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Testing Strategies for Planting Design in Urban Squares to Improve Human Comfort throughout the Seasons

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Abstract: Green urban squares are essential in densely built neighborhoods and enhance their quality of life. Investment in the greening of urban areas will have a beneficial impact, particularly regarding human thermal comfort. Smaller than parks, squares can be easily spread over the cities and should be part of any neighborhood. While the cooling effect of green squares during hot summer days is increasingly well established, microclimatic assessments during all seasons are still missing. This study aimed to determine whether it is possible to identify an optimal greenery design that maximizes human thermal comfort, as indexed by physiological equivalent temperature (PET), in temperate climates across all seasons. This study employed a "research by design" methodology, utilizing the micrometeorological simulation model ENVI-met to analyze the impact of greenery on PET improvement across different seasons. The objective was to identify the most effective combination of greenery for PET improvement. To achieve these objectives, two urban squares in Munich, Germany were selected. This selection was based on the assumption that typical greening practices, exemplified by the presence of trees, shrubs, and grass, would significantly impact urban squares and their microclimatic effects on human thermal comfort. The small square with a grass surface underneath trees, Alpenplatz, is highly influenced by the surrounding buildings, affecting the sky view factor (SVF), a crucial aspect of the urban environment. Marstallplatz, an open, large square that is not highly affected by urban morphology, was analyzed through simulation scenarios combining grass, shrubs, and trees. The results demonstrate that hot summer days are of primary concern for climate-sensitive urban square design in order to avoid health risks and thus need to be prioritized without compromising comfort for cold days. To attend to both needs, increasing the number of deciduous trees for shading during the day and the amount of grass to enhance air cooling at night are particularly effective. Nevertheless, microclimate design for the spring and autumn periods must also be considered, with the provision of adaptable opportunities for sheltered and sun-exposed spaces.

Keywords: urban green infrastructure; urban climate; outdoor thermal comfort; microclimate modeling; ENVI-met

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1. Introduction

As a result of climate change, cities are experiencing more frequent and intense heat waves, which have a significant impact on human health [1–3]. Heat waves, which are associated with periods of unusually high temperatures and a lack of nighttime cooling, affect human health in various ways [4] including increased mortality in vulnerable populations [5–7].

The concept of human thermal comfort is defined as the influence of the thermal environment on the human body. Various indexes can be employed to analyze this phenomenon. In this study, the physiological equivalent temperature (PET) [8] is utilized, which integrates the heat balance of the human body with the variables mean radiant temperature (MRT), air moisture, and air velocity [9].

The necessity to enhance human thermal comfort is concurrently stimulating interest in the advantages of greenery as a strategy for climate resilience, as evidenced by the growing number of studies in this field [10–13]. The impact of urban parks on human well-being and thermal comfort has been investigated by a considerable number of studies for diverse climatic conditions [14–16]. Some studies combine field measurements with interviews to define human thermal comfort in different locations and climates [17–19].

The calculation of PET is feasible with a variety of methodological frameworks and computer software programs. While Chatzidimitriou (2016) [20] utilizes RayMan [21] for obtaining PET values after ENVI-met simulations, the majority of the authors directly obtain their comfort indexes from simulations through the Bio-Met tool, from ENVI-met [22], and validate their results using field measurements [12,16,23,24]. Additionally, recent studies have shown a growing interest in perceived human thermal comfort [25–29].

Although urban green spaces are essential for the achievement of the UN Sustainable Development Goals [30] and are an important tool for cities to adapt to climate change, there is a lack of knowledge about the optimal planting design for urban spaces and its impact on outdoor thermal comfort. Such a design would effectively balance the diverse human thermal needs in temperate climates both during the day and at night and during different seasons, particularly in Germany. Currently, the majority of research in this field is concentrated in China, Italy, and Greece [31].

The morphology of urban areas represents a significant factor influencing outdoor human thermal comfort [32–35]. Urban morphology is related to the phenomenon known as the urban heat island effect (UHI) [36], which refers to the elevated air temperatures within the most densely built parts of cities compared to the surrounding land. The sky view factor (SVF) is an important factor in this context, as it describes the ratio of radiation received from the sky by a planar surface compared to the radiation received from the whole hemisphere [37]. Apart from the fraction of radiation reaching during daytime, SVF is also a measure of the loss of long-wave radiation at nighttime. In densely built areas, the streets are surrounded by high buildings on both sides, creating what are known as urban canyons. With a low SVF, the longwave radiation is retained in narrow street canyons, preventing its loss to the atmosphere. One of the primary causes of the intensification of heat is the replacement of vegetated and permeable surfaces with built and otherwise sealed surfaces with a lower albedo and higher heat storage capacity. This results in elevated sensible heat fluxes at the expense of latent heat [36]. Consequently, human thermal comfort is negatively affected, particularly at night during hot seasons.

In order to ascertain the viability of recovering urban human thermal comfort through vegetation, numerous studies have been conducted employing diverse methodologies, including simulations and field measurements. These studies have demonstrated that healthy and resilient cities require the presence of vegetation to provide lower temperatures at the pedestrian level, particularly during the summer [17,38–41] when the UHI effect is most pronounced.

With higher albedo and lower storage capacity, green spaces play a crucial role in providing thermal comfort in dense neighborhoods [25,42]. Trees situated near residential areas act as a natural coolant, creating a sense of oasis-like refuge [12,20,23,24,26]. However, only a limited number of studies have investigated the potential of vegetated urban squares to provide human thermal comfort across the seasons, particularly on cold days [19,28,29,43–49].

The principal mechanism through which urban climates are influenced by greening is shading. Evapotranspiration is a secondary effect, which is stimulated by the reduction in radiative and convective surface-air heat exchange resulting from the lower temperatures of shaded and vegetated ground compared to non-shaded surfaces [50]. It has been observed that different types of greenery, including grasses, trees, and shrubs, have varying effects on temperature in different environments. This is due to the leaf characteristics of different types of plants, which can affect the cooling temperature of shaded air spaces [51–54]. In a study by Rahman et al. [55], it was observed that latent heat flux (LE) values were approximately half as high in the shade as in the sun when comparing shaded and sunny surfaces. The differences between shaded and sunny grass increased with increasing atmospheric dryness, with average LE approximately three times higher in the sun than average shade values.

To develop practical recommendations for cities and communities in Bavaria, the Center for Urban Ecology and Climate Adaptation of the Technical University of Munich (ZSK) was established in June 2013. Among the interdisciplinary research coordinated by the ZSK, the subproject 100 Places:M investigated the effects of climate change and heat island effects, as well as the design, use, and occupancy of public places in 100 open areas of Munich [56]. To refine the results from the 100 Places:M project and gain further insight into the potential of climate-adapted design to enhance the functionality of public spaces, the follow-up project "Ecosystem Services of Urban Green at Public Squares in Munich" [57] was developed.

The results of "Ecosystem Services of Urban Green at Public Squares in Munich" indicated that the vegetation in a square (including trees, shrubs, and lawn areas) and its spatial structure (such as the distribution, number, and age of such vegetation) contribute significantly to the cooling effect and reduction in runoff and carbon dioxide storage. To elucidate the distinctive roles played by urban morphology and the specific types of greenery, five distinct squares were selected based on their dimensions, pavement type, and tree density to examine plant design strategies. The vegetation was analyzed on five typical days to gain insight into the influence of its arrangement and composition on human thermal comfort throughout the year. The previous study demonstrated the importance of considering various vegetation arrangements in conjunction with urban morphology features to enhance human thermal comfort across different climatic conditions [57].

Despite our recognition of the unique geographic location, surrounding buildings, and vegetation arrangement of each square, we selected two from five previously studied squares to ensure the feasibility of this research. This was due to the significant effort and complexity involved in measuring climate variables and developing microclimate models. The main criterion for selecting the squares was their size, to represent a small and a larger square that are typical for densely built inner cities in central Europe.

The study examines the impact of distinct urban greening arrangements and urban morphology on human thermal comfort in the two urban squares in Munich. The primary objective is to ascertain whether it is feasible to identify an optimal greenery design that maximizes the PET in temperate climates across all seasons. Additionally, the study sought to determine the most effective combination of greenery for PET enhancement across different seasons. The influence of urban morphology on human thermal comfort in the selected public spaces and the impact of different combinations of grass, shrubs, and trees on urban microclimate and thermal comfort at different times of day and night throughout the seasons were investigated. This research thus addresses significant knowledge gaps in the field of urban climate science by exploring the potential of urban green infrastructure for climate-sensitive design of public spaces. For this purpose, micrometeorological simulations were performed using the ENVI-met model [22].

