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Effective street tree and grass designs to cool European neighbourhoods

Yehan Wu [a,b,*], Bardia Mashhoodi [a,c], Agnès Patuano [a]

[a] *Landscape Architecture and Spatial Planning Group, Department of Environmental Sciences, Wageningen University & Research, the Netherlands*
[b] *Section of Urban Design, Department of Urbanism, Faculty of Architecture and the Built Environment, Delft University of Technology, the Netherlands*
[c] *School of Computing and Mathematical Sciences, Faculty of Engineering and Science, University of Greenwich, London, the United Kingdom*

A R T I C L E I N F O

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A B S T R A C T

Street trees and grass are important elements for cooling cities, yet where and how to distribute them at the neighbourhood scale is still unclear. This study aims to identify effective street tree and grass design scenarios to maximise cooling in European neighbourhoods with temperate climate. 32 design scenarios were developed by combining urban design parameters of vegetation type, coverage, and spatial distribution in four neighbourhood typologies. The microclimate effects of these scenarios were then simulated using the ENVI-met model. To evaluate their cooling effects, three indices were applied: PET reduction, percentage change in thermal sensation class, and cooling efficiency. Results reveal that even fully covering streets with grass has a marginal thermal impact in reducing the mean Physiological Equivalent Temperature (PET) by up to 1.1 °C across the neighbourhood, while street trees lower PET by up to 8.7 °C. Neighbourhoods with wide radial streets have higher initial PET values and benefit more from green interventions. Strategically placing two rows of large trees on main streets is more effective for cooling than a single row on both main and secondary streets on the high-radiation side. Neighbourhood-specific practical recommendations for strategically implementing street trees and grass are provided to improve urban cooling.

1. Introduction

1.1. Street trees and grass as urban cooling solutions

Over the past two decades, heatwaves have increasingly impacted people's lives across the globe, leading to thousands of additional deaths due to extreme temperatures (Froment and Below, 2020; Robine et al., 2008; Tollefson, 2023). As climate change intensifies, urban heat stress has become more severe, particularly in Western Europe, which is now identified as a hotspot for these extreme temperature events (Witze, 2022). With the rise in urban heat stress and the ongoing global warming crisis, the search for effective cooling strategies has become more urgent than ever (Georgescu et al., 2024). Among the design-oriented solutions for cooling cities,

* Corresponding author at: Section of Urban Design, Department of Urbanism, Delft University of Technology, Julianalaan 134, 2628 BL Delft, the Netherlands.

E-mail addresses: yehanwu@tudelft.nl (Y. Wu), bardia.mashhoodi@wur.nl, b.mashhoodi@greenwich.ac.uk (B. Mashhoodi), agnes.patuano@wur.nl (A. Patuano).

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vegetation stands out for its ability to mitigate heat through processes such as evapotranspiration, blocking solar radiation, and reflecting sunlight, due to the higher albedo of plants compared to the man-made dark surfaces commonly found in urban environments (Taleghani, 2018).

Street trees are one of the most effective vegetation strategies in improving thermal environments and alleviating pedestrian heat stress (Chen et al., 2023). However, their implementation is constrained by several urban spatial challenges at multiple levels: ground-level planting areas can compete with pedestrian spaces, while above-ground tree canopies may obstruct views, and underground tree roots may interfere with drainage systems (Lachapelle et al., 2023; Mullaney et al., 2014).

Greening of ground surfaces such as introducing lawns, meadows, beds with perennials or flowers, or low shrubs (as of here subsumed under the short term ‘grass’), is also becoming popular in cities, and has shown effectiveness in increasing the evapotranspiration, and reducing surface temperatures (Armson et al., 2012; Lobaccaro and Acero, 2015). Street grass can be grass grown on part of street surfaces, landscaped sidewalks or permeable pavements. In addition to cooling, these green surfaces play a vital role in reducing stormwater runoff, a significant concern in many urban areas (Forman, 2014). Permeable materials combined with grass could facilitate stormwater management, marking street grass as an influential intervention for sustainable development (Tan and Tamminga, 2021). Urban street surface infrastructure is undergoing transformation, with the growing implementation of grass surfaces, such as grass-covered parking spaces (Lin et al., 2021) and grass-planted tram lanes commonly seen in Dutch and German cities (Łukaszkiewicz et al., 2021). With the emergence of autonomous vehicles and the reduction of car-oriented surfaces considering future mobility, covering more street surfaces with grass may become feasible (NACTO, 2019). Autonomous vehicles can drive in precise routes, requiring smaller roads and providing opportunities to introduce green spaces in current streets (Fisher, 2021; Luo et al., 2019). However, street grass poses unique challenges, such as maintenance requirements and its impact on traffic flow, which must be carefully considered. These constraints make it difficult to incorporate street grass uniformly across all neighbourhoods.

Planting street trees and grass becomes increasingly essential in the transformation of urban landscapes, yet with the above real-world constraints for tree and grass plantings in dense cities, it is important to develop insights into where and how to prioritise distributing them for effective cooling. The next section elaborates on a related knowledge gap in the current body of studies.

1.2. *Spatial design scenarios of street trees and grass to cool neighbourhoods*

Research on the cooling effects of street trees and grass, as common forms of urban greening, has grown significantly in recent years (Xi et al., 2023; Ji et al., 2024). Studies show that street trees provide shade and convert solar radiation into latent heat through transpiration, effectively reducing temperatures (Krayenhoff et al., 2020). For example, street trees can lower thermal sensation by up to 16 °C (de Abreu-Harbich et al., 2015; Ouyang et al., 2023), with reductions in mean radiant temperature (MRT) ranging from 20 to 40 °C (Lachapelle et al., 2023; Kántor et al., 2018) and average air temperature decreases of up to 3.5 °C (Santamouris et al., 2017). Street grass cools surfaces primarily through its higher albedo and evapotranspiration, effectively dissipating heat (Armson et al., 2012; Liu et al., 2021). Grass-covered pavements have been shown to reduce thermal sensation in urban canyons by 2–4 °C (Lobaccaro and Acero, 2015; Aboelata, 2020). On a larger scale, combining grass with cooling materials can lower surface temperatures by an average of 2.5 °C annually and up to 5 °C during peak summer months, such as July (Coccolo et al., 2018). Beyond outdoor cooling, street trees and grass also benefit nearby buildings by reducing surface temperatures and improving indoor thermal comfort (Liu et al., 2021; Taleghani, 2018). These effects contribute to reduced summer air-conditioning demand and lower CO_2 emissions (Xi et al., 2023; Aboelata, 2020).

With the expected increase in grass surface coverage due to future mobility infrastructure, questions arise about the relative cooling contributions of street trees and grass when grass covers significant street areas. At the scale of green spaces or urban squares, tree shading has been shown to be more effective than lawn evapotranspiration in reducing cooling loads (Wang et al., 2016; Rahman et al., 2021; Liu et al., 2021). However, in smaller experimental plots, grass reduced maximum surface temperatures by up to 24 °C, compared to 19 °C under tree shade (Armson et al., 2012). At the street level, grass-covering pedestrian lanes can achieve greater air temperature reductions and energy savings than certain tree-planting strategies (Aboelata, 2020). These findings reveal a knowledge gap in understanding the cooling effect of larger grass coverage relative to street trees.

When planning street trees and grass, it is essential to consider the characteristics and arrangement of vegetation. For instance, trees with higher Leaf Area Index (LAI) and Leaf Area Density (LAD) provide denser canopies, which effectively reduce radiant heat and air temperatures (Morakinyo et al., 2017; Manickathan et al., 2018; Lai et al., 2023). Larger tree crowns are particularly effective in cooling (Speak et al., 2020; Li et al., 2024; Manickathan et al., 2018), and increasing the crown-to-trunk height ratio by 1 unit can reduce thermal sensation approximately 2.5 °C during peak hours (Wang et al., 2021). Additionally, cylinder-shaped tree crowns are more effective at cooling than sphere-shaped or cone-shaped crowns (Milošević et al., 2017).

In terms of spatial arrangement, scattered tree arrangements are more effective in reducing air temperature and improving thermal sensation than clustered arrangements, due to increased shade coverage and reduced overlapping of tree crowns (Atwa et al., 2020; Zhao et al., 2018; Liu et al., 2021). Positioning larger canopies on street side that receives higher solar radiation further enhances their shading and cooling benefits (Klemm et al., 2017; Lin and Brown, 2021). The spacing of small trees at 3–10 m intervals significantly decreases MRT, while spacing for larger trees is less sensitive (Park et al., 2019). Double-row planting with dense coverage reduces daytime wall and air temperatures by up to 10.0 °C and 1.0 °C, respectively, whereas lower planting densities weaken these effects (Chen et al., 2021).

Despite these findings, few studies have addressed neighbourhood-scale planting strategies (Segura et al., 2022). Current studies have primarily focused on vegetation coverage, concluding that 20–30 % coverage is optimal for subtropical climates (Ouyang et al., 2020) and 40 % for temperate climates (Ziter et al., 2019). Yet, in dense urban neighbourhoods, achieving high vegetation coverage is often challenging due to space constraints, environmental factors, and maintenance requirements (Mullaney et al., 2014). Under constraints on planting, for instance, should trees be prioritised only in double rows along shallow streets, or placed in single rows on the high-radiated sides of both shallow and narrow streets? Knowledge gaps remain about how different greening arrangements affect thermal sensation at the neighbourhood scale.

