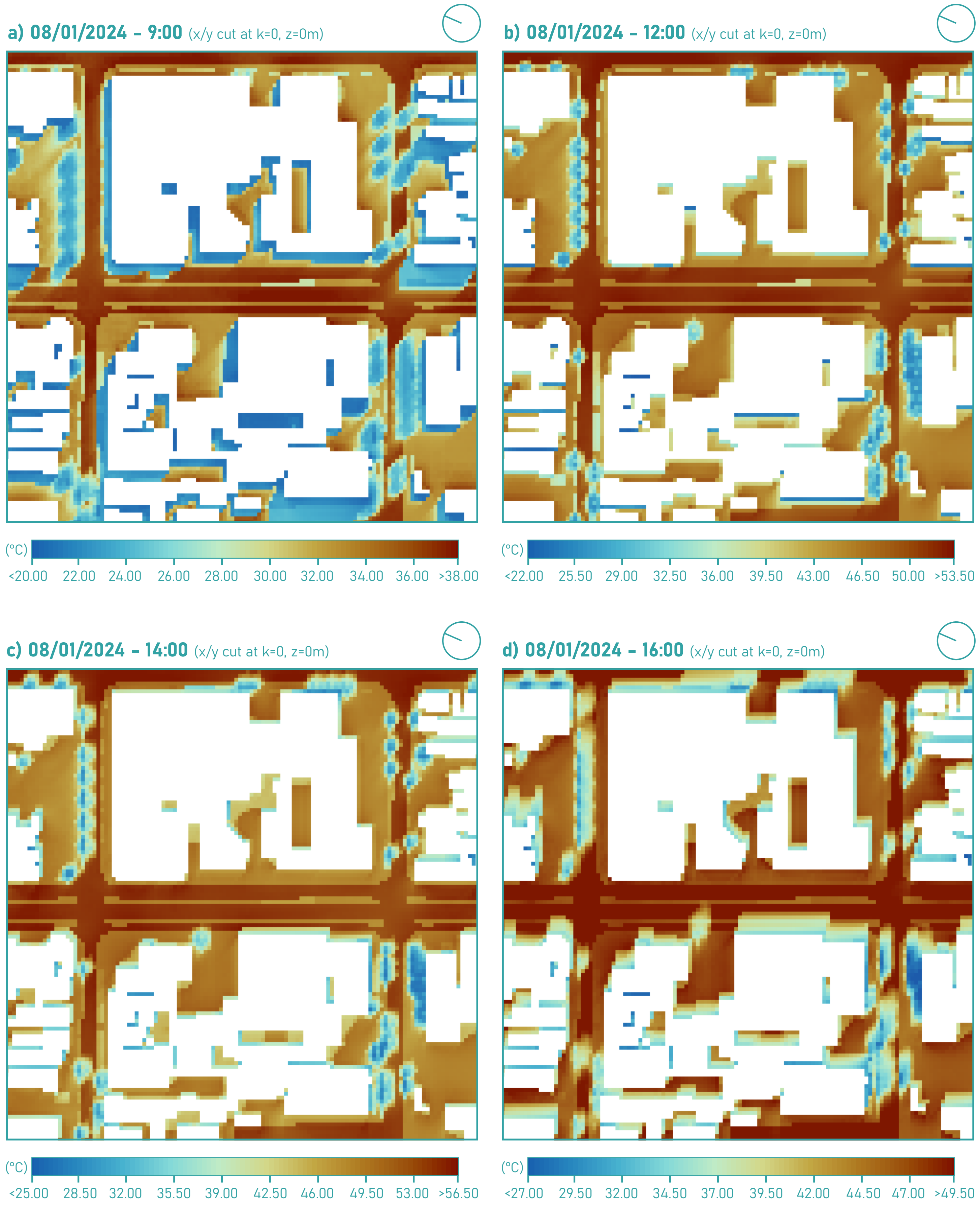
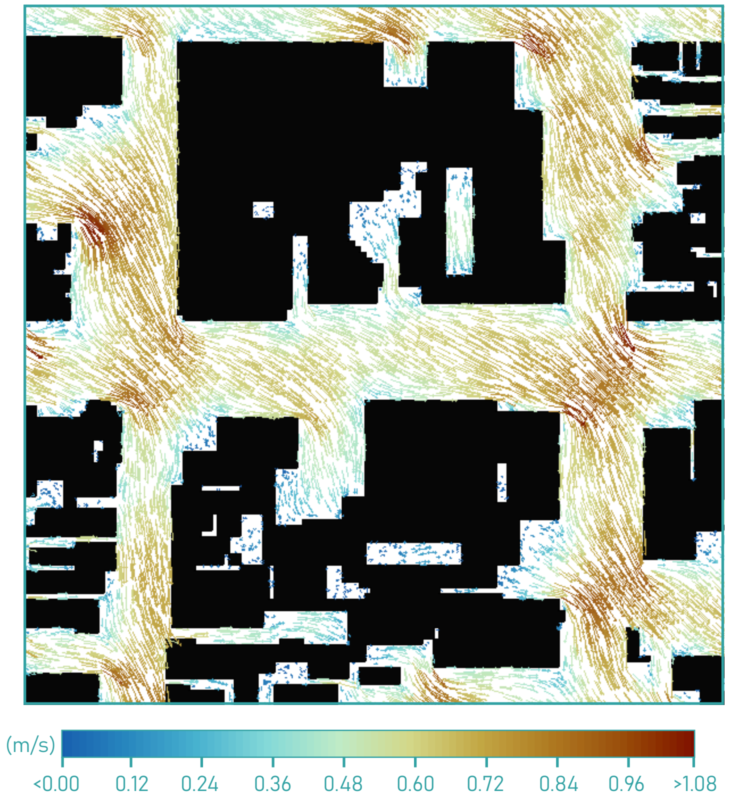


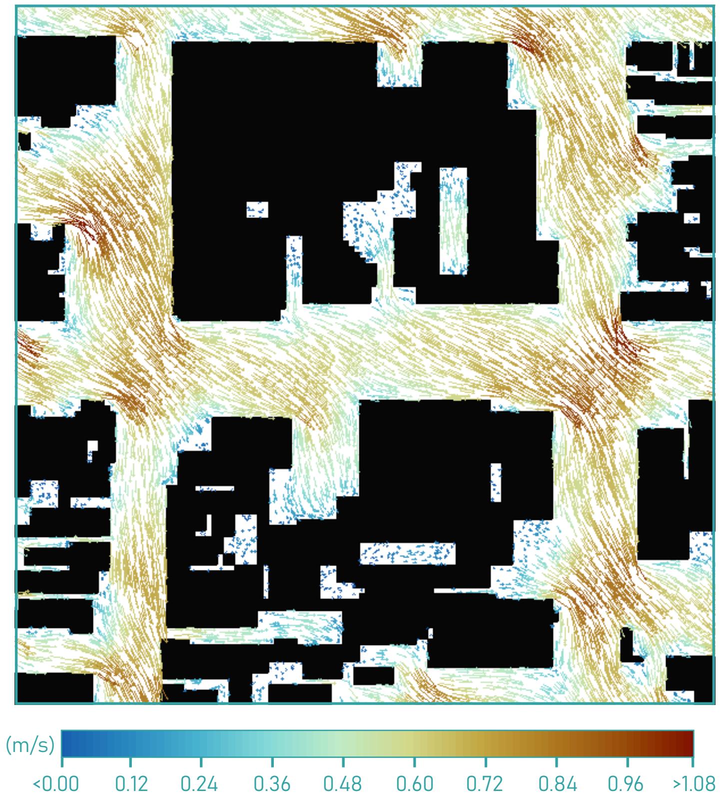
Fig. 150: Site 20 - Current scenario - Wind speed maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00. Source: The author

Wind speed

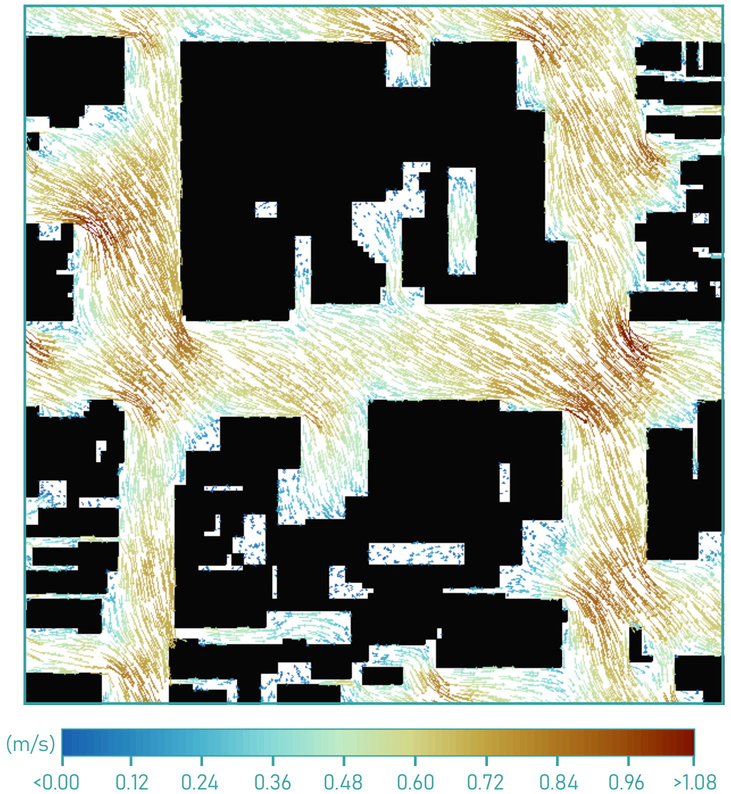
a) 08/01/2024 - 9:00 (x/y cut at k=3, z=1.40m)



b) 08/01/2024 - 12:00 (x/y cut at k=3, z=1.40m)



c) 08/01/2024 - 14:00 (x/y cut at k=3, z=1.40m)



d) 08/01/2024 - 16:00 (x/y cut at k=3, z=1.40m)