2. Materials and Methods

2.1. Study Area

The research was conducted in Munich, Germany. Munich is located in the southern part of the country (48°8′23″ N, 11°34′28″ E, altitude 519 m above sea level), and its climate is classified as Cfb in the Köppen–Geiger classification, with hot summers, no dry seasons, and increased precipitation rates during the summer. Munich is the third most populous city in Germany, with a population of 1.5 million [58]. As the population continues to grow, the city is both expanding and densifying, putting pressure on its green spaces. The challenge is to provide enough green space for its inhabitants. Large green spaces are rare in the densely built city center and surrounding neighborhoods. In this situation, smaller squares within the urban fabric can play a critical role as providers of public open space and thermal comfort close to where people live.

Five urban squares were initially selected and analyzed through micrometeorological field measurements followed by the squares modeling and ENVI-met simulations to gain a better understanding of how human thermal comfort is affected by the layout and vegetation composition during different seasons, as discussed by Stark da Silva et al. [57]. While analyzing the status quo of the squares, measurements were taken to validate the simulations for both summer and winter. Using two sets of mobile weather stations (Onset, MA, USA) with Globe thermometers and surface temperature sensors mounted on two tripods and iButton Hygrochron temperature/humidity loggers, the measurement campaigns were conducted in August 2020 and December 2021. All of the sensors, except the iButtons, were connected to 15-channel HOBO U30 USB Weather Station Data Loggers, which recorded five-second averages every five minutes. The detailed model validation and sensitivity test using the field measurement for the model calibration process are described in Stark da Silva et al., 2023 [57].

In light of the computational constraints and the time necessary for conducting the simulations, two contrasting urban squares from the previous study were selected. This was performed to investigate the impact of typical green design solutions and their resulting microclimate on PET in the context of a temperate climate (Figure 1).

Figure 1. Selected squares: Alpenplatz (**a**); Marstallplatz (**b**). Source: Priscila W. Stark da Silva (with basic geographical data provided by BayernAtlas).

Alpenplatz is a small square measuring 3317 m^2 with 26 trees; out of them, 18 are *Acer platanoides*, 6 are *Acer pseudoplatanus*, and the 2 perennials existing are identified as *Taxus baccata*. The sealed surface covers only 20% of the square, and it is surrounded by six-store high buildings on all sides. In contrast, Marstallplatz is a large square with a surface area of 9517 m^2, of which 91% is sealed. It has only 18 trees and is also surrounded by buildings on all sides. Within Marstallplatz, there are ten *Tilia cordata*, five *Acer platanoides*, two *Robinia pseudoacacia*, and one *Carpinus betulus trees*.

2.2. Scenarios

Five distinct scenarios were developed, combining grass, shrubs, and trees, for analysis across three typical days. Data from DWD station 3379 in Munich City (WST) for 2020 were utilized to identify typical days. The focus was on extended periods of weather stability, with a grouping of days exhibiting similar air temperature and humidity curves and regular patterns. Based on the collected data, the three typical days were classified as mild, warm, and hot, representing a typical spring day, a typical autumn day, and a typical summer day. The method employed for the selection of days is fully detailed in the work of Stark da Silva et al. [57]. Figure 2 illustrates the procedure for selecting the squares. The upper part of the figure shows the five initially selected Munich squares, which differ in size, number of trees, and type of pavement. The current thermal comfort performance of the squares was previously analyzed on five typical days: cold, cold and humid, medium, warm, and hot. The lower part of the figure refers to the part of the work discussed in this paper. This study, in turn, analyzes how different strategies of planting greenery affect human thermal comfort. This study focuses on a typical spring day, a typical autumn day, and a typical summer day. The winter season and rainy days were not considered because the intensity of use of the squares in these conditions is low.

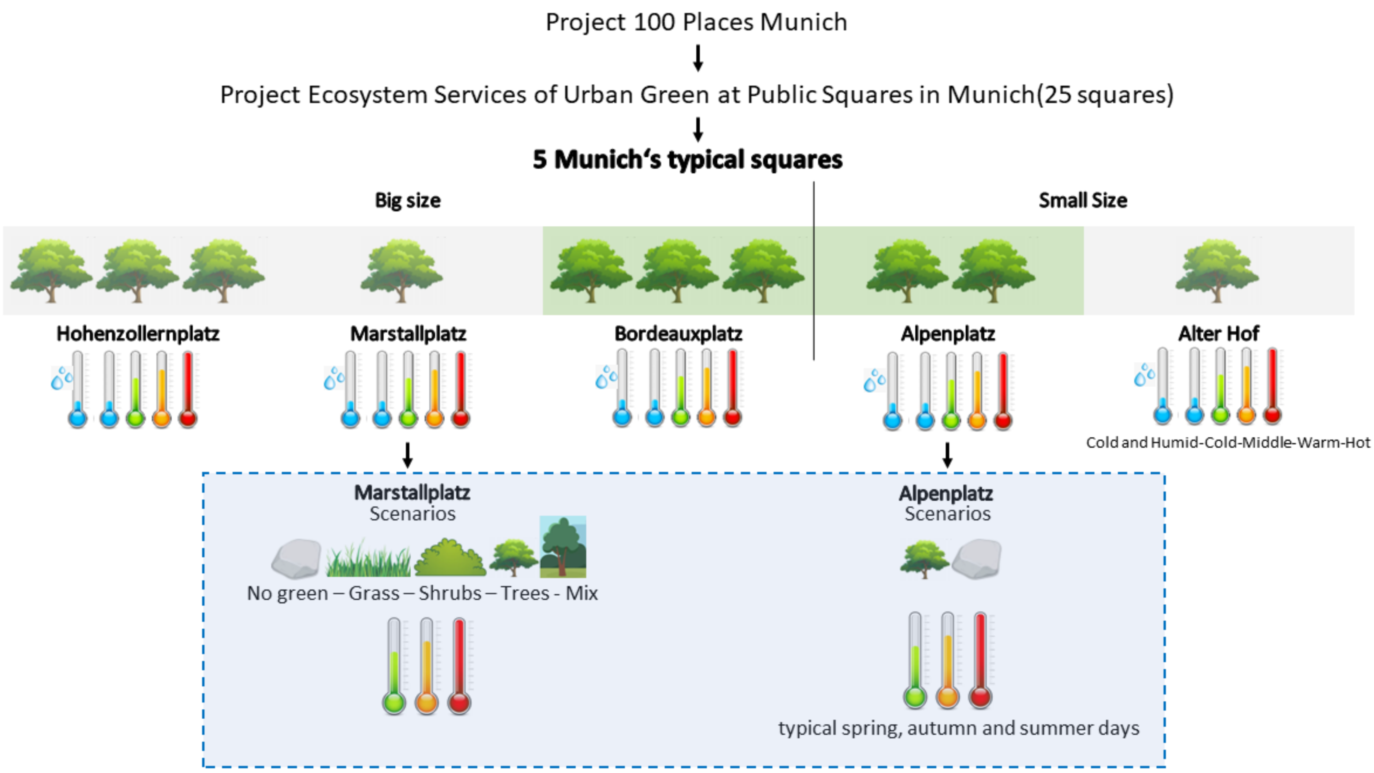


Figure 2. Analytical approach. Upper part: Initially selected squares. The lower part, Marstallplatz and Alpenplatz, is analyzed in more detail in this paper.

The methodology employed in the Alpenplatz study was designed to elucidate the impact of existing vegetation on the PET. This was motivated by the observation of Stark da Silva et al. [49] in their investigation of the role of Munich public squares, which indicated that the lowest PET values were recorded at 12 p.m. and 4 p.m. under the building's shade rather than under the vegetation as previously anticipated.

The study examines the average PET between 10 a.m. and 4 p.m. It employs an extreme situation of no greenery as a baseline to understand how each added element affects human thermal comfort in the cases studied. The different elements of green that are considered include grass, shrubs, and trees (Figure 3).