1.3. Impact of morphologies on different spatial design scenarios

Urban morphologies significantly influence the effectiveness of cooling strategies (Li et al., 2024). Building configurations and layouts shape the conditions of street canyons and neighbourhoods, influencing factors such as building density, street canyon depth, street patterns, and the arrangement of buildings (Kim and Brown, 2021). At the street level, urban canyons with a low height-to-width (H/W) ratio, or aspect ratio, tend to have increased thermal sensation due to greater exposure to solar radiation (Muniz-Gäal et al., 2020; Ali-Toudert and Mayer, 2006). Moreover, increasing canopy coverage reduces MRT more significantly in shallow street canyons (H/W = 0.5) compared to deep canyons (H/W = 2.0) (Lee et al., 2020; Deng and Wong, 2020). Streets oriented east-west experience longer heat stress, making tree planting along these streets more effective for enhancing thermal comfort (Peng and Huang, 2022; Lee et al., 2020).

At the neighbourhood level, studies have examined morphologies in relation to local climate zones and varying densities (Liu et al., 2023; Middel et al., 2014; Ouyang et al., 2020). However, neighbourhoods are not uniform; their morphologies often feature complex variations in street H/W ratios, orientations, and hierarchies. These variations influence factors such as sunlight exposure, airflow, and thermal comfort within streets and surrounding areas (Wu et al., 2022; Yin et al., 2019). For example, main and secondary streets within neighbourhoods may perform differently in terms of thermal sensation (Deng and Wong, 2020). Knowledge gaps remain about how neighbourhood-level morphological differences affect thermal sensation under various planting scenarios. To fill these gaps, the following section presents the aim of this research and the sub-questions.

1.4. Aim and research questions

This research particularly targets European neighbourhoods with temperate climates, which are increasingly affected by urban heat issues due to the rising frequency of heatwaves (Rousi et al., 2022). The aim is to identify effective planting strategies for street trees and grass to enhance cooling effects in neighbourhoods and provide guidelines for urban design practitioners. The main research question is: What are the impacts of different planting scenarios involving street trees and grass on thermal sensation in temperate-climate European neighbourhoods?

To elaborate on the main research question, two sub-questions are raised:

1) What are the impacts of spatial design on the cooling effects of street trees and grass planting?
2) How do these impacts vary across neighbourhoods with different morphologies?

In the following section, we describe the research design aiming to seek answers to these questions.

2. Methodology

The methodology of this research consists of three steps. First, eight design scenarios (denoted S1 to S8) were developed for four neighbourhood typologies with varying urban morphologies (T1 to T4) in European temperate climate. Second, microclimate simulations were conducted using the software ENVI-met to evaluate the thermal sensation performance of each design scenario. Third, three indices were used to compare thermal sensation across different neighbourhoods and scenarios: PET, percentage change in

Table 1
Rationale for the eight greening design scenarios.

Scenario	Street tree or grass distribution	Spatial design rationale
S1	Two rows of large trees in main and secondary streets	Maximise shade coverage when resources are not limited
S2	Two rows of large trees in secondary streets	Plant only on secondary streets when main streets are unsuitable due to factors such as underground infrastructure, high pedestrian traffic, or the need to maintain shopfront visibility.
S3	Two rows of large trees in main streets	When resources are limited due to financial, space, environmental, logistical, and maintenance constraints, plant large trees on main streets to reduce solar radiation.
S4	One row of large trees on high radiated side of main and secondary streets	When resources are limited, plant one row of large trees on high radiated side of both main and secondary streets
S5	Two rows of small trees in main and secondary streets	When large trees cannot be transported or planted due to practical constraints, or when immediate cooling is required, plant small trees to assess their cooling impact compared to fewer large trees.
S6	Grass covered in main streets	Plant grass on main streets to increase pervious surface and use them for autonomous vehicle lanes or as community parks.
S7	Grass covered in main and secondary streets	Plant grass as much as possible when resources are not limited
S8	Grass covered in secondary streets	Plant grass on secondary streets when the main streets require high traffic with hardscape vehicle lanes

thermal sensation class, and cooling efficiency.

2.1. First step: spatial scenarios of street trees and grass in the neighbourhoods

To effectively plan the distribution of street trees and grass in neighbourhoods, it is important first to identify neighbourhoods with a representative morphology of streets and building blocks which significantly influences the microclimate of the area (Yin et al., 2019). Specifically, the dense urban neighbourhoods in European cities with temperate climates have been found to be particularly prone to urban heat stress, therefore, we utilised four neighbourhood typologies found in these areas. The selection of the four typologies was based on the study by Wu et al. (2022), which focused on European cities with temperate climate, using Amsterdam, London, and Paris as representative examples. In their study, Wu et al. (2022) identified local climate zone 2 (LCZ 2, compact mid-rise areas) as the most prone to heat stress in these cities. Within the LCZ 2 including 656 neighbourhoods, they developed four typologies by clustering different morphological combinations of urban features, such as street orientations, street height-to-width ratios, block shapes, and block floor area ratios. Based on collaboration with urban designers and existing research (Park et al., 2019), eight design scenarios were developed, considering street hierarchy and planting strategies for the distribution of street trees and grass (Table 1). The identified typologies are presented in Table 2 and illustrated in Fig. 1 and serve as testbed in our research. The quantitative descriptions of scenarios and typologies are presented in Table 2.

It should be noted that for small trees, only one scenario—S5, which involves two rows of small trees in both main and secondary streets—has been included in our analysis. Extensive research has shown that small trees, due to their limited crown size, provide less cooling effect in terms of air temperature, MRT, and thermal sensation compared to large trees (Fu, 2022; Li et al., 2024). Consequently, scenarios with fewer small trees result in lower cooling benefits than those with large trees. For this reason, additional scenarios involving fewer small trees—such as small trees only on main streets, small trees on secondary streets, or one row of small trees on the high-radiated side—were not prioritised to be tested as scenarios. However, some questions remain for urban greening practitioners regarding the immediate cooling effects of planting only small trees, especially when large trees are not feasible due to practical constraints (e.g., challenges in transporting or planting large trees in certain streets). This also raises the question of whether the cooling intensity observed in S5 could be comparable to scenarios where fewer large trees or those with trees. Given these considerations, we kept S5 as a representative scenario in our analysis.

As eight design scenarios were assessed across each of the four neighbourhood typologies, this resulted in 32 cases of greening. These cases were evaluated in contrast to the baseline scenario, S0, where greening was absent, leading to a total of 36 simulations.

2.2. Second step: ENVI-met simulation

To understand the thermal sensation of what pedestrians experience when walking on the street, this study adopted Physiological Equivalent Temperature (PET). PET is a thermal sensation index widely used in urban climate studies that takes into account mean radiant temperature, air temperature, relative humidity, wind speed, and human factors. Many studies have used PET to indicate thermal sensation values for street trees and grass (Lobaccaro and Acero, 2015; Yin et al., 2019).

To calculate PET for different design scenarios in the neighbourhoods, this study utilised the ENVI-met simulation tool. It is a CFD-based 3D microclimate simulation software that specialises in modelling heat and moisture exchange between building materials, soil, vegetation, and the atmosphere (Simon et al., 2018). ENVI-met's accuracy and reliability in simulating the thermal effects of vegetation, buildings, and streets in Western Europe with temperate climate has been confirmed by many studies, including those by Jacobs et al. (2020), Kleerekoper et al. (2015), and Taleghani et al. (2015). Quantitative comparisons of different design scenarios have been enabled through ENVI-met simulation results in existing studies (Lobaccaro and Acero, 2015; Semeraro et al., 2023; Zölch et al., 2019).

When conducting the ENVI-met simulations, the input requires meteorological data including the air temperature, wind speed, humidity, etc. (Table S1). Data from Paris meteorological stations were accessed to generate weather profiles for representative hot days. The hottest week of the year 2022 was used for the input air temperature and humidity data. The prevailing southwest (SW) wind direction was selected based on the wind rose analysis for the three cities, reflecting typical summer climatic conditions in the study area (Fig. S1). The boundaries of the model were set to 20 m, which according to Bruse (2004) should be at least the height of the buildings in the model. The final analysis focuses on the central 300 m × 300 m area, excluding a perimeter buffer of more than 100 m on all sides to minimise potential boundary uncertainties that could affect the results. The temperature conditions at 2:00 pm were chosen to represent the hottest period of the day.

2.3. Third step: analysis of ENVI-met simulation results

Following the ENVI-met simulations, data were extracted for five microclimate-related indicators—air temperature (Ta), wind speed, mean radiant temperature (MRT), humidity, and PET—at a height of 1.5 m to represent the thermal sensation level at the average body centre of pedestrians. The mean value of each scenario for the five indicators across different neighbourhoods was calculated. PET reduction maps were generated to illustrate the spatial distribution of thermal sensation values across the neighbourhood.

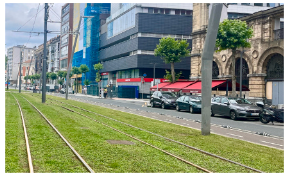
In this study, we used three assessment indices to evaluate cooling effects: PET reduction, percentage change in thermal sensation class, and cooling efficiency. PET reduction was calculated by the average PET change between each greening scenario (S1-S8) and the no-greening scenario (S0) (Ouyang et al., 2023). To determine the significant differences between the cooling effects of various design scenarios, a One-Way Analysis of Variance (ANOVA) was conducted. Tukey's HSD post-hoc test identified which pairs of scenarios

Table 2
Total street area as a percentage of the neighbourhoods, with H/W ratios and orientations as percentages of the total street area; description of street tree and grass design scenarios; visual representation of three H/W types for street widths of 24, 16, and 8 m.