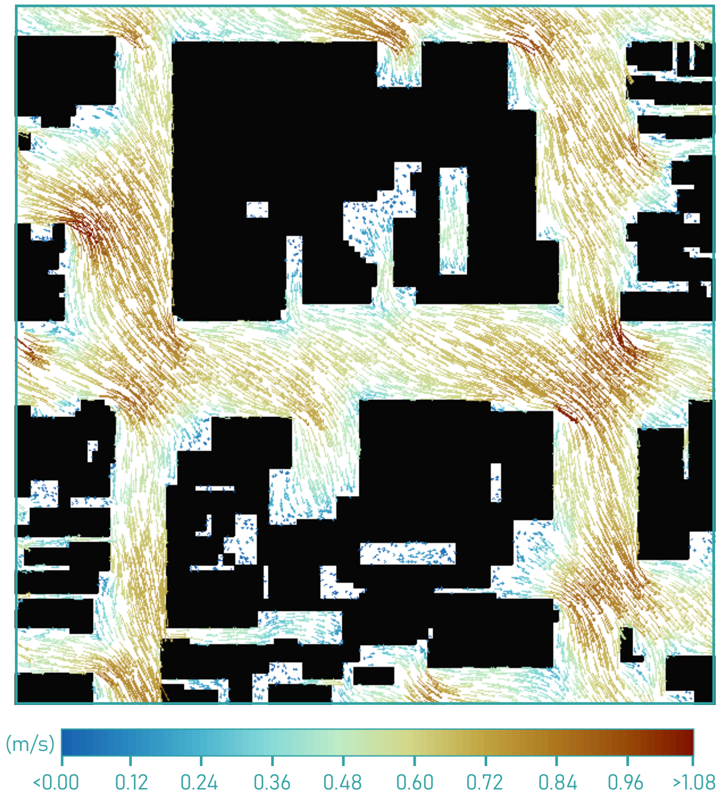
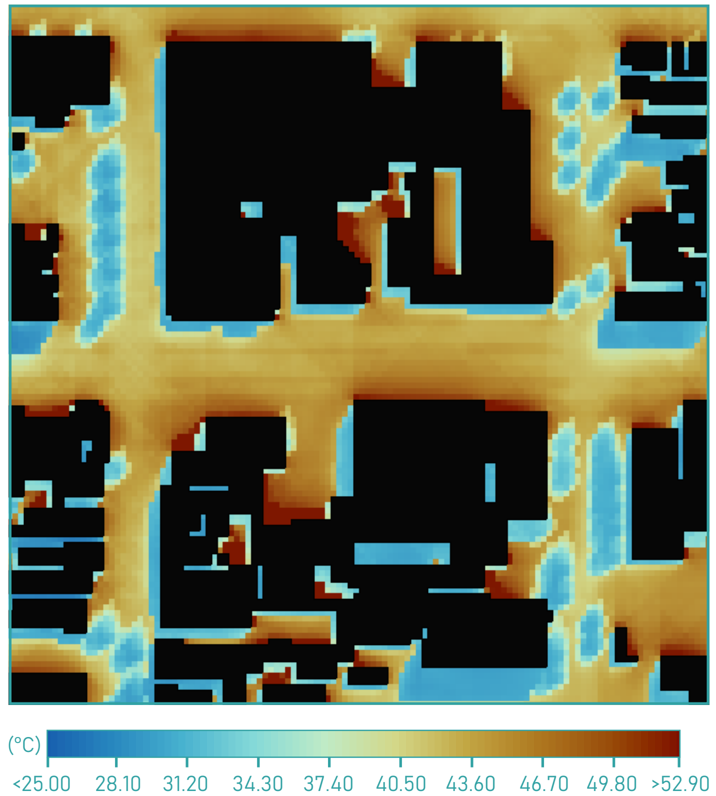


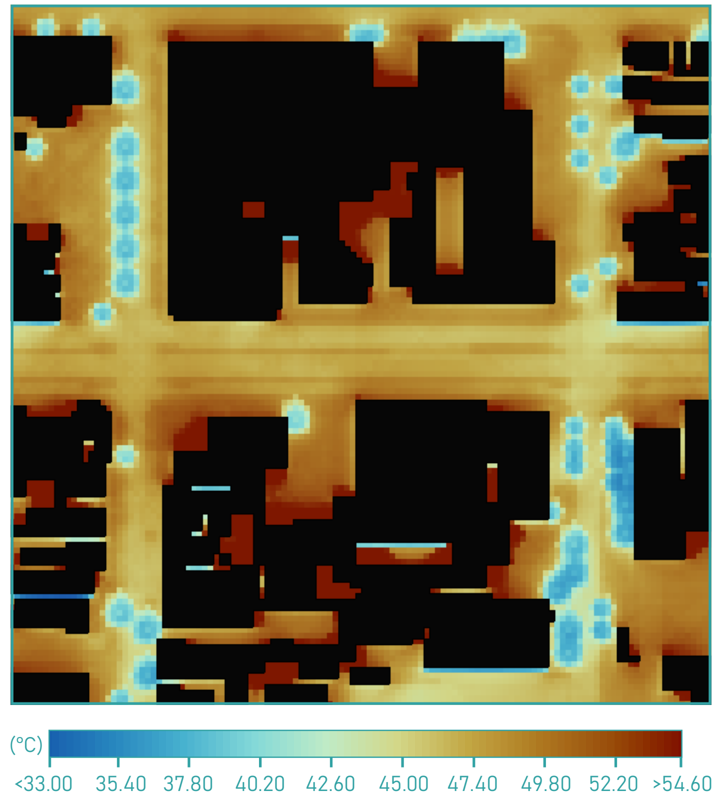
Fig. 151: Site 20 - Current scenario - Physiologically Equivalent Temp. (PET) maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00. Source: The author

Physiologically Equivalent Temperature - PET

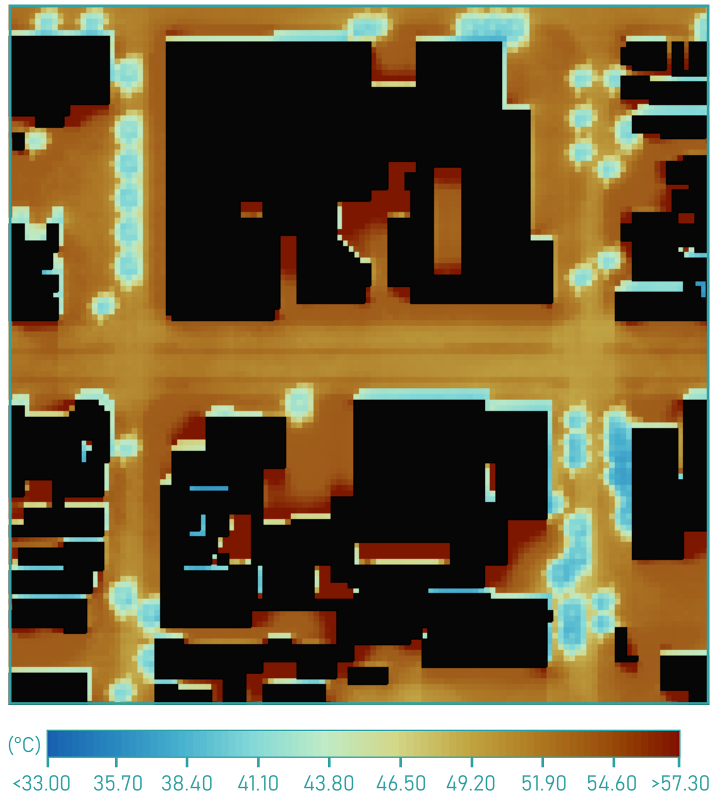
a) 08/01/2024 - 9:00 (x/y cut at k=3, z=1.40m)



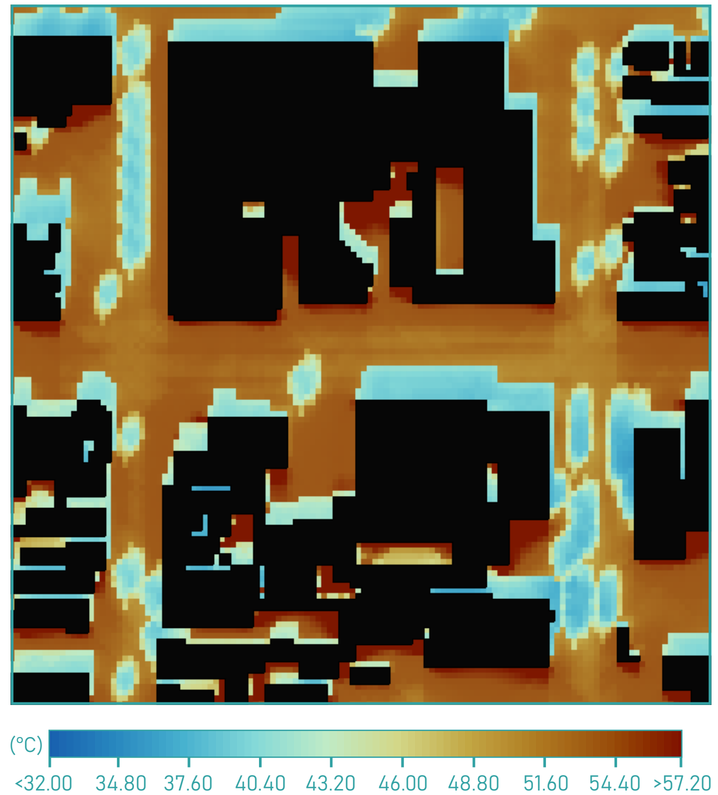
b) 08/01/2024 - 12:00 (x/y cut at k=3, z=1.40m)



c) 08/01/2024 - 14:00 (x/y cut at k=3, z=1.40m)



d) 08/01/2024 - 16:00 (x/y cut at k=3, z=1.40m)



The analysis of Site 20 highlights its strong accessibility to public transportation, further emphasized by its proximity to strategic locations with significant pedestrian traffic. Although current pedestrian flow in the area is low, these factors present a clear opportunity to enhance urban vitality and local dynamism, thereby boosting the site's attractiveness and fostering stronger integration with the surrounding neighborhood.

The street orientation and building morphology represent the area's primary weaknesses. This configuration of low height-to-width ratio leads to prolonged solar exposure throughout the day, causing increased heat accumulation. The situation is worsened by the lack of vegetation and high soil impermeability. Nonetheless, the recent planting of young trees along the street offers a promising long-term prospect for improved shading and enhanced thermal comfort. These factors are reflected in the simulation results (Figure 151), which indicate PET values above 37°C throughout the entire daytime period, characterizing high levels of thermal stress. Regarding air and surface temperatures (Figure 149), milder values are observed in the morning, with a progressive increase throughout the day.