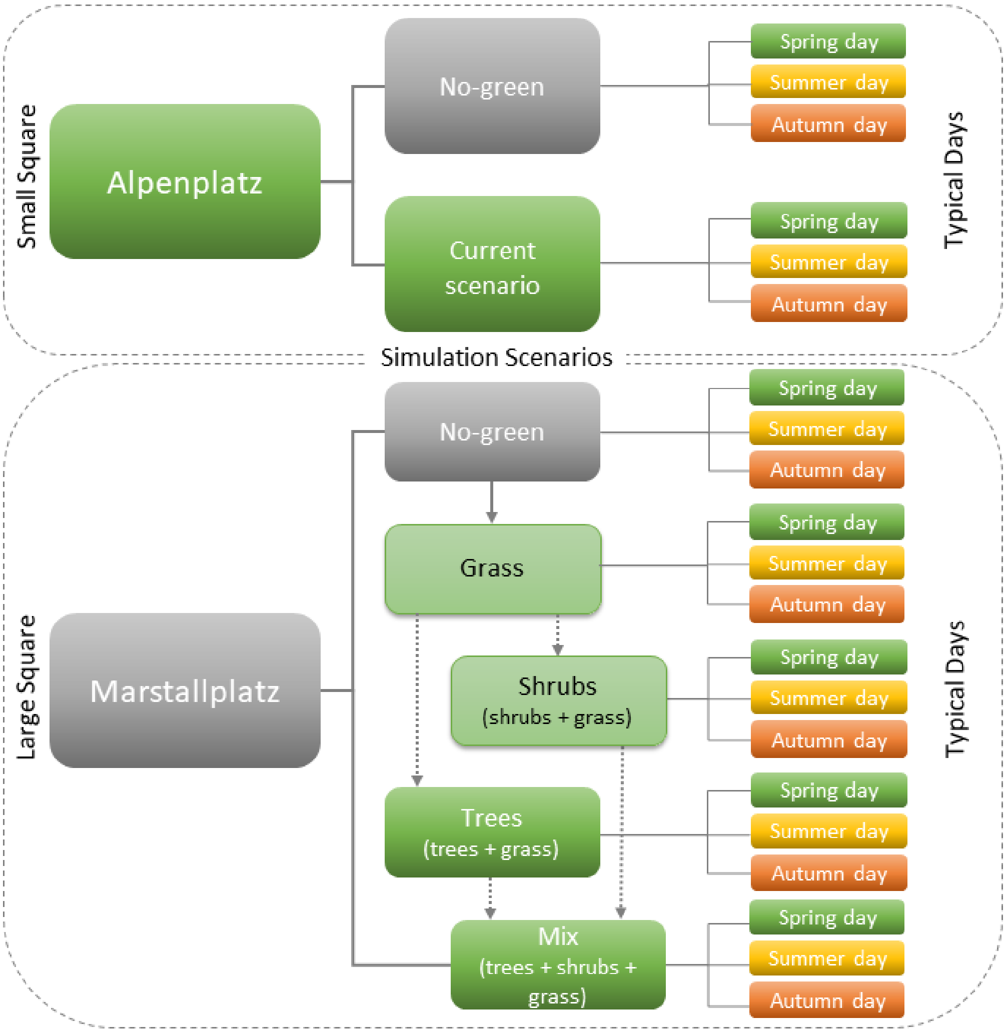


Figure 3. Green infrastructure scenario modeling approach.

2.3. Thermal Comfort Index (PET)

The PET was calculated using the meteorological parameters that influence the human energy balance, including air temperature, vapor pressure, wind speed, and mean radiant temperature of the surrounding environment, which was measured at 1.5 m above ground. Additionally, the PET considers the assumed internal heat production and the thermal resistance of clothing. In this study, the PET was obtained through the Biomet tool from ENVI-met.

2.4. Microclimate Modeling

Simulations were conducted using ENVI-met V4.4.6 [22], a high-resolution microclimate model that employs fluid mechanics and thermodynamics to simulate interactions between soil, vegetation, and the atmosphere at the microscale. The model calculates turbulence, air temperature and humidity, radiation fluxes, and pollutant dispersion in three dimensions [59]. The simulations were validated via field measurements taken during summer and winter conditions, as detailed by Stark da Silva et al. [57] in the initial phase of this study.

The Alpenplatz square was modeled at a size of 300 by 300 m, while the Marstallplatz square, due to its larger size, was modeled at 350 by 350 m. To achieve higher accuracy, the model implemented a 2 by 2 m horizontal resolution without a nesting grid and a 3 m equidistant grid for vertical resolution. The data regarding building heights and dimensions were derived from GIS data provided by the Bayerische Vermessungsverwaltung and subsequently verified on-site. Tree species were provided by the project 100 Places:M (2020), LAD values were used according to the predefined species in ENVI-met. Figure 4 depicts the simulation scenarios for the Alpenplatz area, including the current situation with no green space.

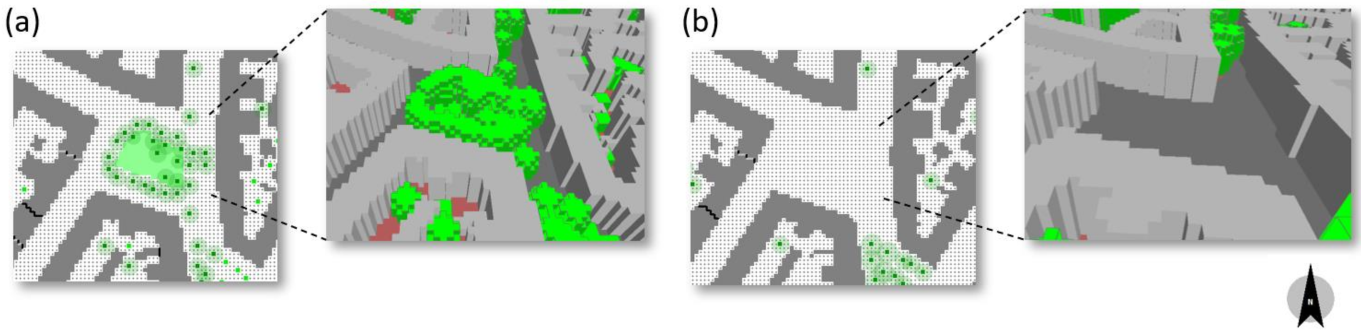


Figure 4. Alpenplatz current scenario (**a**) and no-green scenario (**b**).

Two different scenarios were developed for the Alpenplatz, while five different scenarios were modeled for the Marstallplatz: no greening, grass, shrubs, trees, and a mix of grass, shrubs, and trees (see Figure 5). Since the focus of the study is on the PET results, it was decided not to cover the entire square with shrubs. With branches closer to the ground, a square full of shrubs would make it inviable for human use (Figure 5c). The simulations for both squares began at 2 a.m. and lasted a total of 48 h. To eliminate initial transient conditions, the first 22 h of the analysis were excluded. The results for human thermal comfort were extracted at a height of 1.5 m, at pedestrian level. The meteorological data of typical days in Munich required for the ENVI-met simulation were obtained from the weather station with the city station ID 3379 of the DWD (Table 1).

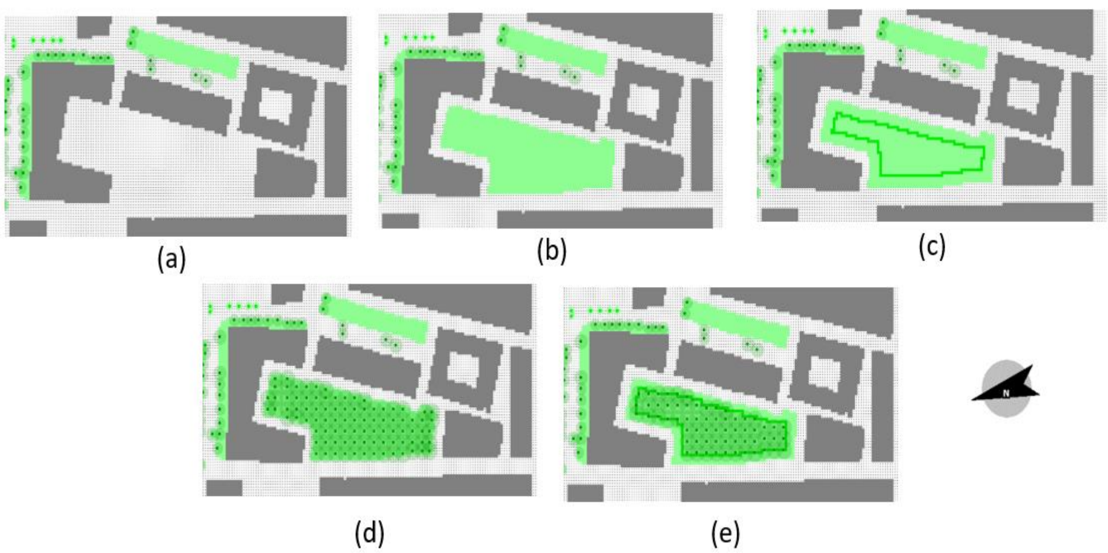


Figure 5. Marstallplatz simulation scenarios: no-green (**a**), grass (**b**), shrubs (**c**), trees (**d**), mix (grass, shrubs, and trees) (**e**).