Typology	Total Street area (% of Neighbourhood area)	H/W = 0.83 (% of Street Area)	H/W = 1.25 (% of Street Area)	H/W = 2.5 (% of Street Area)	N-S (% of Street Area)	*E*-W (% of Street Area)	NE-SW (% of Street Area)	NW-SE (% of Street Area)
T1	35 %	35 % (Main)	47 % (Secondary)	18 %	47 %	53 %	0 %	0 %
T2	29 %	0 %	29 % (Main)	71 % (Secondary)	42 %	58 %	0 %	0 %
T3	29 %	0 %	29 % (Main)	71 % (Secondary)	0 %	0 %	42 %	58 %
T4	31 %	34 % (Main)	25 % (Secondary)	41 %	35 %	35 %	15 %	15 %

Scenario	Street tree or grass distribution	Tree canopy or grass coverage in T1	T2	T3	T4
S1	Two rows of large trees in main and secondary streets	24 %	26 %	26 %	18 %
S2	Two rows of large trees in secondary streets	16 %	18 %	18 %	14 %
S3	Two rows of large trees in main streets	8 %	9 %	9 %	7 %
S4	One row of large trees on high radiated side of main and secondary streets	12 %	13 %	13 %	9 %
S5	Two rows of small trees in main and secondary streets	2 %	2 %	2 %	1 %
S6	Grass covered in main streets	11 %	7 %	7 %	12 %
S7	Grass covered in main and secondary streets	24 %	15 %	15 %	20 %
S8	Grass covered in secondary streets	14 %	9 %	9 %	8 %

Real examples at the street level

Two rows of large trees in 24 m street	One row of large trees on the high-radiated side	Two rows of large trees in 8 m street	Grass-covered street
			

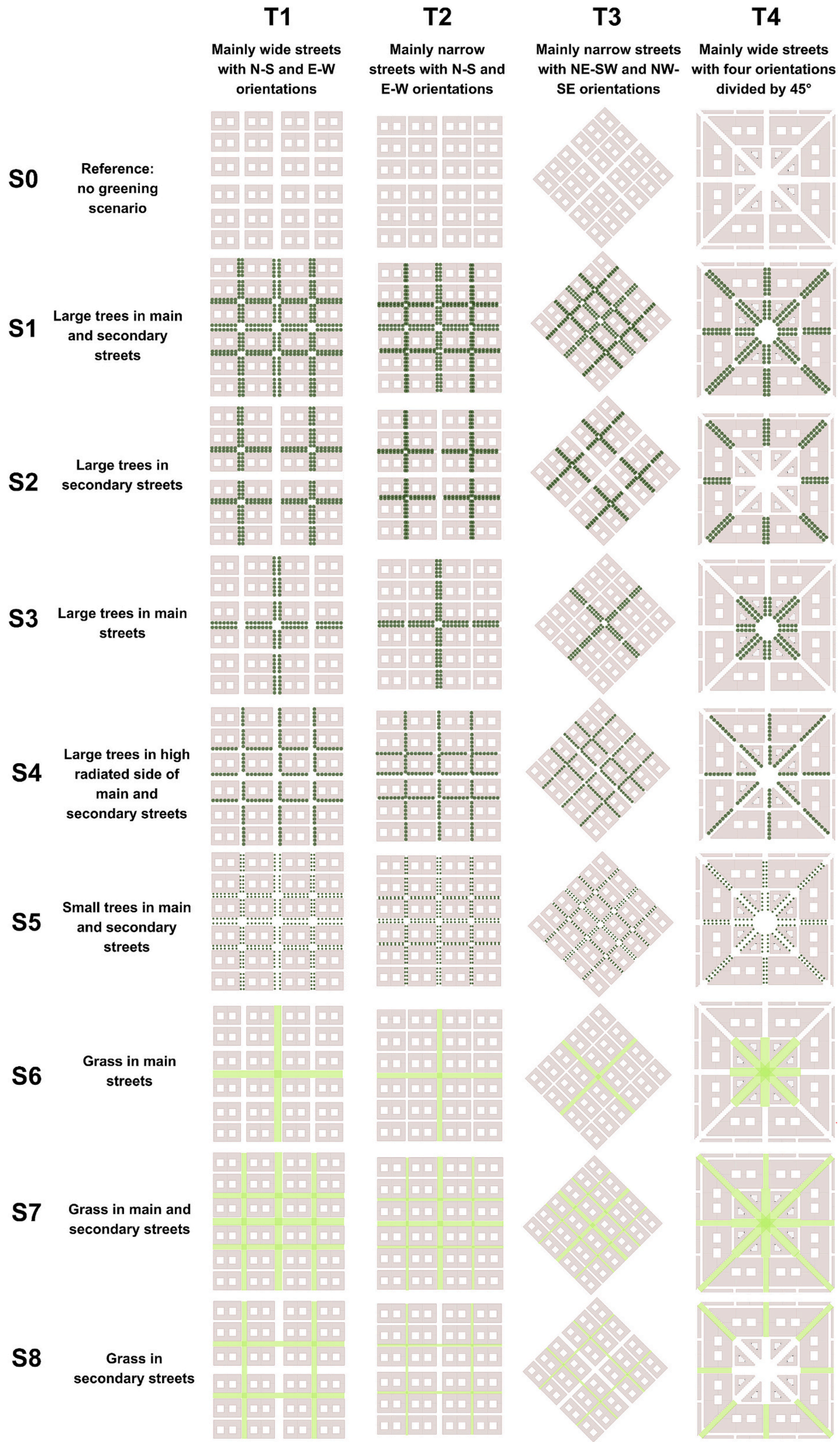


Fig. 1. Design scenarios of street trees (S1-S5) and grass (S6-S8) in different neighbourhood typologies (T1-T4); no-green scenario (S0) as reference. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

differed significantly. R 4.3.1 was used for both statistical analysis and visualization. According to Wu et al. (2025), a hierarchical ranking of cooling effectiveness can be established for each neighbourhood typology, arranging the scenarios from highest to lowest based on PET values.

The percentage change in thermal sensation class was used to calculate the difference of percentage of neighbourhood areas classified as Warm (<35 °C), Hot (35–41 °C), and Very Hot (≥41 °C) compared to the no-greening reference cases. This classification was chosen from adaptive behaviour research in Western Europe (Matzarakis et al., 1999).

Cooling efficiency typically refers to the ratio between cooling benefits (e.g., temperature reduction and improvements in thermal comfort) and resources consumed, such as land cover and canopy cover (Shashua-Bar et al., 2009; Yang and Bou-Zeid, 2019). However, the indicators used to measure cooling efficiency vary significantly. For example, Ouyang et al. (2020) employed PET changes to relate tree canopy cover, while Acero et al. (2021) introduced outdoor thermal comfort autonomy to assess how frequently an area achieves thermal comfort. In this research, we used two metrics to calculate cooling efficiency: 1) eff_delta: the ratio between PET reduction and green coverage (tree canopy or grass coverage); 2) eff_pct: the ratio between percentage area change from Very Hot class (≥41 °C) and green coverage.

To provide practical recommendations, it is essential to develop accessible, clear, and easily understandable guidelines, considering that practitioners, such as urban designers and planners, already face the challenge of learning, reflecting on, and implementing new concepts (Lenzholzer et al., 2020). A hierarchical cooling ranking was established for each neighbourhood typology, ordering scenarios from most to least effective based on the three assessment indices. A scoring mechanism was applied, assigning the highest score to the top-ranked scenario and decreasing incrementally to 1 point for the lowest rank (Wu et al., 2025). The final design recommendations were determined by aggregating scores from each ranking to derive a cumulative score.