In terms of opportunities, notable aspects include the ample space available on sidewalks and streets, which allows for urban and landscape interventions. Careful planning of these strategies is essential to prevent potential drawbacks, such as installing elements that further reduce wind speed and compromise natural ventilation, obstruct visibility of key points like bus stops and commercial establishments, or hinder pedestrian circulation.

Considering the recently planted trees, which are expected to provide more effective shading over time, it is proposed to add large shrubs as a buffer zone between the sidewalk and the central bus lane. This intervention would enhance pedestrian safety and boost the area's visual appeal. Additionally, to increase soil permeability, the project includes the implementation of permeable pavement in parking areas. Finally, a bike lane is proposed to improve intermodality and promote sustainability.

Site 20 - SWOT analysis	
Strengths	▪ An area well-connected by public transportation. ▪ Close proximity to strategic locations including churches, universities, and commercial hubs. ▪ Recent planting of tree saplings along the roadway.
Weaknesses	▪ The low height-to-width ratio and the street's orientation result in high solar exposure throughout the day. ▪ Significant lack of vegetation, reducing shading and environmental comfort. ▪ PET indicators show consistently high thermal stress levels during the entire day. ▪ Despite a central median, the area is mostly covered by impermeable materials, causing higher surface temperatures.
Opportunities	▪ Available sidewalk ans street space, enabling urban and landscape interventions. ▪ Improve pedestrian experience and strengthening connections among strategic sites. ▪ Potential to buffer pedestrian and vehicle flows through vegetative barriers, improving air quality and walkability.
Threats	▪ Installation of elements that reduce wind speed, affecting natural ventilation. ▪ Possible visual obstruction of strategic points, such as the bus terminal and commercial establishments. ▪ Interference with pedestrian circulation, hindering accessibility and urban flow.

Table 14: Site 20 - SWOT analysis. Source: The author

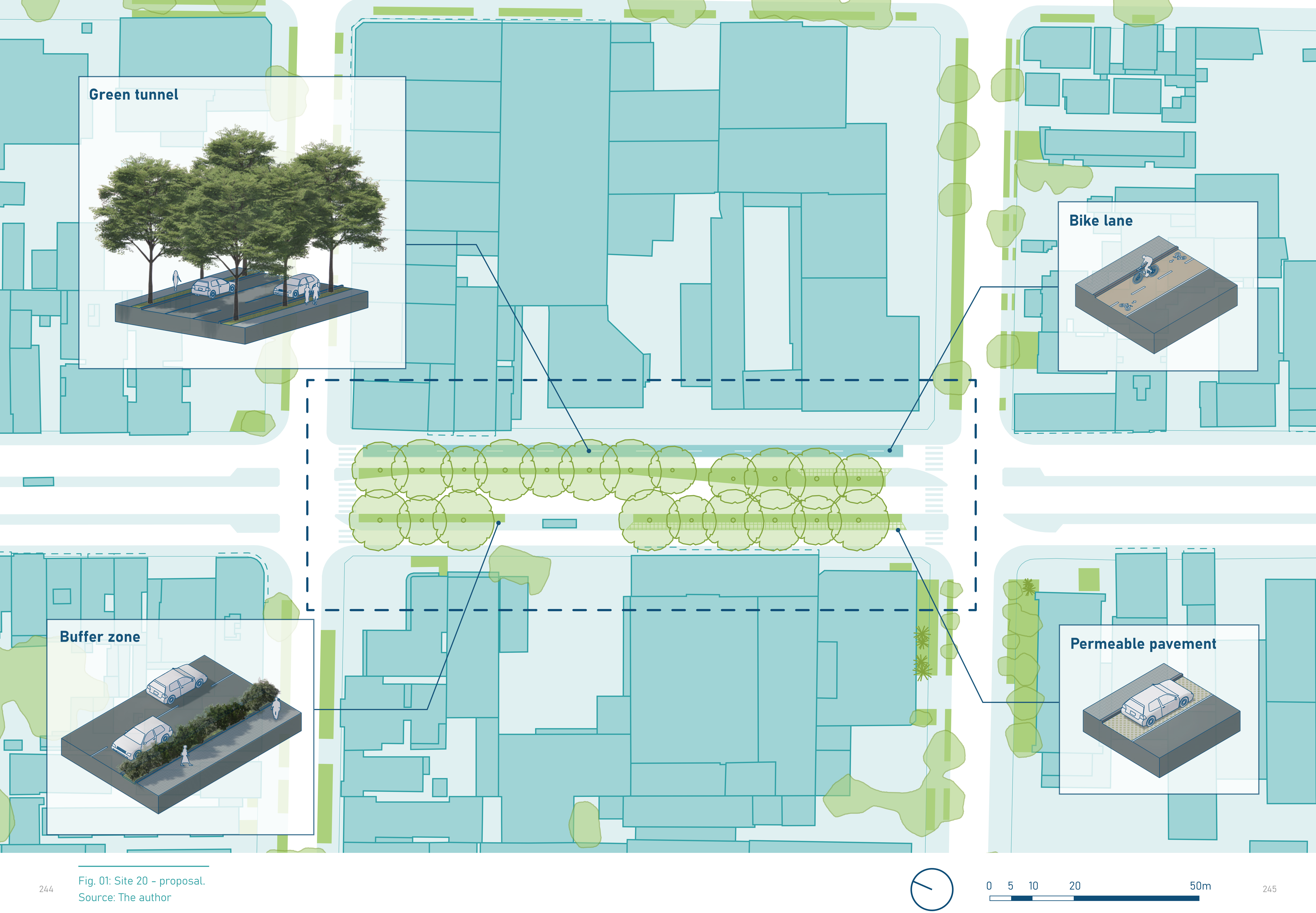


Fig. 01: Site 20 - proposal.
Source: The author

Fig. 152: Site 20 - proposal.
Source: AI-generated image (OpenAI) based on personal project - adapted by the author

Fig. 153: Site 20 - Proposal - Potential Air Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Potential Air Temperature

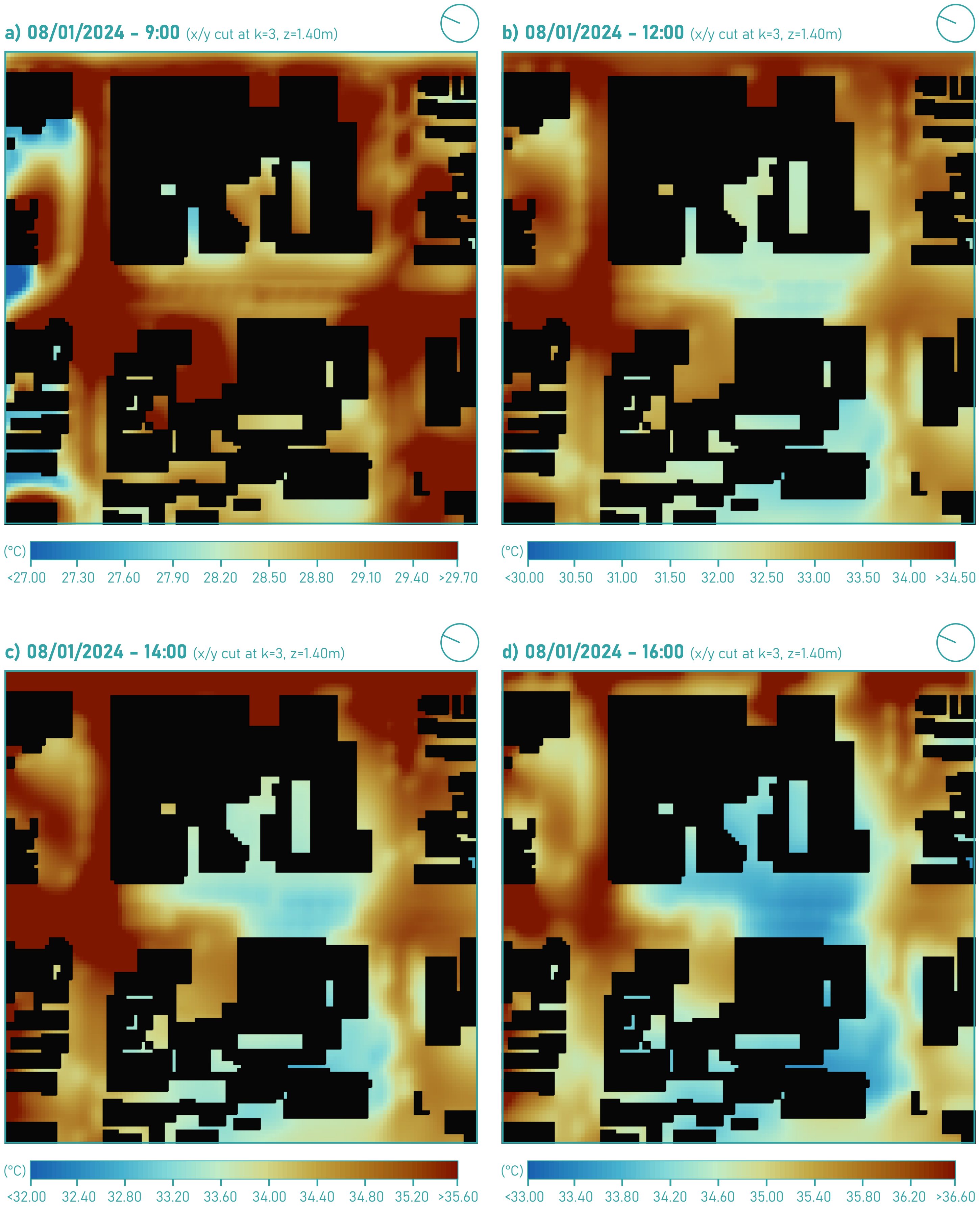


Fig. 154: Site 20 - Proposal - Surface Temperature maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Surface Temperature