Table 1. ENVI-met model setup and meteorological input data.

Day Classification	Typical Spring Day	Typical Summer Day	Typical Autumn Day
Start of simulation	26 March 2020	30 July 2020	18 September 2020
Duration of simulations	48 h	48 h	48 h
Modell grid size/resolution	Alpenplatz 300 × 300 × 25 (x, y, z) Vertical equidistant grid Marstallplatz 350 × 350 × 25 (x, y, z) Vertical equidistant grid		
Building material	Default wall—moderate insulation		
Soil material	Sandy Clay Loam, Granite, Asphalt with Gravel		
Grass (Grass, Shrubs, Trees and Mix scenarios)	Simple plant: Grass 25 cm aver. dense		
Shrubs (Shrubs and Mix scenarios)	Simple plant: Hedge dense, 2 m		
Trees (Trees and Mix scenarios)	3D plant: Tilia Cordata		
Min/Max Ta	−2.00/16.50 °C	17.60/33.7 °C	7.10/22.40 °C
Min/Max RH	35/80%	33/91%	49/91%
The daily sum of solar incoming radiation	1770 J/cm^2	2676 J/cm^2	1786 J/m^2
Relative soil humidity	Upper layer: 70%, Middle and Deep layer: 75%		
Lateral boundary conditions			Full forcing

The ENVI-met database contains the most common soil types and tree species found in temperate climates. The vegetation types used in the models were selected from the ENVI-met default, which includes dense grass at 25 cm and dense shrubs at 2 m. The tree species used was *Tilia cordata* (Tc), which was chosen for its characteristics as a deciduous species commonly found in Munich's urban squares. The trees were positioned in a 6 × 6 m grid. In the vegetated scenarios, a four-grid paved surface was considered to provide a natural transition between the grass and the buildings.

3. Results

3.1. Alpenplatz

As stated in Section 2.3, two distinct scenarios were developed for Alpenplatz: the no-green and current scenario.

The absence of green spaces demonstrated the impact of urban morphology. In all analyzed periods, the lowest PET was observed in proximity to the buildings' walls (Figure 6). The period between 10 a.m. and 4 p.m. is distinguished by the highest temperatures of any season in Munich. Therefore, this study will focus on the analysis of the average PET from 10 a.m. to 4 p.m. to gain insights into the critical daytime temperature patterns. The average PET, compared to the current and no-green scenarios, was only significantly influenced by the vegetation on a hot day.

The Matzarakis and Mayer [60] PET range interpretation indicates that, on the day in question, the average PET (between 10 a.m. and 4 p.m.) in the current scenario was classified as experiencing moderate heat stress (33.97 °C). In contrast, in the no-green scenario, the average PET was classified as experiencing strong heat stress (40.96 °C).

Table 2 illustrates that both scenarios exhibited slight cold stress on a typical spring day. Conversely, both scenarios demonstrated no thermal stress on a typical autumn day. These findings underscore the significance of greenery in small squares on hot days in Munich city and reinforce the importance of urban morphology in Munich's squares with low SVF [37].

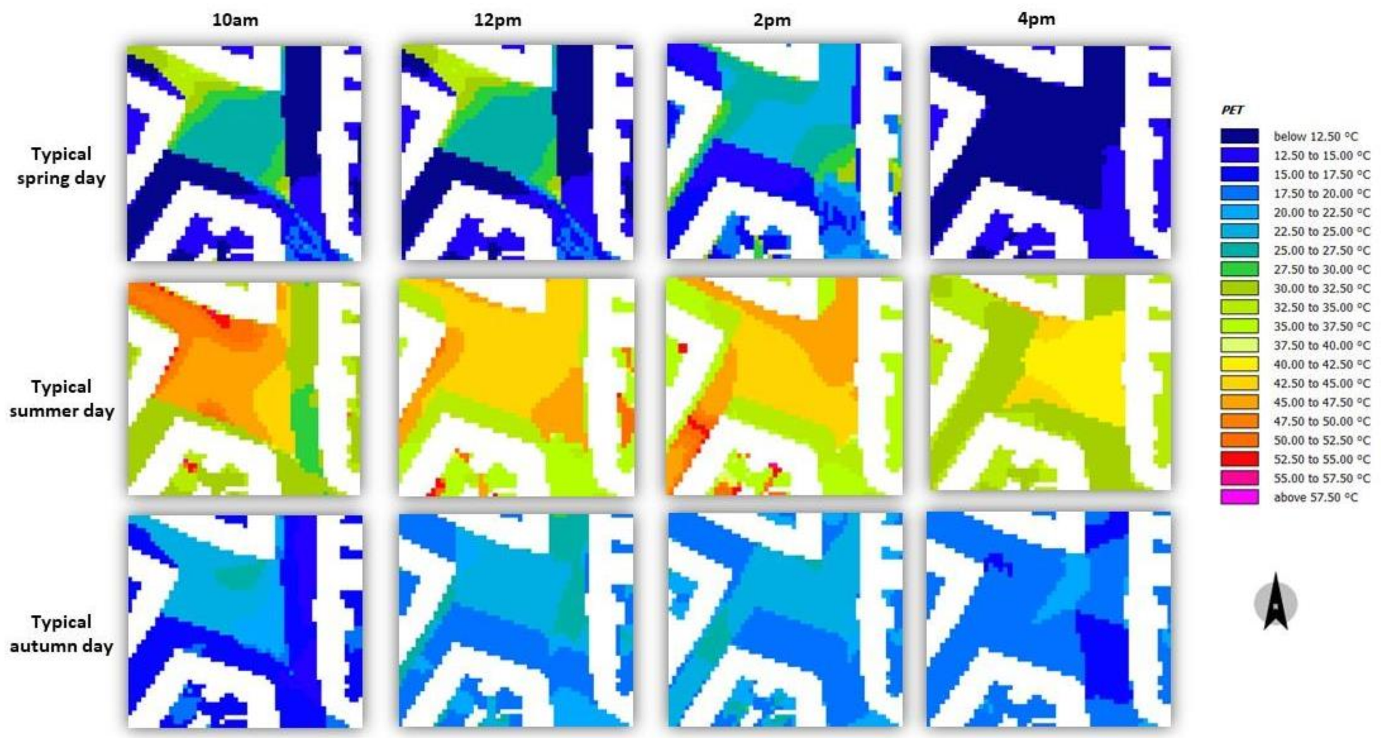


Figure 6. Alpenplatz's no-green scenario PET variation during the typical days: spring, autumn, and summer.

Table 2. Alpenplatz's average PET.

Average PET between 10 a.m. and 4 p.m. PET Range Interpretation, According to Matzarakis and Mayer (1996)		
Typical Day	**Current Scenario**	**No-Green**
Typical spring day	13.98 °C (Slight cold stress)	18.04 °C (Slight cold stress)
Typical summer day	33.97 °C (Moderate heat stress)	40.96 °C (Strong heat stress)
Typical autumn day	19.46 °C (No thermal stress)	20.48 °C (No thermal stress)

Despite the significant disparity in PET levels on the typical summer day, the minor differences observed on the typical spring and autumn days indicated that the focus of the analyses should be on Marstallplatz, given the time-consuming and computational demands of the task.

The decision to focus the study on Marstallplatz was also supported by Morakinyo et al. (2020) [61], who observed that high-density trees perform best when placed in areas with low sky view factors, and underperform in places like Alpenplatz due to the competing shading effect of the building. The area is currently heavily vegetated and strongly influenced by the urban morphology. The decision was also corroborated by Ouang at al. (2024) [62] who found results where PET was higher reduced on hot summer days in areas shaded by buildings compared to those shaded by trees. Based on these results, we decided to focus our study on Marstallplatz in order to test different vegetation scenarios in more detail, since Marstallplatz is a large square and urban morphology does not have as strong an effect on PET as observed in Alpenplatz, especially on medium and warm days.