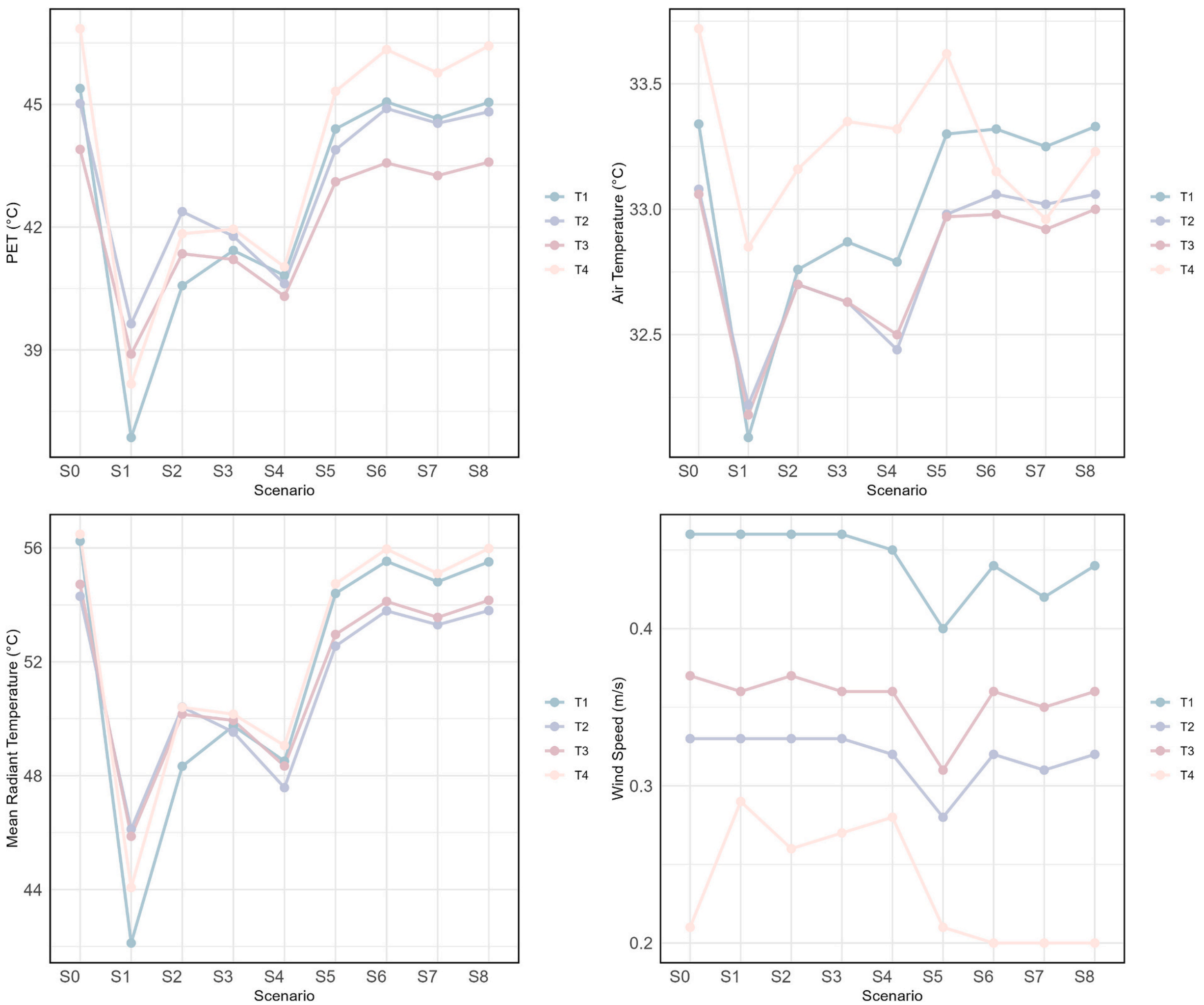


Fig. 2. Mean value of PET, MRT, Wind speed and Ta for different scenarios and neighbourhood typologies.

3. Results

The mean PET of each scenario was used to indicate the thermal sensation values. The main contributing factors, including air temperature, MRT, and wind speed, were also analysed using mean values to explain PET variations (Fig. 2). It can be observed that

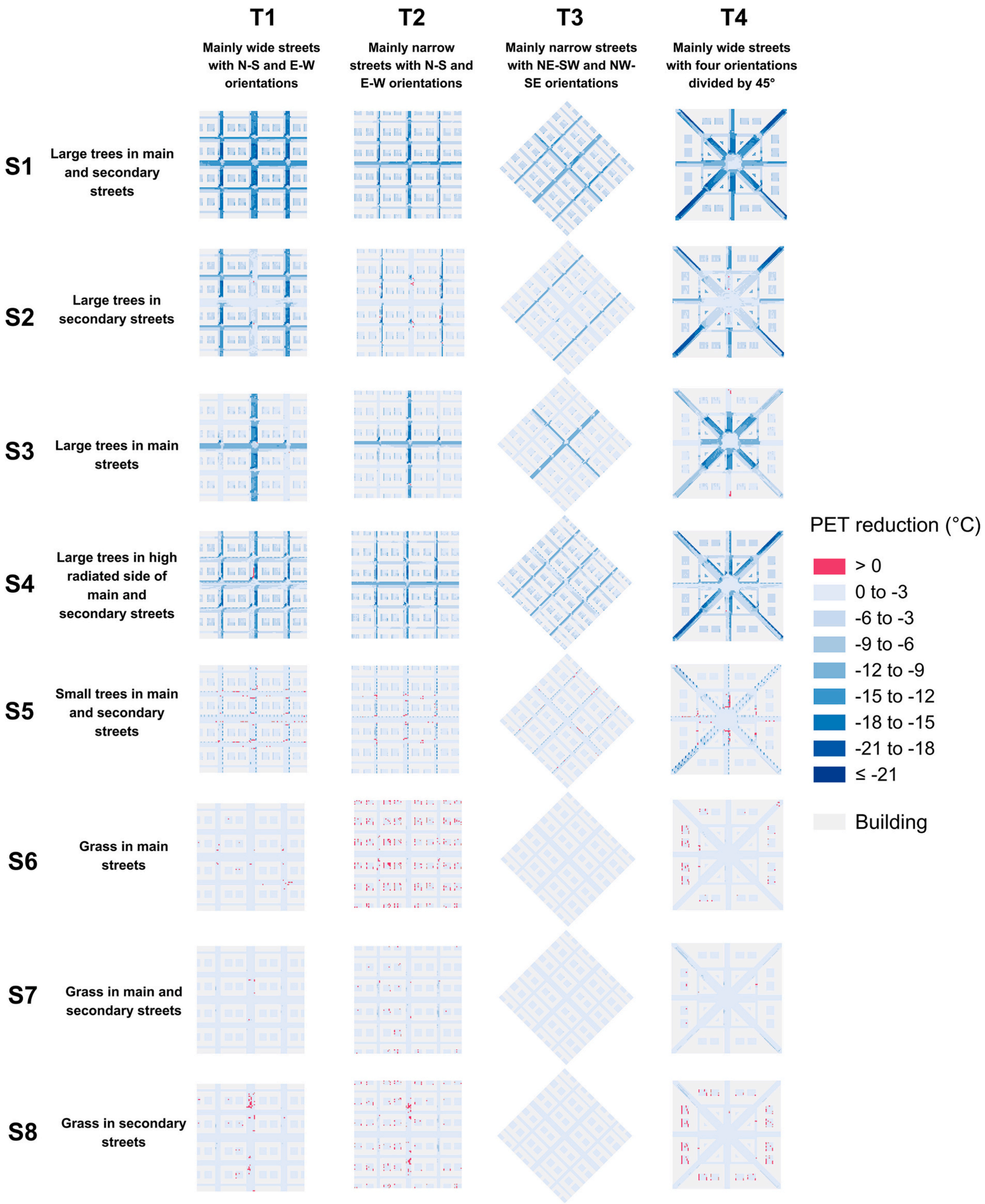


Fig. 3. PET reduction map from ENVI-met simulation results.

within each neighbourhood typology, the scenario's PET varies, and for each scenario, its performance in different neighbourhoods is also different. In the following subsections, the results of comparing scenarios and of comparing neighbourhoods are described separately.

3.1. Comparing the thermal performance of different scenarios

To compare the cooling effects of different scenarios within each neighbourhood typology, we looked at three cooling effect assessment aspects – PET reduction, percentage change of thermal sensation change, and cooling efficiency. In the following subsections, we examine the three indicators separately.