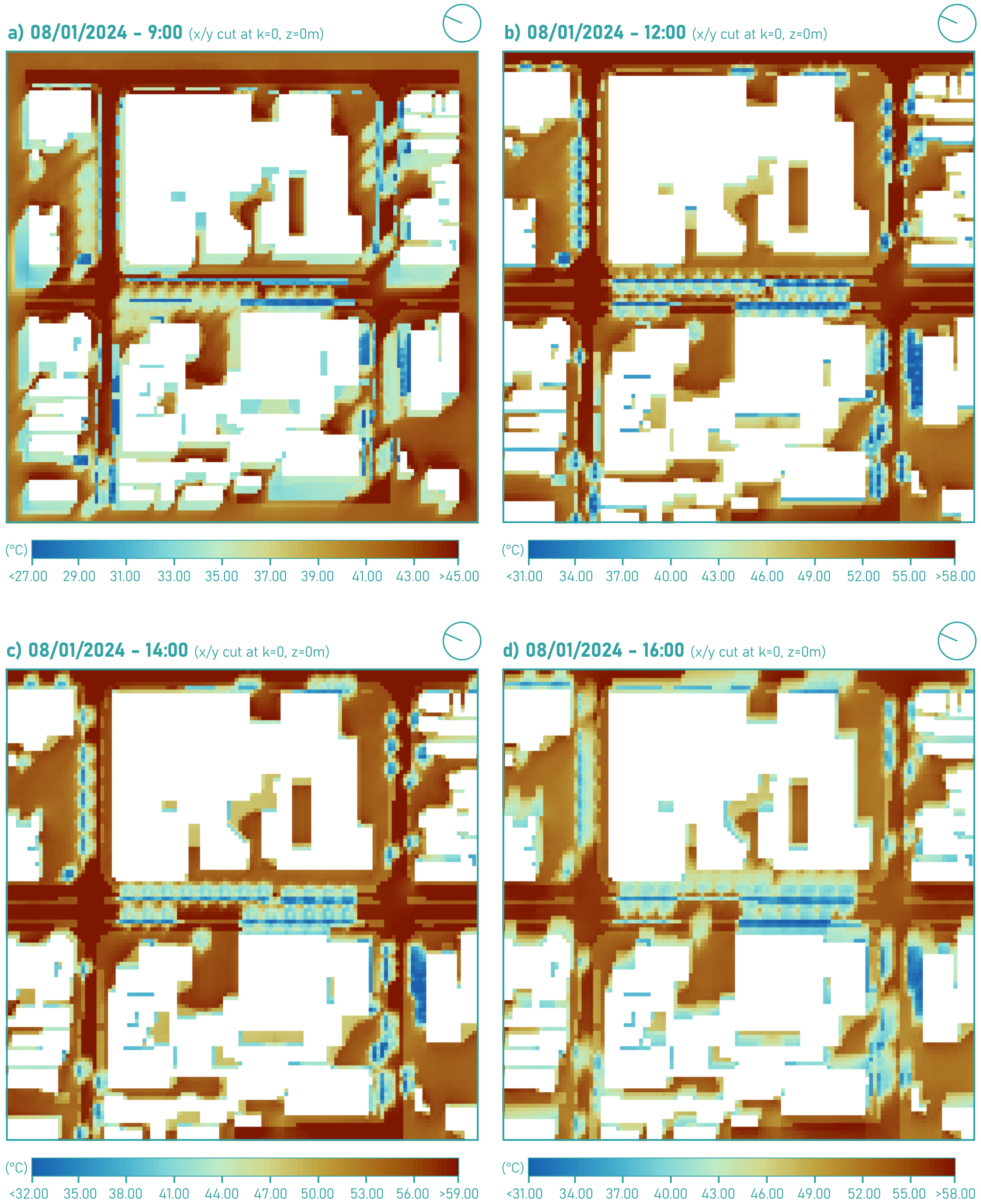
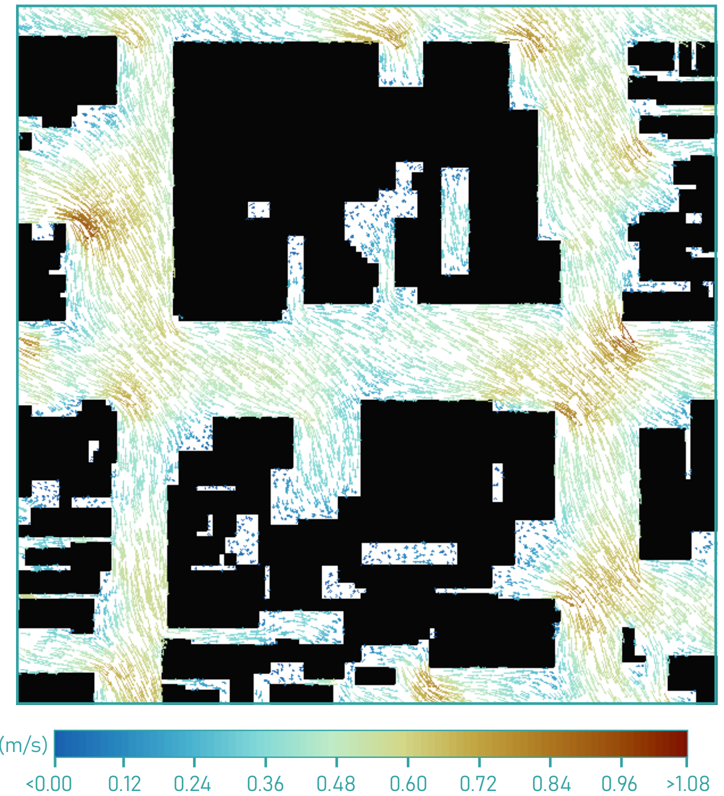


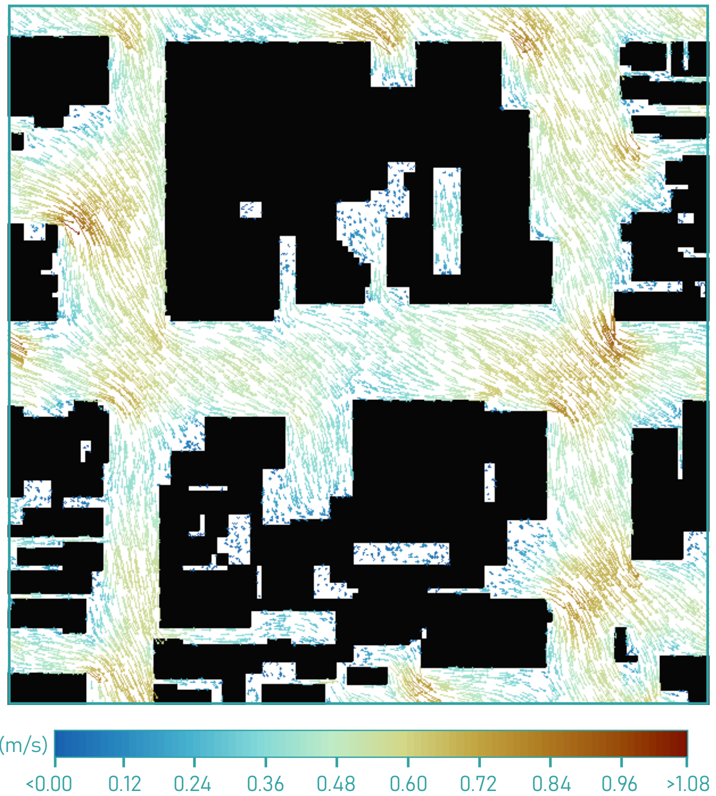
Fig. 155: Site 20 - Proposal - Wind speed maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Wind speed

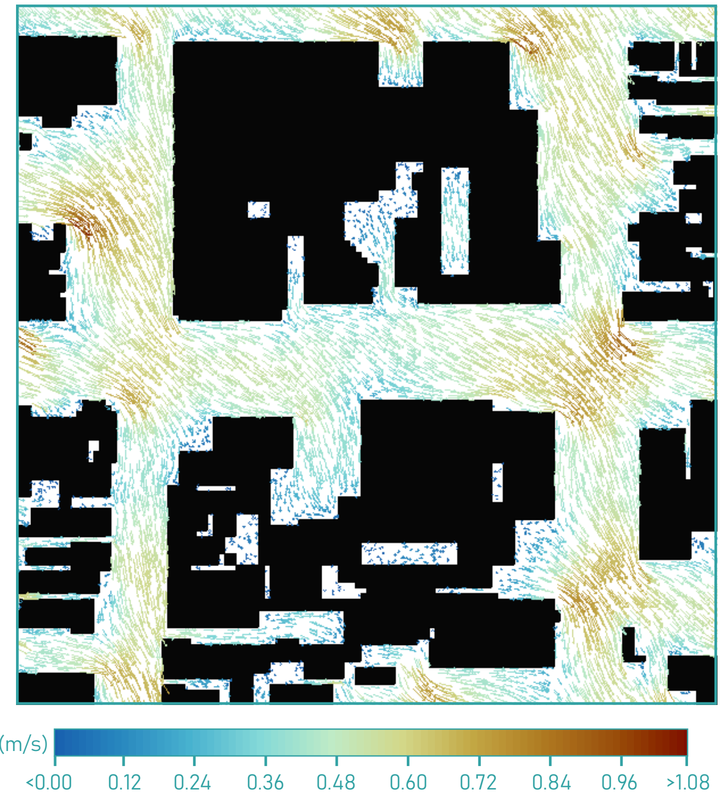
a) 08/01/2024 - 9:00 (x/y cut at k=3, z=1.40m)



b) 08/01/2024 - 12:00 (x/y cut at k=3, z=1.40m)



c) 08/01/2024 - 14:00 (x/y cut at k=3, z=1.40m)



d) 08/01/2024 - 16:00 (x/y cut at k=3, z=1.40m)