3.2. Marstallplatz

3.2.1. Typical Spring Day

In the morning, it was observed that in the no-trees scenarios, a higher PET provided no thermal stress results, while the trees and mix scenarios were under slight cold stress. Figure 7 illustrates the influence of the buildings' shade on Marstallplatz's PET at 4 p.m. All analyzed scenarios presented moderate cold stress due to the buildings' shade.

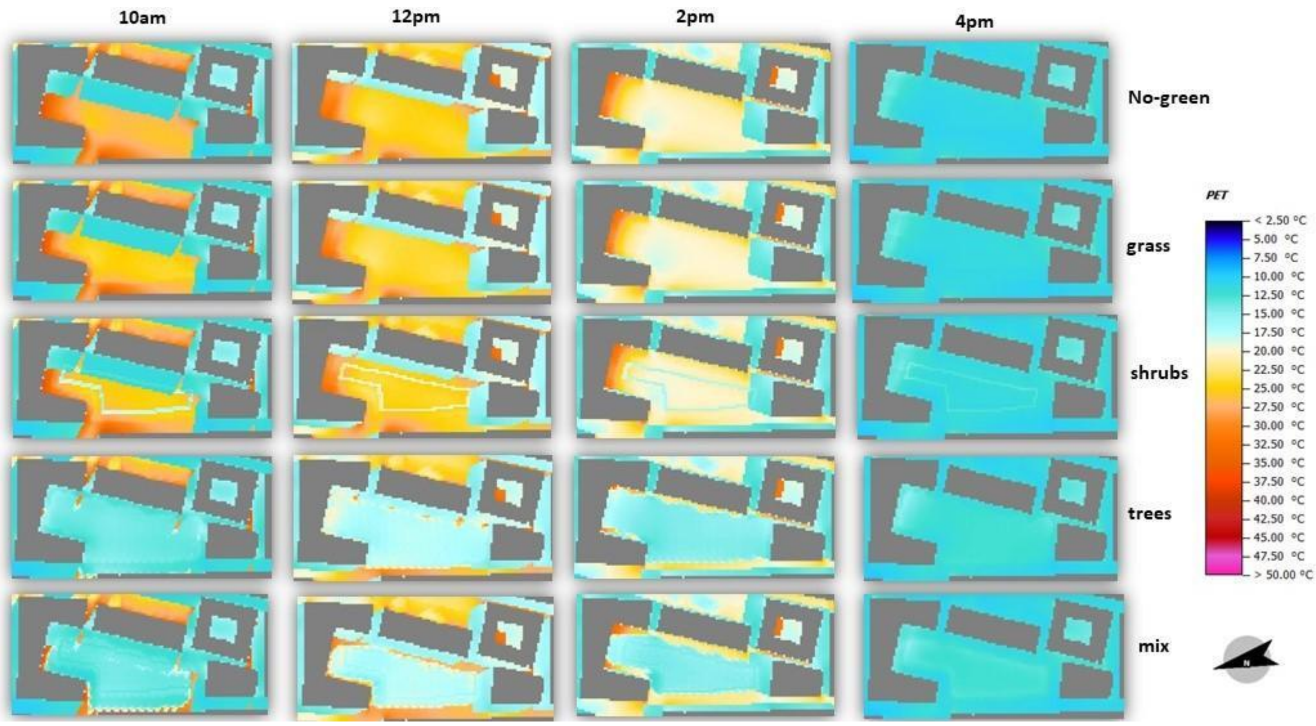


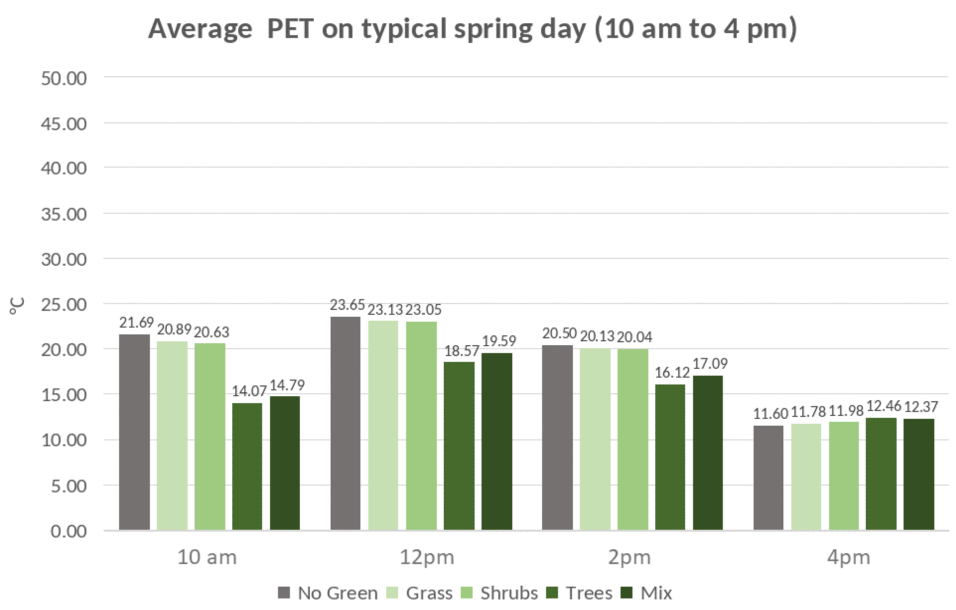
Figure 7. Marstallplatz's PET variation during the typical spring day.

Due to the absence of leaves, the shade of the trunks and branches was responsible for the lowest average PET values (18.57 °C) observed in the tree scenario at 12 p.m. In addition, the tree scenario also exhibited the lowest average MRT (12.44 °C) and average surface temperature (14.94 °C). Conversely, the highest average air temperature and lowest wind speed were observed in the scenario with trees. The scenarios with no trees exhibited equivalent values for PET and air temperature. The grass scenario exhibited the highest average surface temperature (18.00 °C), while the no-green scenario exhibited the highest average MRT (40.19 °C) and average wind speed.

At 4 p.m., the buildings' shade is also responsible for the uniformity of the PET values at that time. A small difference between 11.60 °C and 12.46 °C results in the highest average PET for the tree scenario, while the lowest average PET is observed in the absence of green. A similar pattern emerges when examining the average air temperature, which varies between 15.54 °C and 15.63 °C. However, in this case, the green scenario exhibits the highest value (16.92 °C), while the tree scenario exhibits the lowest (14.52 °C). Conversely, the tree scenario exhibited the highest average MRT (15.10 °C), while the no-green scenario exhibited the lowest (11.75 °C). The highest maximum MRT value was observed in the shrubs scenario (18.03 °C).

The highest average wind speed was observed in the no-green scenario, while the lowest was observed in the shrubs scenario.

In Figure 8, it is possible to observe the PET average values on the typical spring day. Deciduous trees were central to achieving no thermal stress in all scenarios at noon. The absence of leaves increases access to shortwave radiation, and hence the PET. However, the presence of tree trunks and branches of trees and their shade decreases the PET in the morning, providing slight cold stress in tree and mix scenarios.



PET Range	Interpretation
<4	Extreme cold stress
4~8	Strong cold stress
8~13	Moderate cold stress
18~23	No thermal stress
23~29	Slight heat stress
29~35	Moderate heat stress
35~41	Strong heat stress
>41	Extreme heat stress

	No Green	Grass	Shrubs	Trees	Mix (Trees, Shrubs and Grass)
Day average	**19.36 °C**	**18.98 °C**	**18.93 °C**	**15.30 °C**	**15.96 °C**

Figure 8. Marstallplatz's average PET on the typical spring day and PET range interpretation according to Matzarakis and Mayer (1996).

The presence of shrubs was beneficial to wind blocking when combined with the trees, resulting in a subtle increase in the average air temperature from 31.88 °C in the tree scenario to 32.37 °C.

3.2.2. Typical Summer Day

Figure 8 clearly demonstrates the impact of trees on PET. While the average PET is in extreme heat stress in the no-trees scenarios, the trees and mix scenarios are under slight heat stress. The surface temperature is the variable most affected by the lack of trees, varying between 29.08 °C and 29.32 °C in the no-green, grass, and shrubs scenarios. A comparison of the tree and grass scenarios revealed a maximum difference of approximately 4 °C.