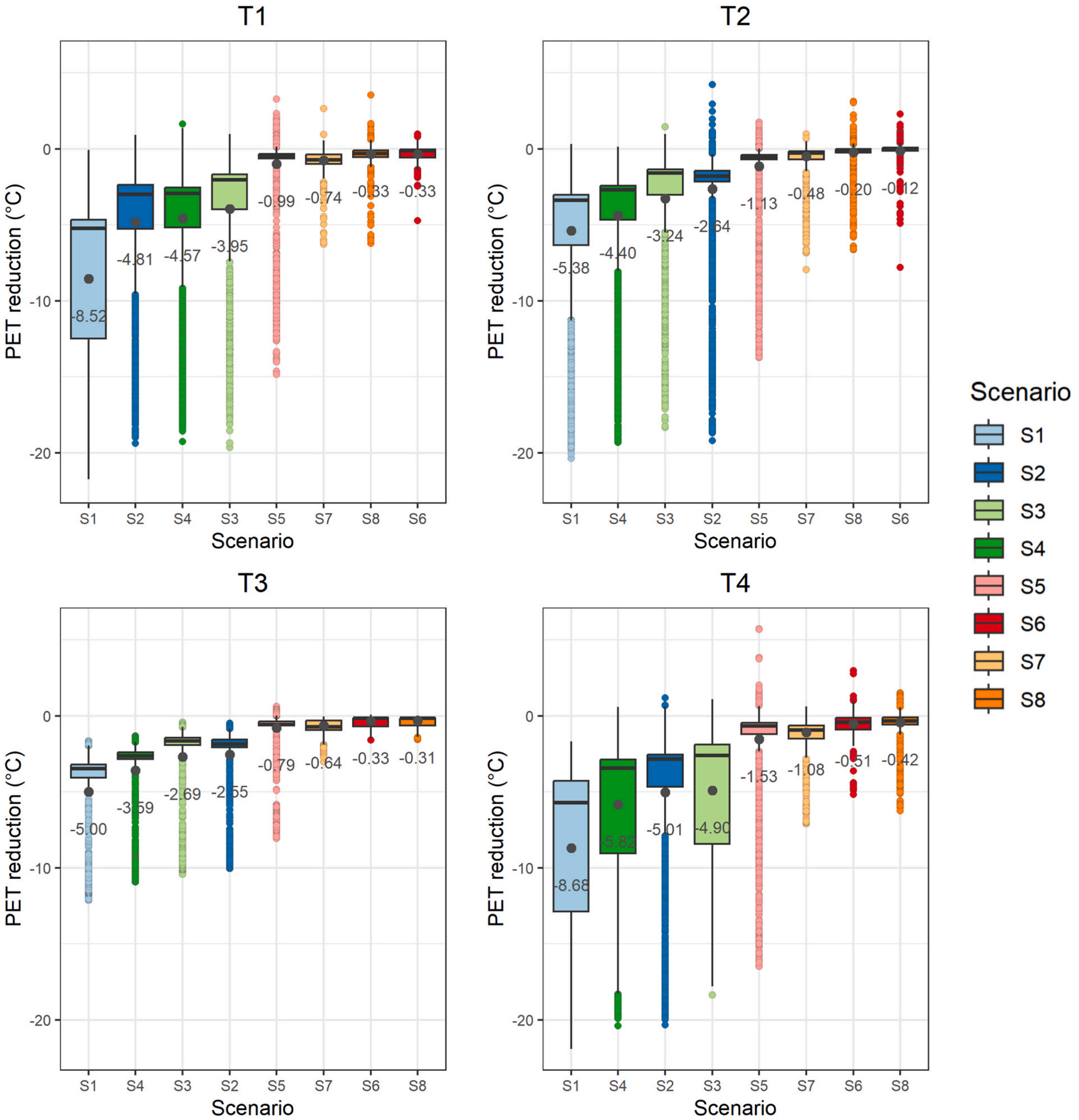


Fig. 4. PET reduction comparing different scenarios in each typology. Within each typology, scenarios are ranked from the most effective (on the left) to the least effective (on the right) based on the mean PET reduction value.

3.1.1. PET reduction

PET reduction is the difference between the scenario and the no-greening conditions. The PET reduction maps at the neighbourhood scale provide insights into thermal sensation performance from a spatial perspective (Fig. 3). The legend of this map shows that the difference between the coolest and hottest spots exceeds 21 °C, indicating substantial variability in thermal sensation within the neighbourhoods after interventions. It can also be found that in the small tree and grass scenarios (S5-S8), certain spots of the neighbourhood are above 0 °C, especially the areas within the courtyard block. Additionally, we observed that the cooling effect can extend beyond the immediate shade of the trees, which is especially evident for S2 and S3 in T4 for streets where trees are not present. But for small trees and grass, the cooling tends to be localised and does not extend beyond the immediate vicinity, limiting their overall contribution to neighbourhood-scale cooling.

It can be seen on the boxplot in Fig. 4 that despite certain spots in the neighbourhood being above 0 °C, the mean PET delta of all scenarios is below 0 °C. This means that all scenarios provide a cooler overall environment than the baseline scenario S0. It also shows that within each typology, the ranking of the cooling effect is from the most effective on the left to the least effective on the right. The results of the ANOVA and subsequent post-hoc pairwise comparisons are provided in Table S2.

For the first neighbourhood typology **T1**, S1 (two rows of large trees on both main and secondary streets) achieves the highest PET

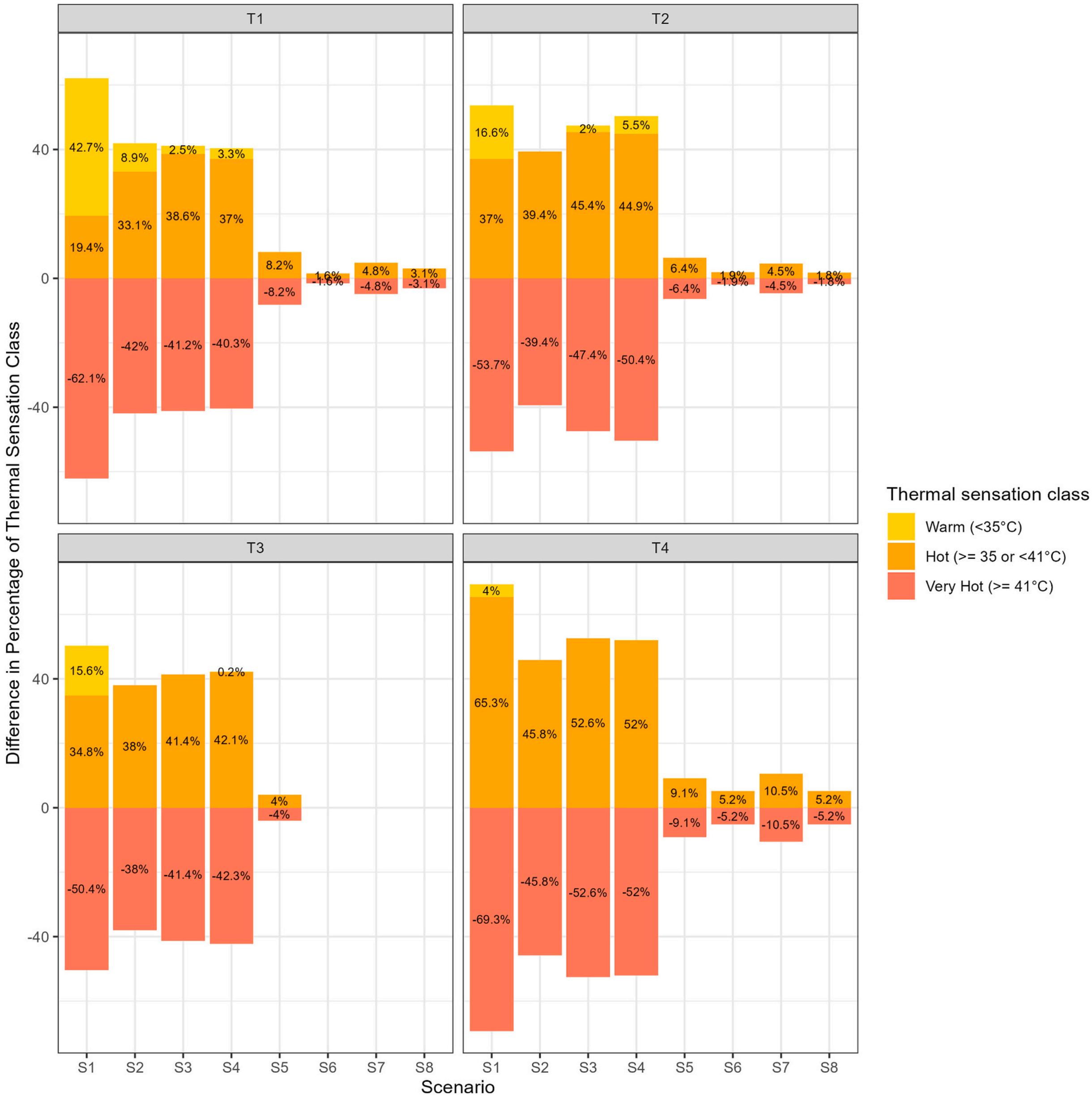


Fig. 5. Percentage change in thermal sensation class comparing eight scenarios in each typology.

reduction with an average of 8.52 °C across the neighbourhood and a maximum PET reduction of more than 20 °C locally. As shown in Fig. 2, the low Ta and MRT contribute to the low PET in S1. S2-S4 (two rows of large trees on main/secondary streets, or one row of large trees on the highly radiated side of the streets) provide a similar PET reduction of around 4 °C, while S5-S8 (small tree and grass scenarios) provide the smallest cooling effect with less than 1 °C PET reduction. The effect of wind speed is negligible in influencing the