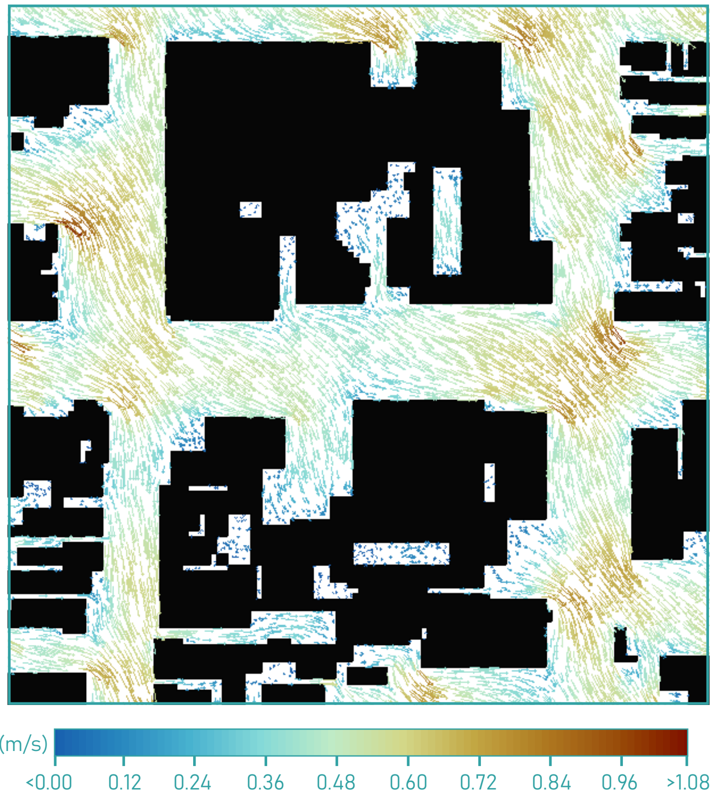
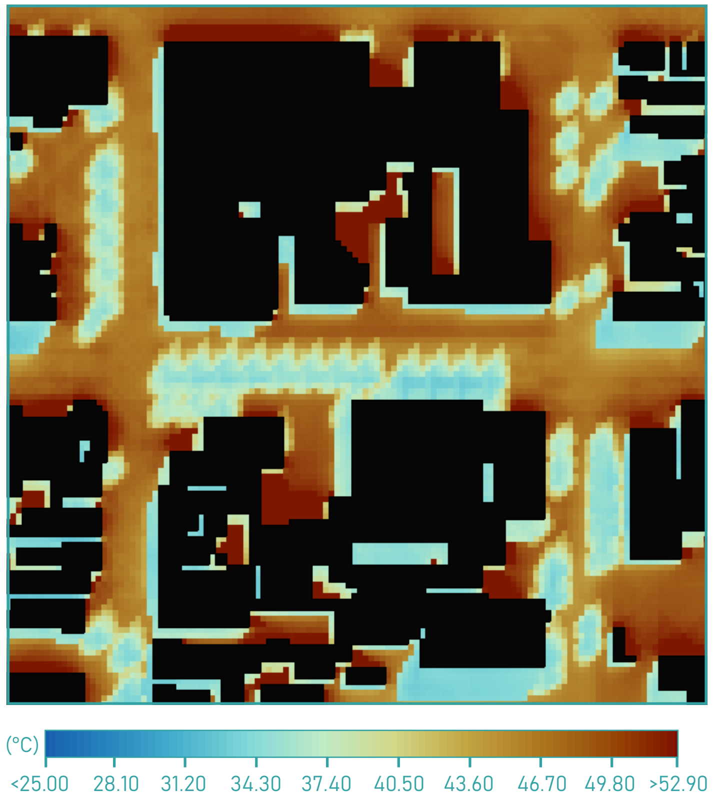


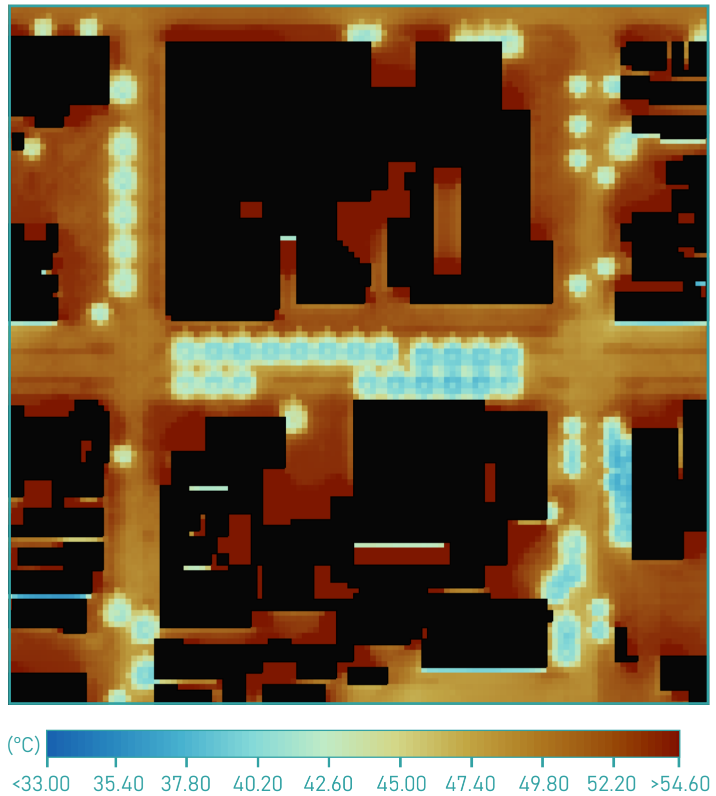
Fig. 156: Site 20 - Proposal - Physiologically Equivalent Temp. (PET) maps on January 8, 2024 - (a) 9:00, (b) 12:00, (c) 14:00, (d) 14:00.
Source: The author

Physiologically Equivalent Temperature - PET

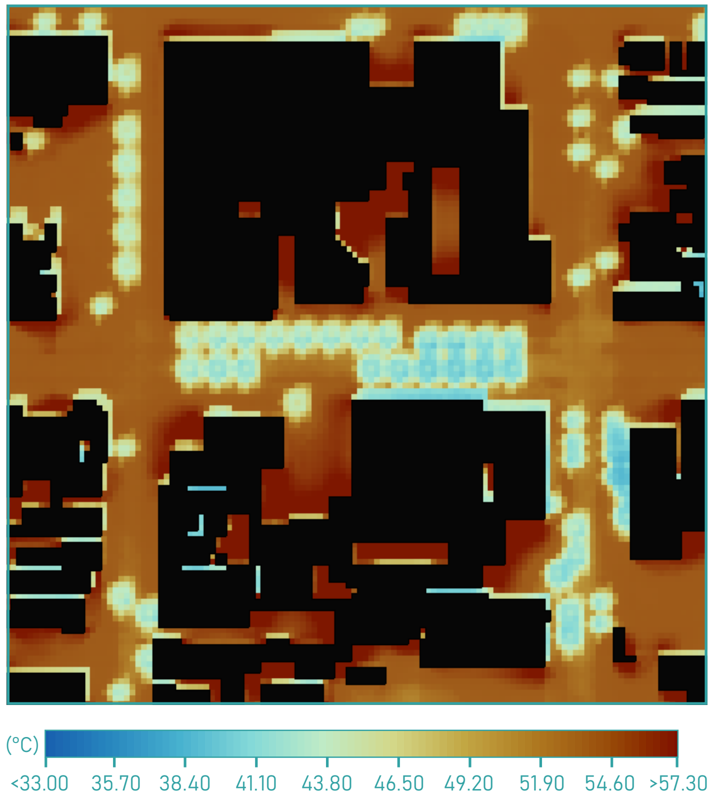
a) 08/01/2024 - 9:00 (x/y cut at k=3, z=1.40m)



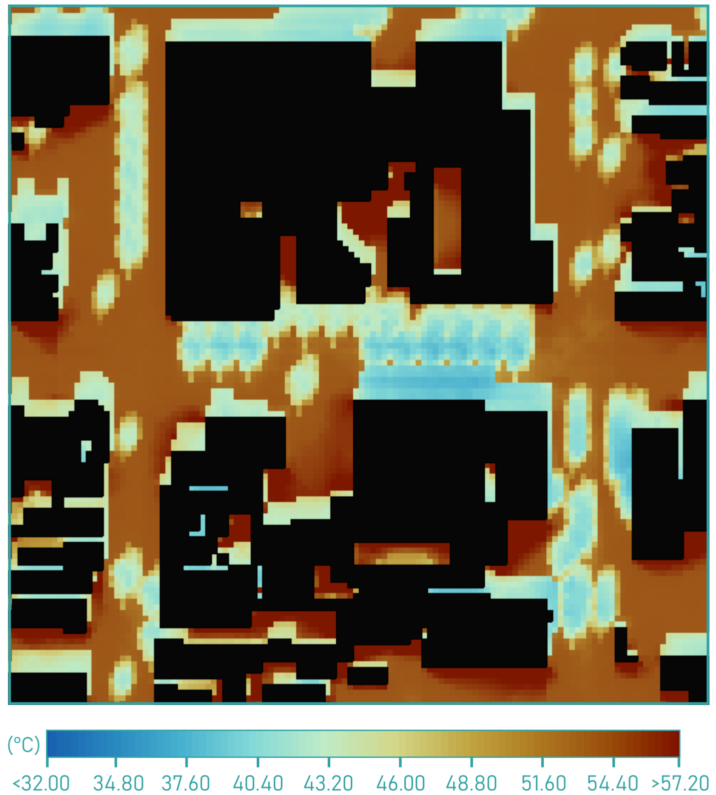
b) 08/01/2024 - 12:00 (x/y cut at k=3, z=1.40m)



c) 08/01/2024 - 14:00 (x/y cut at k=3, z=1.40m)



d) 08/01/2024 - 16:00 (x/y cut at k=3, z=1.40m)



In analyzing the results of the strategies applied to site 20, it is essential to account for certain limitations inherent to the ENVI-met software. Methodological discrepancies arising from recent system updates affected the calculation of microclimatic variables, leading to significant variations in baseline temperature between the current and proposed scenarios. Consequently, the evaluation will be based solely on the maps generated for the intervention scenario, with comparisons drawn against the immediate surroundings to ensure greater interpretative consistency of the simulated data.

Analysis of the Potential Air Temperature maps indicates a progressive increase in the effectiveness of tree shading throughout the day. In the morning, temperature differentials between shaded and sun-exposed areas are approximately 1 °C, reaching up to 3 °C by 16:00 (Figure 153d), highlighting the cumulative cooling effect of vegetation over time.

The Surface Temperature maps (Figure 154) highlight the effectiveness of vegetated areas in reducing heat retention throughout the analyzed period. Moreover, a more pronounced cooling effect is observed in regions where large shrubs were implemented, indicating their greater capacity to moderate surface thermal loads.

Although wind speed values showed a slight reduction following the implementation of interlaced trees (Figure 155), Physiological Equivalent Temperature (PET) indices (Figure 156) improved when compared to adjacent areas without vegetation. Figures 157 and 158 illustrate these variations. This indicates that, overall, the combination of implemented strategies is effective in mitigating thermal stress, resulting in PET values below 37 °C in the intervention areas — the threshold defined for high heat stress conditions.