The impact of shrubs on the PET on the typical summer day is only discernible within the vegetation, as illustrated in Figure 9. This is particularly evident at 10 a.m., 12 p.m., and 4 p.m., where the PET is observed to decline in comparison to the surrounding grass and paved areas.

A comparison of all scenarios at 12 p.m. revealed that the lowest observed PET was under the trees in the tree scenario, as anticipated. Among the variables comprising the PET index, the lowest MRT values were observed under the trees and the building shade in the tree scenario. In the shrubs scenarios, the lowest MRT values were observed under the shrubs, in the building shade, and the no-green and grass scenarios. The lowest average air temperature was observed in the tree scenario and the no-green scenario, likely due to the highest wind speed values observed in the no-green scenario. The highest average air temperature was observed in both the shrubs scenario and the grass scenario.

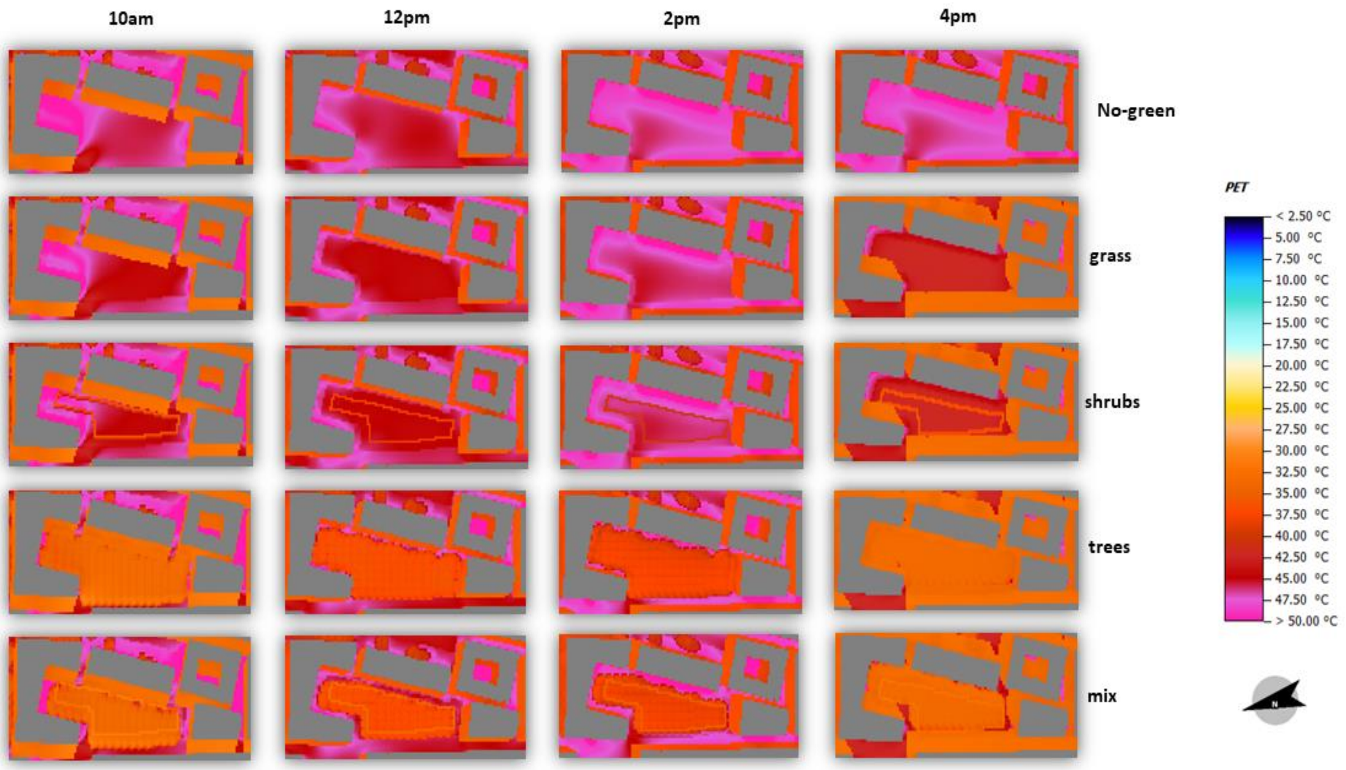


Figure 9. Marstallplatz's PET variation during the typical summer day.

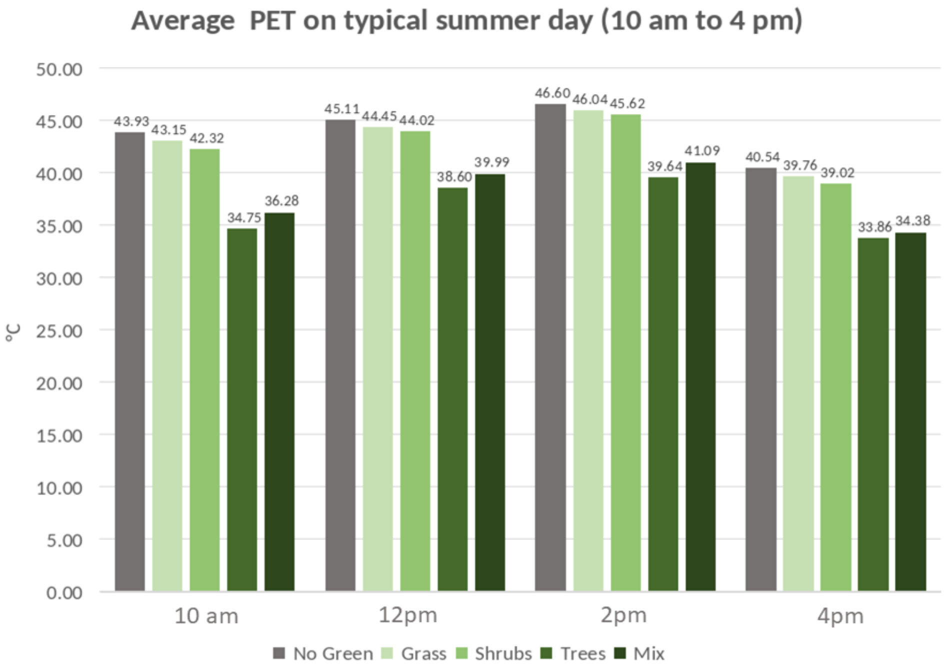
The highest average surface temperature was observed in the grass scenario (37.49 °C) and the lowest in the tree scenario (29.79 °C). The highest average wind speed was observed in the no-green scenario, while the lowest was observed in the shrubs scenario.

Conversely, at 4 p.m., while the lowest PET value (32.26 °C) was observed beneath the trees in the tree scenario, in the other scenarios, the lowest PET was observed in the shade provided by buildings. It can be observed that shade plays an important role in reducing the PET on summer days affected by the MRT, as evidenced by the observation of the lowest average MRT occurring beneath trees and the highest average MRT occurring in the absence of green vegetation. The lowest air temperature value was also observed under the trees, the same scenario exhibiting the lowest average air temperature (31.88 °C). The influence of the canopy shade was also evidenced in the average surface temperature (29.26 °C), while the other scenarios exhibited less notable differences in values. The highest average wind speed was observed in the tree scenario, while the lowest average wind speed was observed in the shrubs scenario.

Figure 10 illustrates the significance of tree shade in reducing PET during hot days. This is due to the combined effect of evapotranspiration and shortwave radiation protection. Additionally, it can be observed that shrubs exert a negative influence on PET during hot days. This is evidenced by the wind-blocking effect, particularly when trees and shrubs are present in the vicinity.

3.2.3. Typical Autumn Day

On the typical autumn day, despite the onset of senescence, the trees still have leaves that provide shade that impacts the PET values. However, at 10 a.m. and 4 p.m., the buildings' shade is the factor that affects the PET the most, decreasing the values to 12 °C when compared to the sun-exposed areas, as can be seen in Figure 11. This results in slight cold stress for the PET under the buildings' shade at 10 a.m. and 4 p.m. in all scenarios. However, the average PET observed is not under any thermal stress.