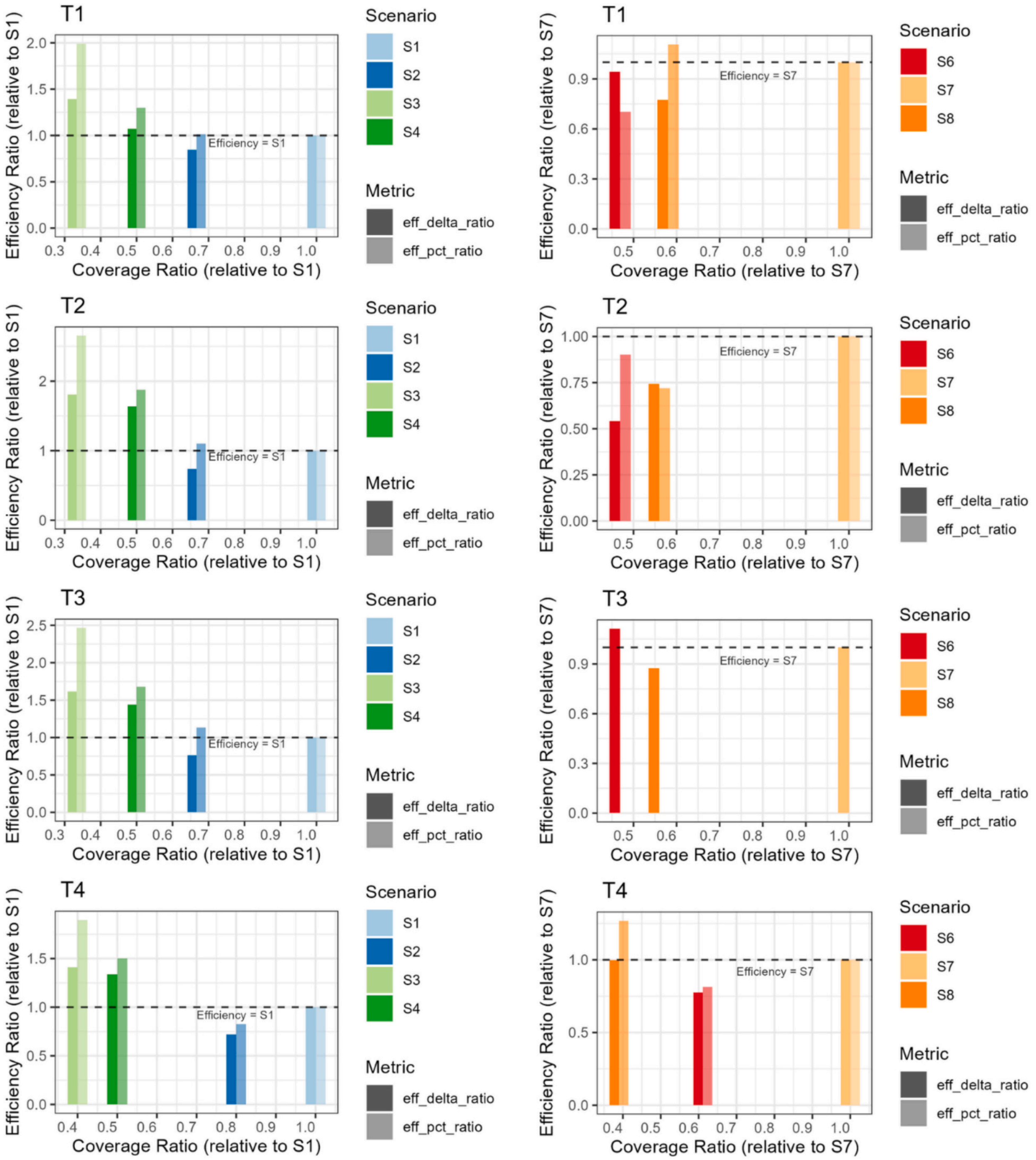


Fig. 6. Cooling efficiency of each large tree scenario compared to S1, and each grass scenario compared to S7. The x-axis represents the difference in green coverage. Bars positioned above the dashed y = 1 line indicate that the scenario is more effective than S1 (for large trees) or S7 (for grass), whereas bars below the line indicate lower effectiveness. The dark bars represent efficiency calculated based on PET reduction, while the light bars represent efficiency calculated based on the percentage change in thermal sensation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

PET between S1 and S2-S4. For **T2**, S1 is the coolest with a 5.38 °C PET reduction. S4 is also effective with a 4.40 °C PET reduction. There is less variance between each scenario, as from S1 to S4, S3, S2, S5, it is around 1 °C between every two scenarios. For **T3**, it has the same ranking of street tree scenarios as T2. It is noted that the range of the scenarios in this neighbourhood is less, indicating a less variable impact on thermal sensation across the neighbourhood. For **T4**, S1 is still the coolest, producing an 8.68 °C PET reduction, which is mainly due to the low MRT (Fig. 2). The coolest small tree scenario achieves a 1.53 °C PET reduction. For all the typologies, S1 provides the strongest cooling effect across all typologies, with S2-S4 following in effectiveness. S5-S8 offer the least cooling effects on PET.

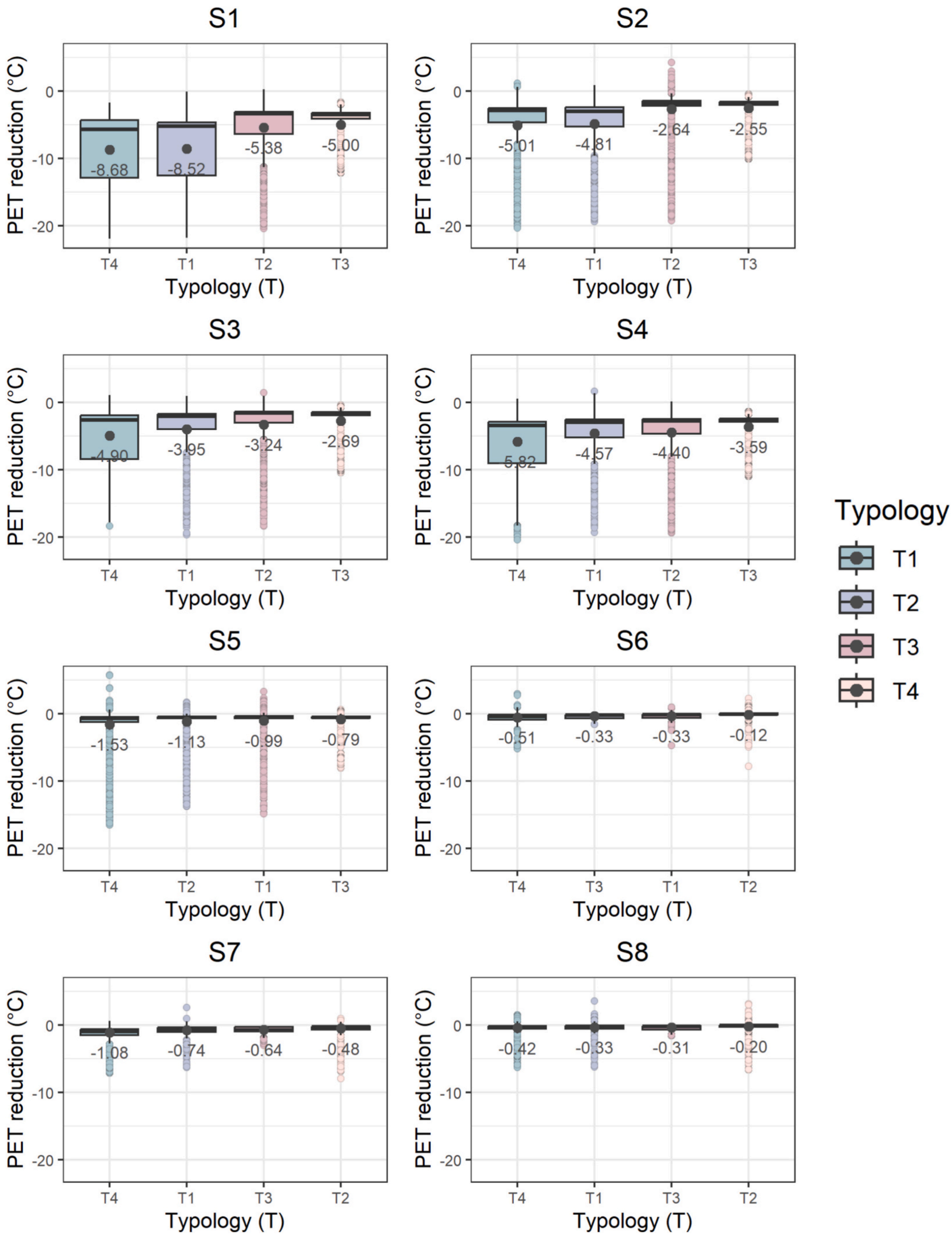


Fig. 7. PET reduction comparing four typologies in each scenario. Within each typology, scenarios are ranked from the most effective (on the left) to the least effective (on the right) based on the mean PET reduction value.