Beyond the observed microclimatic benefits, the intervention also led to an increase in permeable surface area—from 5% to 11%. This change enhances the site's hydrological performance by facilitating greater stormwater infiltration, decreasing surface runoff, and improving soil moisture levels. These conditions, in turn, contribute to the cooling potential of vegetation through elevated evapotranspiration rates, reinforcing the environmental effectiveness of the adopted strategies.

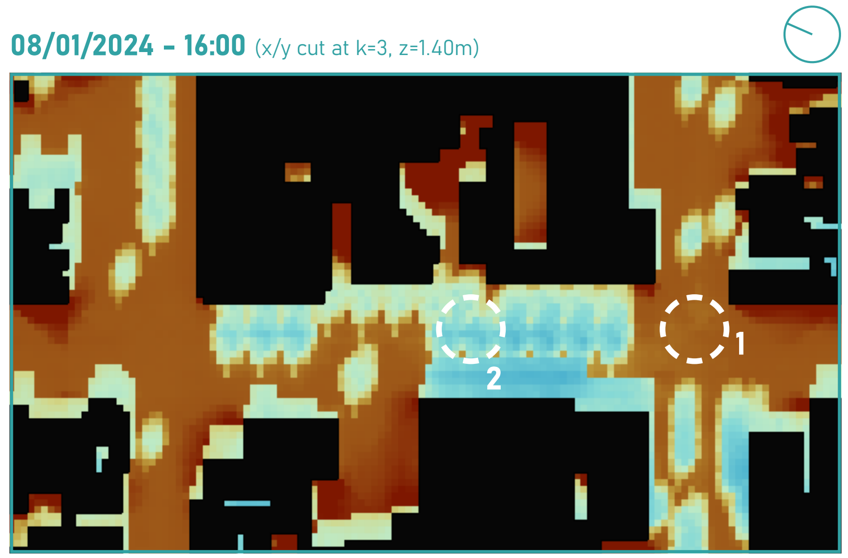


Fig. 157: Site 20 - PET peak variation point.
Source: The author

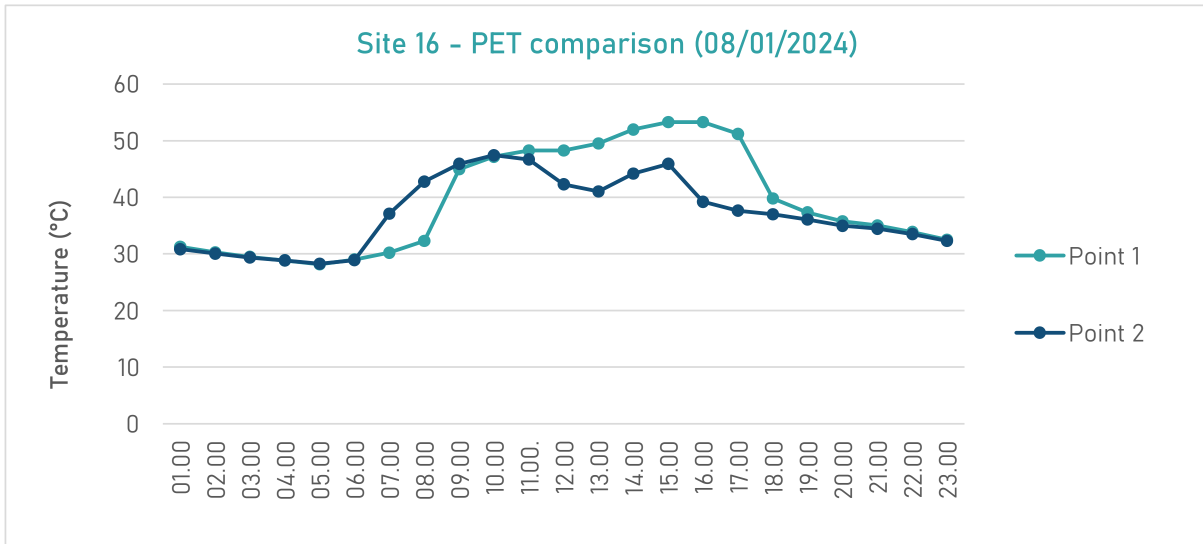


Fig. 158: Site 20 - PET peak variation point comparison with and without tree shading.
Source: The author

4. DISCUSSION

4.1 Microclimatic analysis

When analyzing the four sites collectively, it becomes evident that solar exposure has a clear influence on determining thermal comfort levels throughout the day. Areas shaded either by vegetation or built structures consistently exhibit lower temperatures compared to those fully exposed to sunlight, as clearly demonstrated in Figures 159. This shading effect contributes significantly to moderating local microclimates and improving comfort for pedestrians and residents alike. As a result, Sites 06, 13, and 20 show comparable thermal behavior despite some architectural differences. For instance, Site 13 has a high aspect ratio, which typically influences airflow and shading patterns; however, its street orientation (east-west) allows for substantial solar incidence, aligning its thermal conditions closely with the other two sites. In contrast, Site 16 stands out by presenting unique conditions that differ from the other locations, likely due to variations in its urban design and exposure characteristics.

08/01/2024 – 9:00 (x/y cut at k=3, z=1.40m)

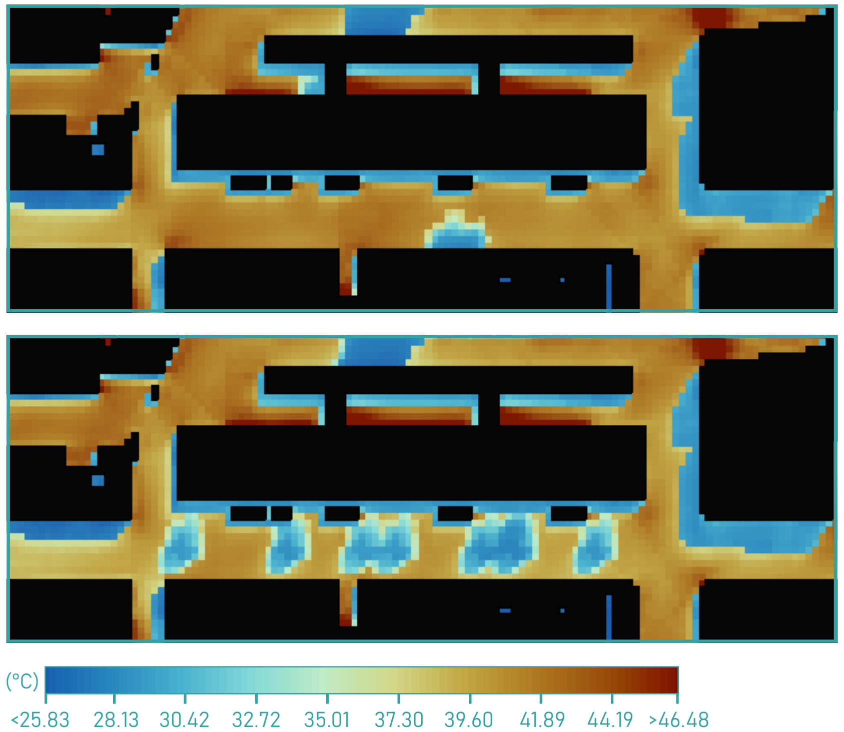


Fig. 159: Site 06 – detail of Surface temperature map at 12:00 p.m. before(top) and after (bottom) the proposal.
Source: The author

In terms of surface materials and ground cover, asphalted areas demonstrate greater heat retention, as shown by the surface temperature maps. With the application of low green infrastructure, such as shrubs, urban meadows and green pavements, milder temperature values are observed, as illustrated by Figures 160. However, the impact is less significant when assessed using Physiological Equivalent Temperature (PET) indices.

08/01/2024 – 12:00 (x/y cut at k=0, z=0m)

a |

b |

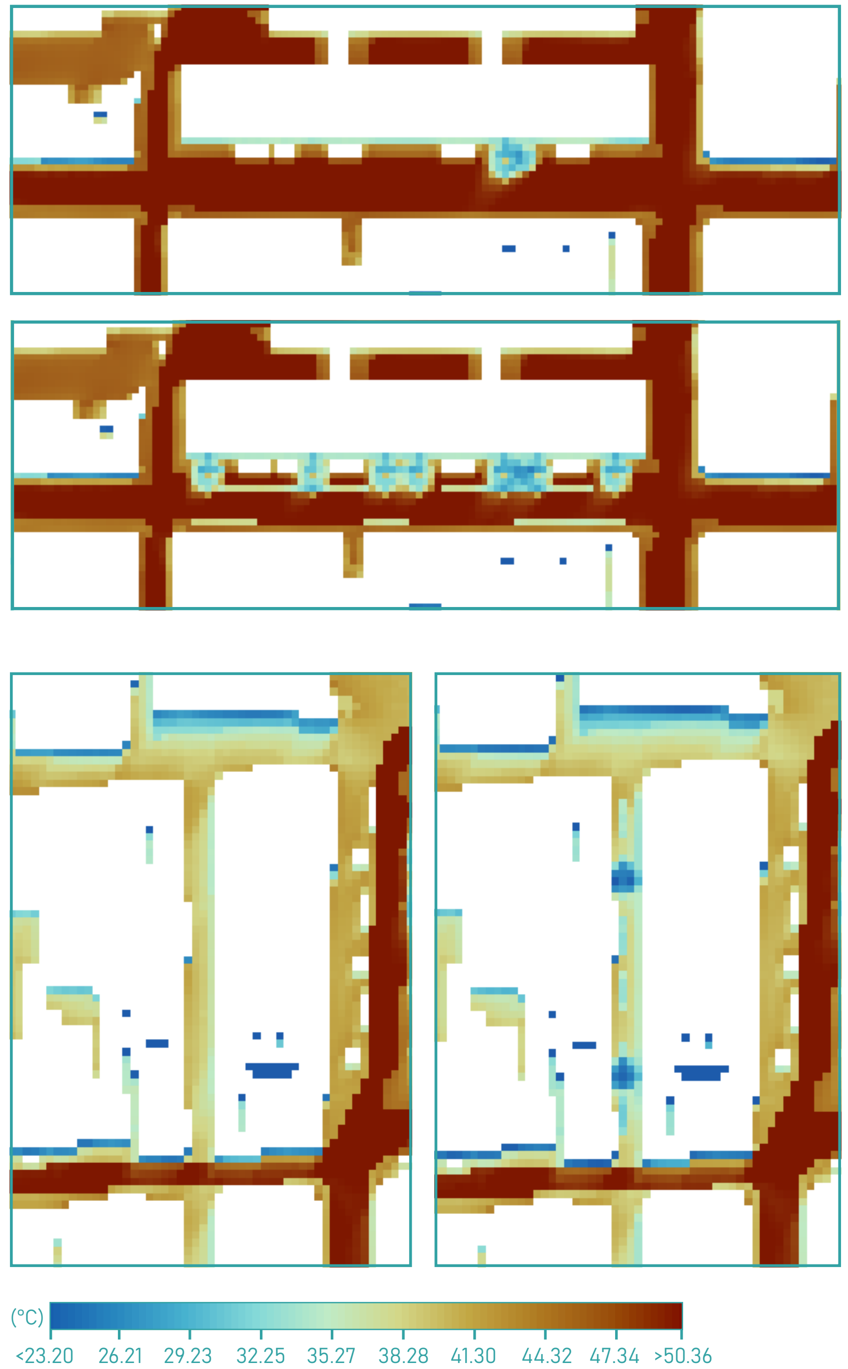


Fig. 160: Detail of Surface temperature map at 12:00 p.m. – (a) Site 06 before and after the proposal
(b) Site 13 before and after the proposal.
Source: The author