	No Green	Grass	Shrubs	Trees	Mix
Day average	**44.04 °C**	**43.35 °C**	**42.74 °C**	**36.71 °C**	**37.93 °C**

Figure 10. Marstallplatz's average PET on a typical summer day.

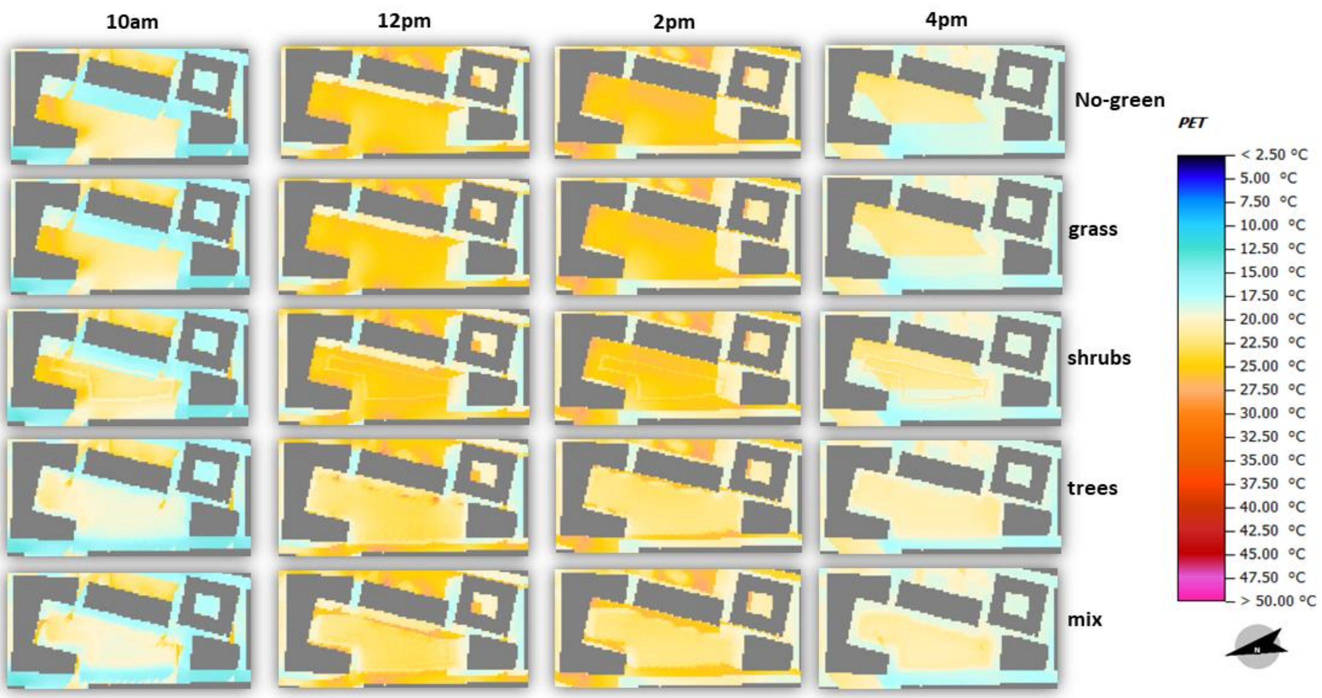
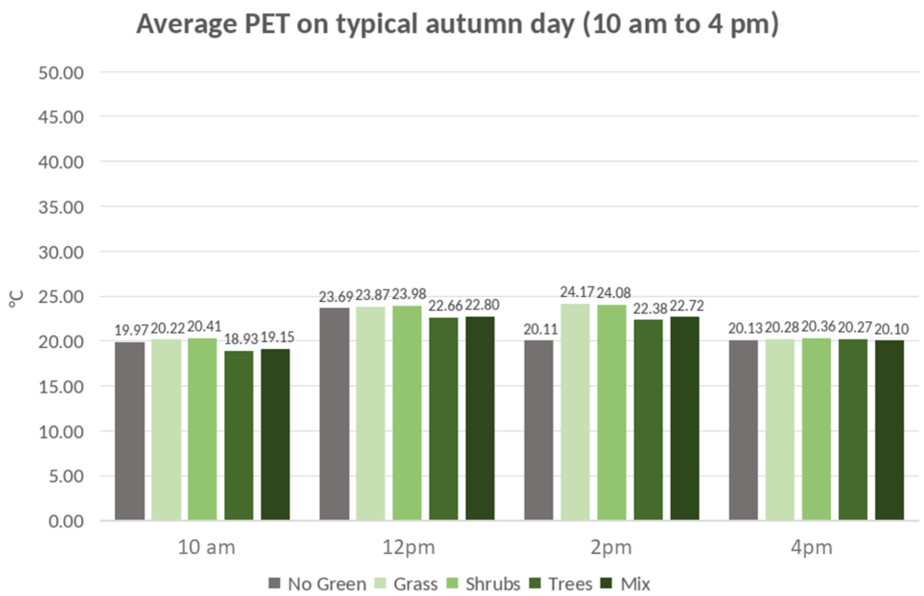


Figure 11. Marstallplatz's PET variation during the typical autumn day.

At noon, the highest average PET was observed in the shrubs scenario (24.00 °C), while the lowest average PET was observed in the tree scenario (22.66 °C), which also had the lowest average wind speed. The highest average wind speed and MRT were observed in the no-green scenario (31.98 °C), while the tree scenario presented the lowest average MRT (28.34 °C). Conversely, the tree scenario exhibited the highest average air temperature (20.84 °C), with the other scenarios demonstrating minimal differences in average air temperature (20.68 °C to 20.71 °C). The no-green scenario exhibited the lowest average surface temperature (19.22 °C), while the shrubs scenario exhibited the highest average surface temperature (20.17 °C).

At 2 p.m., the influence of tree shade on PET on the typical autumn day is more evident. At this time, the average PET of no-trees scenarios is under slight heat stress, as shown in Figure 12. In contrast, the tree and mix scenarios remain with no thermal stress. It is also possible to observe a slight increase of the PET in shrubs scenarios in almost all analyzed hours. This is probably due to the shrubs' wind-blocking effect combined with the sun exposure between 12 p.m. and 2 p.m.



	No Green	Grass	Shrubs	Trees	Mix
Day average	**20.98 °C**	**22.13 °C**	**22.21 °C**	**21.06 °C**	**21.19 °C**

Figure 12. Marstallplatz's average PET on the typical autumn day.

The PET and MRT are significantly influenced by the shade of the surrounding buildings at 4 p.m. The highest average wind speed, surface temperature (20.47 °C), and air temperature were observed in the tree scenario (21.22 °C), while the difference in average wind speed and air temperature between the other scenarios was not statistically significant. With regard to the variable surface temperature, the minimum average value was observed in the scenario with no green (19.45 °C).

The effects of shortwave radiation on PET are also observed in scenarios with no green vegetation or grass. However, the lower albedo of autumn grass, in comparison to granite, is likely responsible for the higher PET value remaining for a longer period.

3.2.4. Nighttime

Additionally, the nighttime PET was analyzed to ascertain the role of vegetation in the PET decrease. Table 3 illustrates the variation in PET values across all simulated scenarios at 2 a.m.

Table 3. Marstallplatz's average PET at nighttime.

Average PET 2 a.m.					
Typical Day	**No-Green**	**Grass**	**Shrubs**	**Trees**	**Mix**
Typical spring day	3.22 °C	3.13 °C	3.08 °C	2.41 °C	2.63 °C
Typical summer day	13.57 °C	14.02 °C	14.39 °C	15.28 °C	15.17 °C
Typical autumn day	7.55 °C	7.80 °C	7.95 °C	8.49 °C	8.32 °C

On the typical spring day, the lowest PET value (0.65 °C) and lowest average PET (2.41 °C) were observed in the tree scenario due to the highest wind speed values. Despite this, the same scenario presented the highest average air temperature (1.60 °C), the highest average MRT (−1.29 °C), and the second highest average surface temperature (4.77 °C). The remaining scenarios exhibited comparable PET values at 2 a.m. (averaging between 3.07 and 3.22 °C). The lowest average wind speed and MRT were observed in the no-green scenario, which also exhibited the highest average surface temperature (7.32 °C). The highest MRT value was observed in the "shrubs on Shrubs 2" scenario. The lowest surface temperature observed at 2 a.m. was in the grass scenario (3.84 °C) due to the surface albedo and high sky view factor. The average air temperature in the no-trees scenarios was between 1.43 and 1.48 °C.