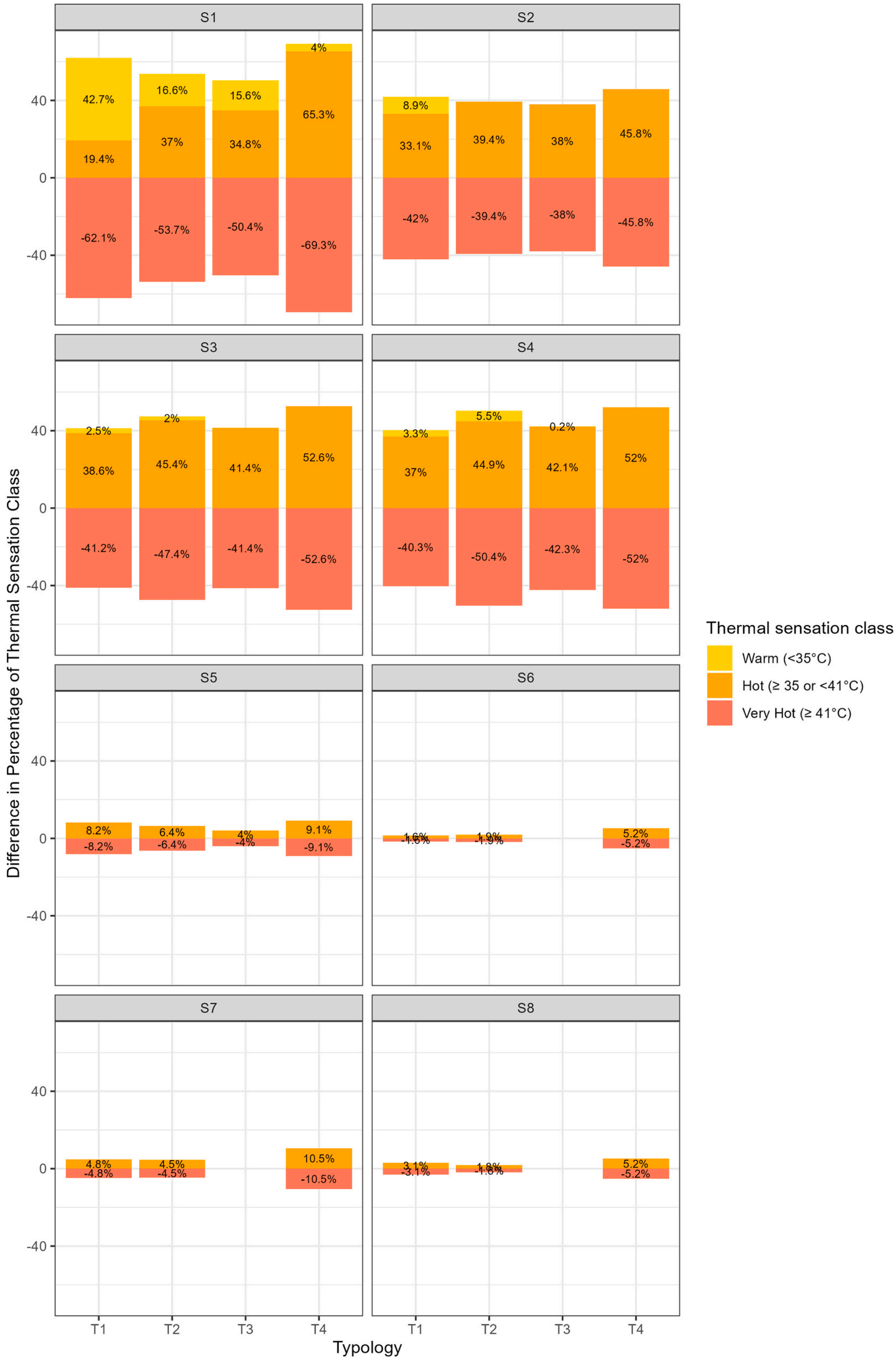


Fig. 8. Percentage change in thermal sensation class comparing four typologies in each scenario.

3.1.2. Percentage change in thermal sensation class

The percentage change of thermal sensation class relates to the direct human experience and perception, providing another perspective on the effectiveness of cooling effects. It helps to understand not just how much the temperature changes (as seen in PET reduction) but whether that change matters in terms of significantly improving human thermal sensation. In Fig. 5, three classes are observed in the scenarios: "Warm", "Hot", and "Very Hot".

For **T1**, S1 provides the most cooling effect, with 62.1 % of the Very Hot area changing to cooler thermal sensation classes, while 42.7 % of areas become Warm or 19.4 % of areas become Hot. The percentage of Very Hot areas in S2-S4 is lower than in S1, with around 41 % change. S5 is the least effective of the tree-included scenarios as only 8.7 % of the neighbourhood changes from Very Hot areas. Grass scenarios are the least effective overall as the Very Hot area changes are all below 5 %. For **T2**, S1 is still the scenario providing the most cooling. Meanwhile, S4 becomes the second best in providing the cooing with 50.4 % areas not Very Hot anymore, while S2 provides much less cooling where 39.4 % Very Hot areas changed and no Warm areas increased. For **T3**, the differences between scenarios are similar to T2, but the percentage changes are all less. Moreover, there is no change at all concerning the grass scenarios (S5-S8). For **T4**, S1 has the most Very Hot area change compared to all other scenarios in all the typologies, where in 69.3 % areas not Very Hot anymore, yet it can only provide 4 % Warm areas. S7 has the most change from Very Hot areas (10.5 %) among all the grass scenarios. For all the typologies, there is no Warm areas in scenarios S5-S8.

3.1.3. Cooling efficiency

Fig. 6 presents both indicators of cooling efficiency (eff_delta and eff_pct) with respect to the coverage of street trees and street grass. The green coverage of S1 was chosen as a baseline for the comparison and to examine if the cooling efficiency is the same for scenarios with different distributions.

For **T1**, Fig. 6 indicates that S3 is the most efficient, followed by S4. The efficiency of S2 can be lower than S1. Meanwhile, the grass scenarios S6-S8 do not have much variations. For **T2**, the eff_pct of S3 can reach more than 2.5 times that of S1. The eff_delta of S2 is less than S1. S7 has better cooling efficiency than S6 and S8. For **T3**, the pattern is similar to T2. For **T4**, it is evident that for both efficiency indicators, S3 performs best, followed by S4, S1, and S2.

This analysis shows that the cooling efficiency for the same greenery profile (large trees S1-S4, or grass S6-S8) can differ depending on the their distribution of greenery. In general, the efficiency ranking for large trees is S3 > S4 > S1 > S2. And the efficiency ranking for grass scenarios is similar for the three scenarios.

3.2. Comparing thermal performance of different typologies

3.2.1. PET reduction

Regarding PET reduction, according to Fig. 7, the order of scenarios in each typology is ranked from the most effective, with the greatest PET reduction on the left, to the least effective on the right. It is evident that for S1-S4, T4 shows the greatest PET reduction, followed by T1, T2, and T3. It is noted that for S1 and S2, the difference between T4 and T1 is within 0.2 °C, and the difference between T2 and T3 is within 0.38 °C. For S5, the maximum difference between typologies is within 0.74 °C, and for S6 and S8, the differences between T1 and T3 are not significant. The results of the ANOVA and subsequent post-hoc pairwise comparisons are provided in Table S3.

3.2.2. Percentage change in thermal sensation class

Regarding the percentage change in thermal sensation class, it was found that for S1, the maximum reduction in the percentage of Very Hot areas occurs for T4, where 69.3 % of the area is not Very Hot anymore (Fig. 8). The reduction is followed by T1, T2, and T3. For S2, it follows the same order as S1, although the reduction is less for all typologies compared to the ones in S1. For S3 and S4, T4 still brings the most reduction, but both scenarios have a percentage reduction ranking of T4 > T2 > T3 > T1. For S5-S8, it follows the same pattern as S2, though the Very Hot area reduction is significantly less, with all the cases less than 10.5 % in Very Hot area change.

3.2.3. Cooling efficiency

Regarding cooling efficiency, it represents the ratio between cooling benefits and the green coverage of street trees and street grass. A comparison with T1 was added to examine if one scenario has the same cooling efficiency across different typologies (Fig. 9). The bars above the $y = 1$ dashed line indicate that the typology is more effective than T1, and if below, it is less effective.

For S1 and S2, T2 and T3 have similar performance, where the efficiency is 0.5–0.8 times that of T1, while T4 is 1.2–1.5 times that of T1. For S3 and S4, T2 and T3 have similar efficiency to T1, while for S4, the efficiency of T4 can reach 1.7 times that of T1. For S5-S8, the efficiency can be 2–3 times that of T1. For S6-S8, the eff_pct of T3 has no change compared to the reference no-greening scenario, therefore it shows zero in the bar chart. For S7 and S8, T2 and T3 can have similar or higher efficiency as T1.

4. Discussion

We split the discussion into four subsections. In the first two subsections, we discuss the variations of cooling impacts across design scenarios and neighbourhoods with different morphologies. In the last two subsections, we reflect on the novelty of this study, its limitations and possible directions of further studies.