The limited effect of these structures on PET can be attributed to the nature and scale of the vegetation used. Shrubs and small trees, although effective in reducing surface temperatures through shading and evapotranspiration, provide limited vertical shading and do not significantly alter wind patterns or the microclimate at pedestrian level. As a result, despite localized surface cooling, there is little influence on factors such as mean radiant temperature, air temperature, and wind speed, variables that have a strong impact on PET values.

As previously noted, large trees have a significant impact on reducing thermal stress. In this context, Figure 161 demonstrate that within the same area, unshaded asphalted zones and those covered by tree canopy exhibit temperature differences exceeding 10°C. These findings underscore the effectiveness of the recent tree planting initiatives proposed by the city government. However, it is important to highlight that such benefits materialize only over the medium to long term, making it essential to complement these measures with other solutions that provide immediate effects.

08/01/2024 - 12:00 (x/y cut at k=3, z=1.40m)

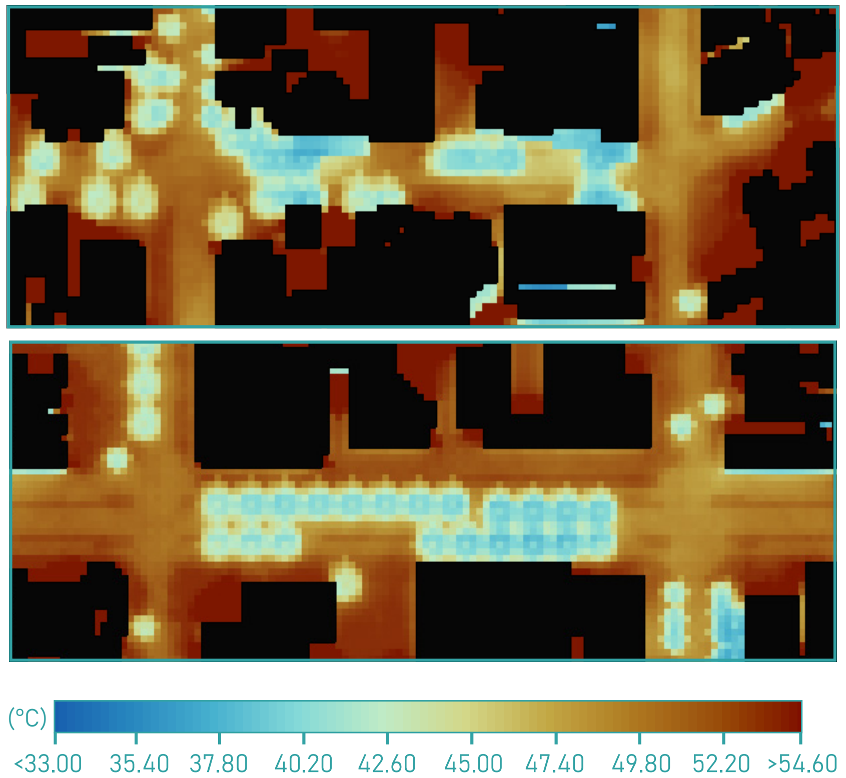


Fig. 161: Detail of PET map at 12:00 p.m. site 16 (top) and site 20 (bottom) the proposal.
Source: The author

4.2 Strategies

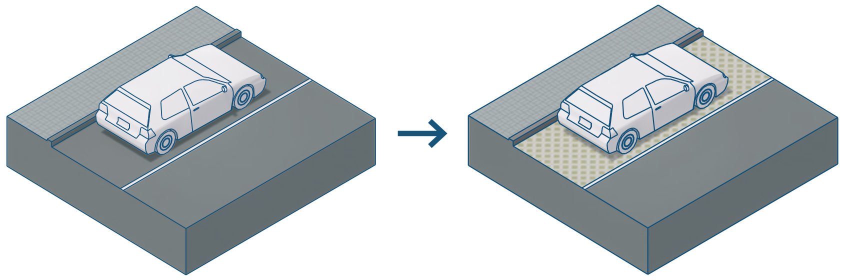
The analysis of the proposed strategies highlights the strong benefits of introducing large canopy trees, which provide extensive shading and contribute to moderating daytime temperatures. Nonetheless, as observed in multiple cases, spatial and typological limitations often constrain interventions in urban streetscapes. These strategies are also characterized as medium-term solutions, best applied in combination with measures that have immediate effects. Therefore, among the lower-cost and less technically demanding alternatives, the integration of large shrubs and small-scale urban meadows, combined with underdrained rain garden systems, emerges as the most feasible and effective approach.

In the context of Curitiba's streetscapes, several solutions emerge as replicable and adaptable. The following section presents a categorization of these strategies, emphasizing their primary benefits and limitations. Furthermore, these tools can be effectively interconnected to enhance their overall impact.

4.2.1 Replicable strategies

Green Parking Solutions

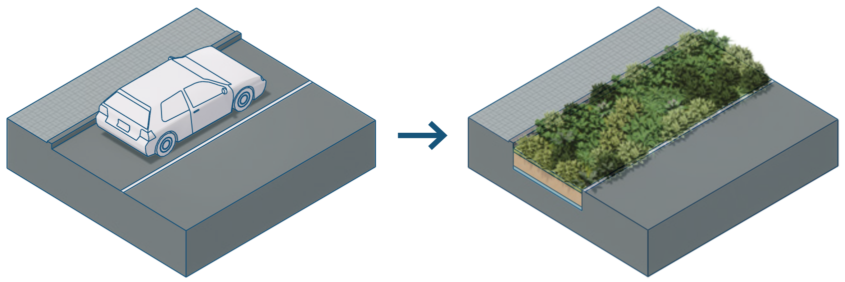
- **Permeable pavements**



Benefits: The implementation of permeable pavement in conventional parking spaces maintains their functionality while improving water management, protecting soil, and reducing surface temperatures. This strategie is characterized by its immediate efficacy and long lifespan (Starzewska-Sikorska et al., 2022).

Limitations: Permeable pavements showed limited impact on PET values and do not offer significant benefits to air quality. Moreover, these strategies may involve moderate implementation and maintenance costs (Starzewska-Sikorska et al., 2022).

- **Urban meadows functioning as rain gardens**

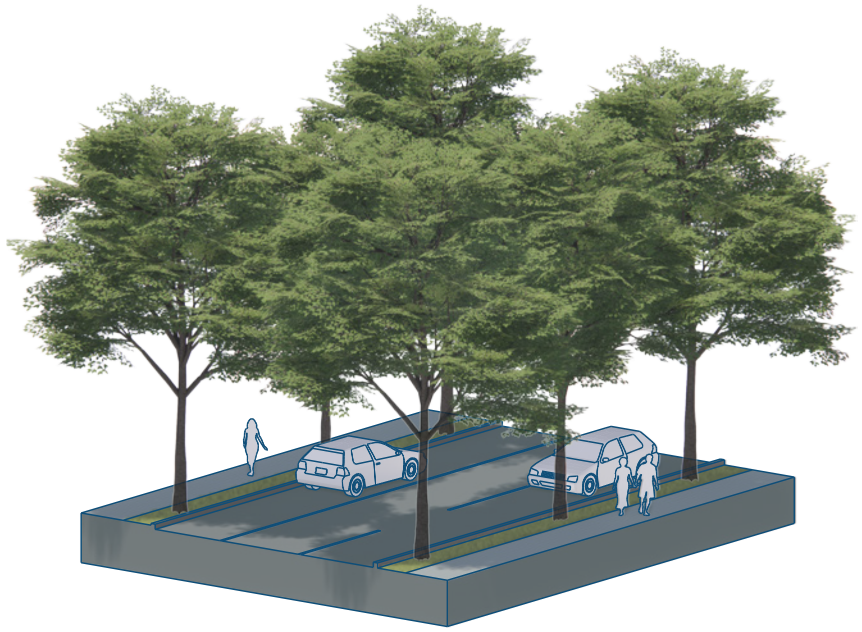


Benefits: Urban meadows integrated into underdrained rain gardens, when replacing parking spaces, offer immediate effectiveness and low maintenance costs (Starzewska-Sikorska et al., 2022). These structures promote soil unsealing and efficient stormwater capture. Additionally, they contribute to surface temperature reduction, enhance pedestrian appeal, and support local biodiversity. Their use of existing urban space also gives them high replication potential across the city.

Limitations: These structures do not produce significant effects on pedestrian thermal comfort. Furthermore, according to Starzewska-Sikorska et al. (2022), they do not contribute to air quality improvement and have a reduced lifespan.