In contrast, on a typical summer day, the shrubs scenarios presented the highest PET values, as they also had the slowest average wind speed. The tree scenario had the highest average PET of all analyzed scenarios and the highest average values of wind speed and air temperature. The MRT values of shrubs scenarios were also the highest, presenting the highest values in the shrubs. Notably, the no-green scenario exhibited the highest average surface temperature, whereas the tree scenario exhibited the highest minimum and maximum surface temperatures.

In the context of the typical autumn day, the tree scenario exhibited the highest average PET at 2 a.m. (8.49 °C), attributable to the canopy of deciduous trees that maintains the air temperature and MRT. Consequently, the tree scenario also exhibited the highest average air temperature (8.80 °C) and average MRT (5.55 °C), despite exhibiting the highest average wind speed. It is notable that the no-green scenario exhibited the lowest observed average PET (7.55 °C), lowest average MRT (0.76 °C), yet the highest average surface temperature (16.26 °C). Conversely, the lowest average air temperature (8.33 °C) and surface temperature (10.33 °C) were observed in the grass scenario. Additionally, the lowest average wind speed was observed in the shrubs scenario.

4. Discussion

The city of Munich is notable for its numerous urban squares, which exhibit considerable variation in terms of size, pavement type, and the presence of vegetation [63]. These distinctive configurations, in conjunction with the city's urban morphology, profoundly influence human thermal comfort, which varies considerably depending on the season and time of the day.

The influence of urban morphology on human thermal comfort has been studied in different climates, examining the effect of SVF on urban canyons [35,64,65] and parks [66]. Yangki, 2023 [65] observed that the PET can be comparably affected by trees and buildings' shade in temperate climates, reinforcing the influence of urban morphology evidenced in the case of Alpenplatz, where the building shade was found to be responsible for the lowest PET values on typical spring and autumn days, as also observed by Chen et al. [67] in their study for tropical climates and also observed by Deng et al. [68] in their study of Guangzhou, China, with humid subtropical climate. The previous results justify our decision to focus this study on Marstallplatz. Here, the average PET is not so strongly affected by the shading of the buildings.

In the context of typical spring and autumn days, it was expected that solar radiation would have a significant positive effect on PET in the absence of trees. However, our results did not support this hypothesis, suggesting that deciduous trees also have beneficial effects in the interseasonal and winter periods, as observed by Yilmaz et al. [69] and also by Xiao and Yuizono [19]. Our study found that deciduous trees are more beneficial in dense urban areas of temperate climates. While Azimi et al. (2024) [70] found that evergreen trees are preferable in sparsely populated areas with hot summers and cold winters of humid subtropical climate. This underscores the importance of acknowledging the intricate climatic necessities of each climatic zone and geography, as well as the unique characteristics differentiating one solution from the other, as also previously emphasized by Qureshi, 2023 [71].

Despite the observation by Zheng et al. [72] of a considerably higher thermal comfort in summer when shrubs and trees were combined on their modified thermal humidity index (MTHI), this strong influence was not observed on the PET in our study. This is probably due to our decision not to cover the entire area with shrubs in order to simulate a real situation of human use. Nor on typical spring and autumn days where the shrubs' wind-blocking effects were expected to affect the PET strongly. This result can be justified by the shrubs' leaf senescence, which enables the wind flow. Conversely, the combination of shrubs and tree trunks has the effect of reducing wind flows, which in turn increases the PET on typical spring and autumn days.

On a typical summer day, the benefits of vegetation for improving human thermal comfort are readily apparent in our study, as have been discussed by numerous authors in their studies of summertime in all climates [11,13,16,24,69,73]. As Wong et al. [74] observed with climbing green walls, which can be compared to the characteristics of shrubs, the PET effect of shrubs in this study could only be observed within the vegetation but not in the surrounding area. This observation is consistent with the findings of Stark da Silva, 2018 [75], who conducted simulations and field measurements and found that the PET effect of shrubs could only be observed within the vegetation. In contrast, Li et al. [76] observed that shrubs actually deteriorate the PET on the pedestrian level due to wind speed reduction and increasing relative humidity in the tropical climate of Singapore. Our study observed that the effect of shrubs on PET was diluted in their surrounding environment. Consequently, among the analyzed greenery types, the tree climate regulation ecosystem service was the most significant factor in the observed improvement in PET values. On average, the PET decreased by up to 8 °C on a typical summer day, indicating a clear correlation between the presence of trees and the reduction in temperature.

Another variable that affects the PET is surface temperature. In the process responsible for the UHI, surfaces absorb the sun's shortwave heat during the day, storing it for release at nighttime. The floor surface materials analyzed in this study are granite and grass. These materials were also studied by Hendel et al. [77], who observed a "cool" behavior of the granite pavement during the day and a "hot" behavior at night. Hendel et al. also observed that, due to evapotranspiration, the grass surface exhibited the lowest surface temperatures and the highest thermal inertia. It has been observed that the most critical factors influencing surface heating are the surface albedo and evapotranspiration [77]. However, evapotranspiration is not an effective cooling mechanism at night due to the closing of the stomata [78].

It is also important to note that the leaf density of trees, which reduces the PET during the day, also slows the decrease in PET at night due to the SVF effect. This is evidenced by the influence of the SVF on PET, with the majority of scenarios without trees and consequently higher SVF exhibiting the lowest PET. However, on a typical spring day, the tree scenarios exhibited lower PET. The higher wind speed and the lack of tree leaves resulted in a lower PET under the trees despite the higher surface temperature observed in the no-green scenario (7.32 °C) when compared to the grass surface of the other scenarios (average value of 4.20 °C).

Conversely, it can be observed that on the most critical days (typical autumn and summer days), the scenarios with no green, grass, or shrubs present the lowest PET, which contributes to the reduction of the urban heat island (UHI) effect. In contrast, the presence of leaves makes it challenging for the loss of heat in the atmosphere to occur during the nighttime. Furthermore, our research observed a convective heat loss from vertical building walls compared to an open grass area, which reduced PET values at nighttime. This finding is consistent with the observations made by Spronken-Smith and Oke in 1999 [78] and Irmak et al. [79]. The aforementioned findings serve to reinforce the results previously obtained, which indicated that open areas covered by grass are the configuration most conducive to a reduction in the UHI at night.

5. Conclusions

The impact of vegetative elements on the enhancement of PET across varying seasons was evaluated through the implementation of a "research by design" methodology and the micrometeorological simulation model ENVI-met. The objective of this study was to identify the most effective combination of greenery for the improvement of PET. The impact of different arrangements of urban greenery on thermal comfort in temperate climates across all seasons was evaluated. In order to achieve this objective, two urban squares in Munich were analyzed through micrometeorological simulations, which enabled the impact of diverse variables on PET to be investigated throughout the year. These variables included the morphological characteristics of the urban area in question and the specific green arrangements that had been implemented. The aim of the study was therefore to identify the most effective combination of greenery design that would result in the optimal physiological equivalent temperature (PET) across all times of year.

Despite the heat storage capacity of granite, the observed benefits of scenarios without vegetation on PET on typical spring and autumn days are not strong enough to justify paved areas without vegetation in urban squares. Furthermore, shrubs do not have a significant effect on the PET in the analyzed scenarios where strong wind protection is provided by the surrounding buildings. It is therefore recommended that the use of shrubs on urban squares in Munich be related more to their other ecosystem services than to climate regulation and their benefits for PET.

The findings of this study demonstrate the profound impact of urban morphology on PET within Munich's small urban squares. This is attributed to the shading provided by surrounding buildings, which is comparable to the shading effect of trees but adds an additional wind blocking effect in small squares. Additionally, tree shading and evapotranspiration effects play a vital role in reducing PET on typical summer days. Moreover, their influence is particularly pronounced on typical spring and autumn days.

In conclusion, to achieve human thermal comfort in urban squares in temperate climates, it is preferable to focus on the necessities of summer days. This can be achieved by increasing the number of deciduous trees that reduce the PET due to the provided shade and evapotranspiration effect without blocking the radiation access on mild days. Furthermore, the amount of grass should be increased to provide a higher SVF and reduce the nighttime UHI.

Future research should investigate the potential of incorporating common green infrastructure designs and measuring their microclimatic impacts in enhancing human thermal comfort in the context of anticipated climate changes.

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