Tree Canopy Strategies

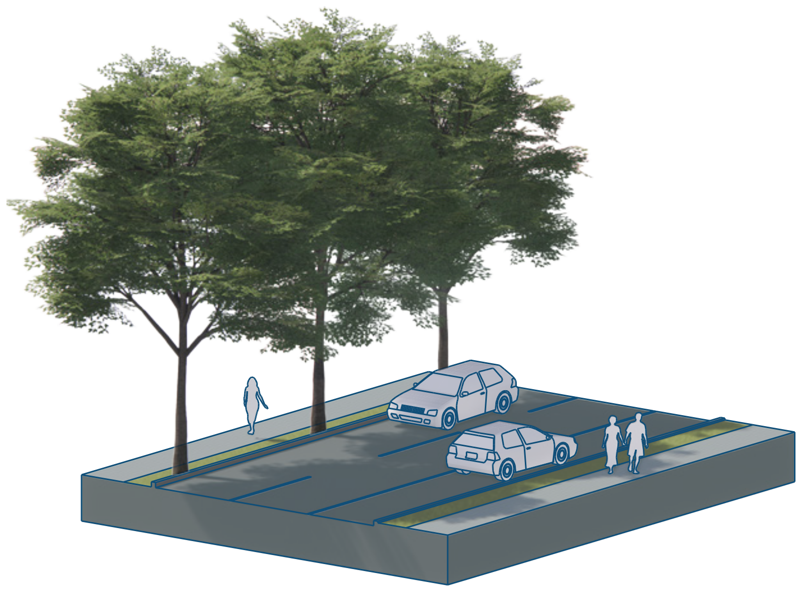
- **Green tunnel**



Benefits: The green tunnel formed by large canopy trees provides the significant benefit of continuous shading, which has a strong impact on local PET values and helps to reduce thermal stress. In addition, these structures enhance the urban landscape, support the conservation of native species, and offer long-term durability (World Bank, 2021; Starzewska-Sikorska et al., 2022).

Limitations: These structures require substantial space for implementation and offer effectiveness in the medium term. Depending on the street typology and morphology, their implementation may prove unfeasible.

- **Single-row tree alignment**

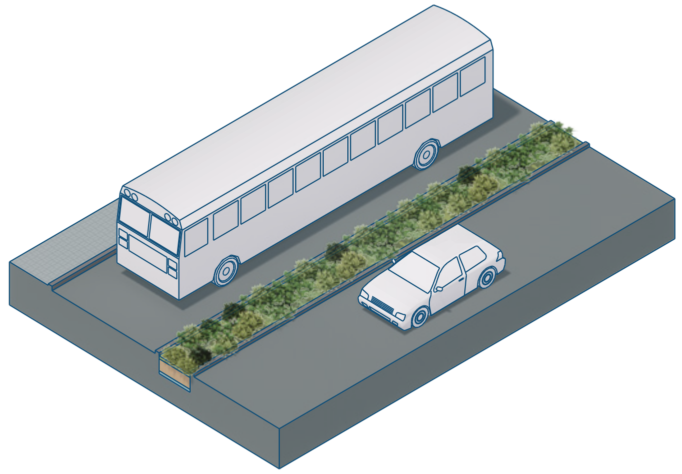


Benefits: Single-row alignments occupy less space than green tunnels and, depending on the roadway's orientation, can provide shade, improving thermal comfort. Like the first configuration, they enhance the urban landscape, promote the conservation of native species, and offer long-lasting durability (World Bank, 2021; Starzewska-Sikorska et al., 2022).

Limitations: While they demand less space than the previous solutions, these structures still require a significant footprint and offer only moderate effectiveness over the medium term. Their performance is also inferior to that of continuous tree canopies on both sides of the street. In certain urban settings, particularly in narrow streets, their implementation may not be feasible.

Linear Green Strips

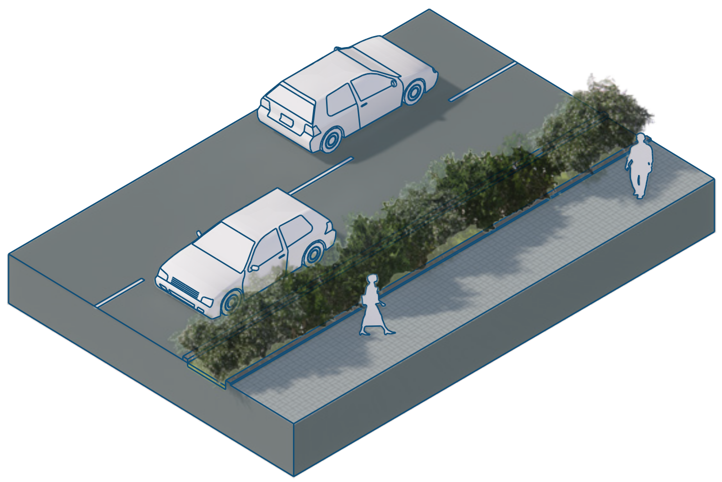
- **Street dividers/medians**



Benefits: Green stripes of urban meadows integrated with rain gardens used as street dividers offer multiple benefits, including a reduction in asphalted areas, improved water management, soil unsealing, lower surface temperatures, and enhanced local biodiversity. Additionally, these structures are immediately effective and involve low maintenance costs (Starzewska-Sikorska et al., 2022).

Limitations: Implementing this strategy requires additional space within urban streets. Furthermore, low-height green stripes provide limited improvements to local thermal comfort and, according to Starzewska-Sikorska et al. (2022), have a short lifespan and do not significantly affect air quality.

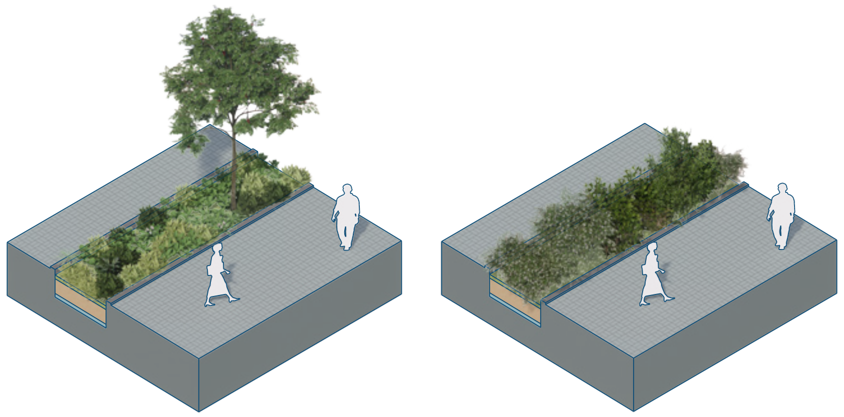
- **Buffer zones**



Benefits: Buffer green stripes offer benefits for pedestrian safety and walkability by acting as barriers between sidewalks and busy streets. This solution allows for the use of large shrubs which, according to Starzewska-Sikorska et al. (2022), positively influence air quality, have immediate effectiveness, long lifespan, and low implementation and maintenance costs. Additionally, they help reduce surface temperature and enhance local thermal comfort.

Limitations: The implementation of these structures requires the availability of wide sidewalks or additional space within the streets.

- **Pedestrianized green streets**



Benefits: The addition of green stripes in pedestrian streets enhances the pedestrian experience and local attractiveness, while also improving biodiversity, increasing permeable areas, and reducing soil temperature.

Limitations: As they are implemented in narrower streets, these solutions cannot accommodate larger vegetation such as tall trees. As a result, they have limited impact on local PET (Physiological Equivalent Temperature) indices and, according to Starzewska-Sikorska et al. (2022), have a short lifespan and do not significantly affect air quality.

5. CONCLUSION

This research aimed to investigate how the methodology of urban acupuncture, integrated with Nature-Based Solutions (NBS), can contribute to the mitigation and adaptation of the city of Curitiba to the impacts of the urban microclimate and the climate crisis, with an emphasis on heat waves.

The findings indicate that, given the city's challenges in engaging the community and accelerating bureaucratic processes related to urban management, the urban acupuncture methodology stands out as a viable strategy, particularly due to its low cost and agile implementation. When combined with Nature-Based Solutions, which can be integrated as targeted interventions yet have the potential to generate large-scale environmental impacts, this approach offers a sustainable and easily applicable solution.

The analysis revealed an uneven distribution of vegetated areas as well as the presence of critical microclimates in Curitiba, particularly in central regions and along structural corridors. Although these areas are often well-equipped with public squares and leisure spaces, a notable lack of vegetation was observed, particularly along urban streets, which are characterized by high pedestrian and vehicular traffic. These findings highlight the importance of prioritizing green infrastructure in streetscapes to address heat mitigation and improve public spaces in the city.

The investigation of the selected segments also indicated that areas with low vegetation cover and high levels of soil impermeability tend to exhibit higher levels of thermal stress. Although punctual green infrastructure interventions have a limited range of influence, their low implementation and maintenance costs make them viable for replication on an urban scale. In this way, it is possible not only to increase the overall permeability of the urban system but also to multiply zones of milder microclimates and enhance the attractiveness of public spaces through accessible and effective biophilic solutions.

From the analysis of the proposed strategies, it is evident that large canopy trees play a key role in providing shade and reducing daytime heat, and can be applied in various configurations, generating positive effects even when of smaller scale. However, their implementation in urban streetscapes can be limited by physical and typological constraints, and they may require time to produce noticeable impacts. In this context, these strategies are most effective when combined with immediate-impact and low-maintenance solutions, such as large shrubs, small urban meadows, and rain gardens with underdrained systems. Although these elements have shown limited effectiveness in improving thermal comfort, they contribute to surface temperature reduction, soil stabilization, stormwater management, and biodiversity enhancement, while creating more appealing environments for pedestrians. Therefore, they offer practical alternatives that can be more readily implemented across the urban landscape, acting as catalysts for broader transformation.

This research offers a reinterpretation of the concept of Urban Acupuncture, previously applied in the context of Curitiba's urban development, adapting it to the contemporary challenges posed by the climate crisis. Simultaneously, it contributes to the promotion of local climate adaptation strategies that combine environmental protection, thermal regulation, technical effectiveness, affordability, and the potential for gradual implementation. The approach also aims to adapt well-established methodologies from the European context to the realities of Latin American cities, acknowledging their unique social, economic, and urban conditions.

It is important to note that the findings are not universally generalizable and must be considered in light of each territory's specific physical, social, and institutional characteristics. Furthermore, as mentioned earlier, this study is limited to public spaces to avoid the complexities linked to land ownership and dependence on non-public funding. However, future research could explore the development of public policies that promote the adoption and financing of these strategies in privately owned areas as well. There is also valuable scope for further investigation into the long-term monitoring of intervention outcomes and for fostering community engagement in the local-scale implementation of Nature-Based Solutions.

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