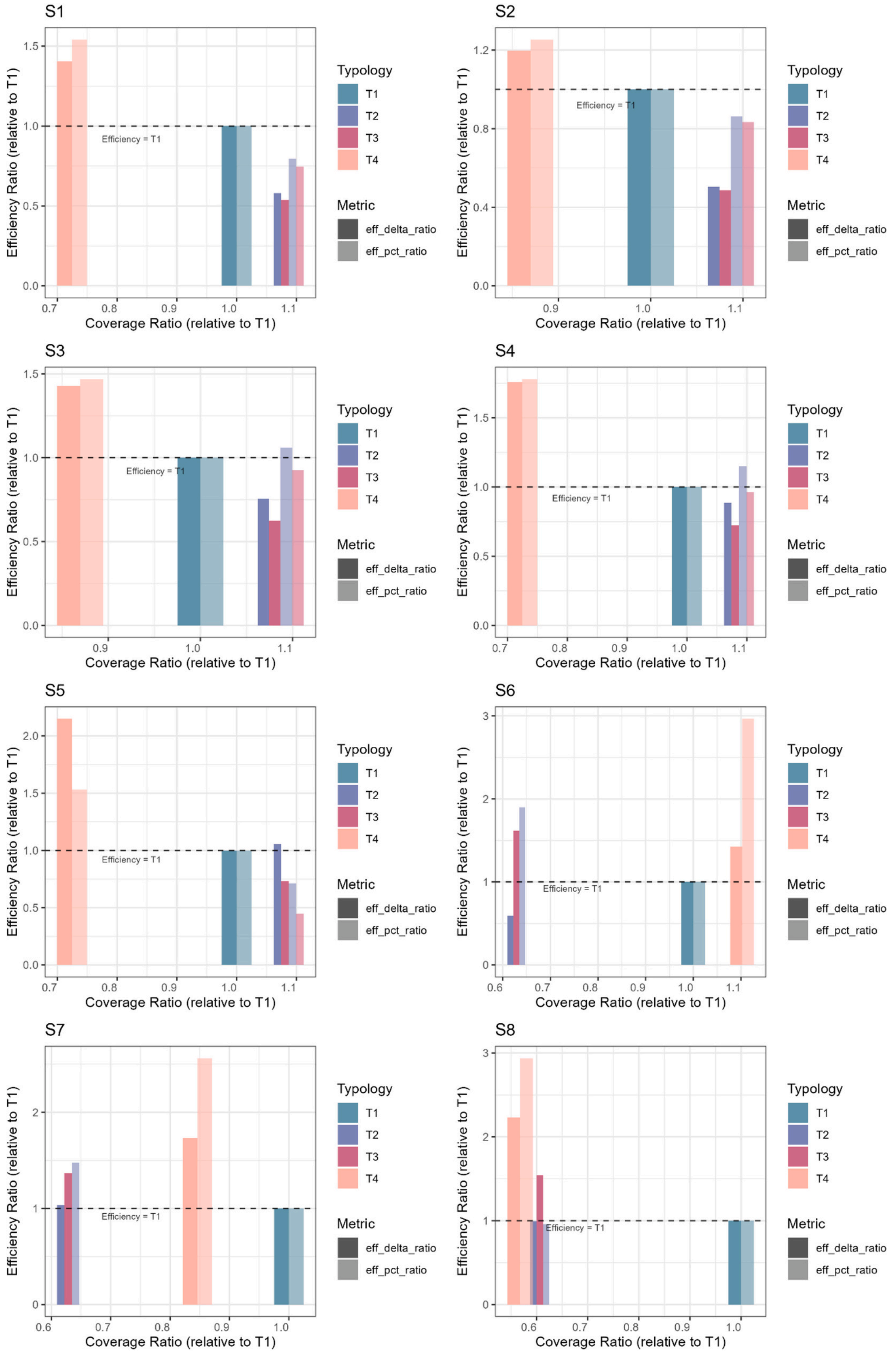


Fig. 9. Cooling efficiency of each typology compared to T1. The x-axis shows the difference in green coverage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1. Influence of design scenarios on cooling effects

We found that the cooling effects vary across different greening design scenarios, and depend on three aspects of a scenario: vegetation type (i.e. tree vs grass), tree canopy coverage, and distribution. In the following subsections, we elaborate on these three aspects separately.

4.1.1. Vegetation type: Street grass vs. street trees

Our results demonstrate that even when street grass fully covers street surfaces (S6-S8), its cooling effect is significantly lower than that of either small or large street trees. Generally, grass scenarios can reduce the overall neighbourhood PET by 1.08 °C or less, changing 10.5 % or less of the area into a cooler thermal sensation class ("Very Hot" to "Hot").

It should be noted that, as shown in Fig. 2 and Fig. 3, grass scenarios (S6–8) can result in lower air temperatures than small tree scenarios (S4), e.g., T1S7, T3S7, T4S6, T4S7, and T4S8, indicating that grass is effective in reducing air temperature compared to some tree scenarios. Lee et al. (2016) also observed a similar phenomenon, noting that in certain urban contexts, air temperature reductions provided by grass-only scenarios are more effective than those involving trees. However, the lower air temperature does not substantially affect the mean PET reduction, as MRT plays a more dominant role. In Fig. 2, the MRT and PET for tree scenarios are consistently lower than for grass scenarios. This outcome highlights that, without vertical elements like trees to provide shade, ground-level greenery alone—even with full street surface coverage—is insufficient to mitigate high thermal sensation stress. This finding echoes Aboelata (2020) conclusion that grass contributes to cooling primarily through evapotranspiration but lacks the significant shading effect provided by trees.

It is worth noting one exception where street grass can be cooler than street trees in terms of thermal sensation class: covering both main and secondary streets with grass (S7) changes 10.5 % of the area into a cooler thermal sensation class ("Very Hot" to "Hot") in T4. In comparison, small trees (S5) only change 9.2 % of the same area. This effect can be attributed to grass scenarios cooling a larger surface area below 41 °C. In contrast, while small trees provide greater overall PET reduction, their limited canopy cover restricts cooling to shaded areas, leaving many parts of the street—particularly central open spaces—impervious and highly exposed to solar radiation. Apart from this, for small trees, PET reduction and percentage change in thermal sensation class are lower than in large tree scenarios but higher than in grass scenarios.

Another phenomenon that should be noted is the increase in PET in certain areas of scenarios that mainly involve grass (Fig. 3). These areas, particularly semi-enclosed courtyard spaces, lack vegetation, leading to minimal changes in MRT. However, the surrounding plantings increase evapotranspiration, releasing moisture into the air and increasing humidity in the environment (Liu et al., 2021). The combination of increased humidity, minimal changes in MRT, and limited ventilation in these enclosed spaces resulted in a higher PET.

4.1.2. Tree canopy coverage

We discovered that although some scenarios provide more canopy coverage, that does not lead to more cooling in the neighbourhood. Loridan and Grimmond (2012), Ouyang et al. (2020) and Ziter et al. (2019) have all noted that the relationship between cooling effects and tree canopy cover is non-linear, with the cooling rate significantly slowing after reaching a 20–40 % coverage ratio, depending on different scales and climates. In our study, the neighbourhoods are highly dense, with limited space for tree canopy cover. The highest coverage is 26 % (T1S1), which aligns with the theoretical threshold of 20–40 %. However, contrary to previous studies, we found that greater canopy coverage does not always result in more cooling. For example, for scenario S2 in T2 and T3, where two rows of large trees are planted in secondary streets (14–18 % canopy coverage), the canopy coverage is higher than in S3, which involves planting two rows of large trees in main streets (7–9 % canopy coverage). Despite this higher canopy coverage, all three assessment indices (PET reduction, percentage change in thermal sensation class, and cooling efficiency) indicate that S2 cannot cool as efficiently as S3. This suggests that at the neighbourhood scale, coverage alone should not determine tree planting strategies for cooling; the distribution within different neighbourhoods must also be considered.

When examining the cooling efficiency, as illustrated in Fig. 6, strategically placing large trees with lower tree canopy coverage can have higher cooling efficiency (S3 and S4). Lachapelle et al. (2023) also concluded that planting a shade tree on a previously unshaded street provides approximately 1.5–2 times the radiative cooling effect on MRT compared to planting the same tree on a street already benefiting from tree shade. Our findings further indicate that strategically placing two rows of large trees in main streets, such as wide streets with a low H/W ratio, is the most effective approach and should be prioritised. A single row of large trees on the high-radiation side is the second most effective strategy.

4.1.3. Distribution

Similarly, our analysis reveals that the distribution of trees can be more important than the overall canopy coverage for certain planting strategies. In scenario S4, where one row of large trees is planted on the highly sun-exposed sides of both main and secondary streets (9–13 % canopy coverage), the cooling effect is generally greater than in scenario S2, which involves planting two rows of large trees in secondary streets (14–18 %). This finding indicates that strategically planting trees in areas with higher solar exposure is more effective in reducing outdoor heat, maximising both air temperature and radiative cooling (Lachapelle et al., 2023; Morakinyo et al., 2017). In general, planting two rows of large trees only on main streets is more efficient than planting one row of large trees on the highly radiated side of both main and secondary streets. It is followed by planting two rows of large trees on both main and secondary streets, which is generally more efficient than planting two rows of large trees on secondary streets. Thus, careful consideration of tree placement can yield more substantial cooling benefits than simply increasing canopy coverage.

Moreover, we found that planting trees along streets provides not only localised shade but also contributes to broader cooling effects throughout the neighbourhood. As can be seen on Fig. 3, courtyard spaces within building blocks can be 3 °C cooler due to tree planting outside the building blocks. Similarly, streets with the same planting conditions and profiles can experience a 2 °C reduction in thermal sensation if the surrounding streets are covered with street trees (Fig. S2). The mechanism underlying this phenomenon involves the cooling of air beneath the tree canopy, which is then dispersed into adjacent areas by wind, effectively lowering the temperature of the surrounding street environment (Wong et al., 2021). This further underscores the importance of strategic tree planting in enhancing thermal comfort for nearby areas. In contrast, street grass typically has only localised effects, cooling the immediate vicinity without extending beyond the streets where it is planted.

4.2. Influence of neighbourhood morphologies on cooling effects

Regarding the morphological impact on the neighbourhoods without greening, it was found that the initial no-greening PET values follow the order T4 > T1 > T2 > T3 (Fig. 2). PET is highest in T4 due to increased air temperature and low wind speed, likely resulting from heat accumulation in central open areas and variations in street orientation and H/W ratios, which cause greater blockage. T1 has higher PET than T2, as its lower H/W (Table 2) leads to greater solar exposure, consistent with studies showing that shallow streets increase thermal sensation values (Muniz-Gäal et al., 2020; Ali-Toudert and Mayer, 2006). T2 exceeds T3 in PET because its N-S and E-W street orientations (Table 2) receive more radiation than NW-SE streets, which are less sun-exposed (Wang et al., 2024). Although NE-SW streets experience high afternoon solar exposure combined with high ambient temperature (Chatzidimitriou and Yannas, 2017), being parallel to the prevailing wind improves air movement, increasing wind speed (Deng and Wong, 2020). Consequently, T2 is warmer than T3 in thermal sensation.

Wind speed and airflow patterns, influenced by morphology and prevailing winds, also affect thermal sensation. The results show that the wind speed ranking for different neighbourhood typologies is T1 > T3 > T2 > T4 (Fig. 2). While wind speed varies within each typology due to differences in greening distribution, these variations are less significant than the overall range within each typology. T1 exhibits the highest wind speed due to its regular grid layout and wide streets. This minimises obstructions and facilitates smooth airflow, allowing cooler air to disperse more effectively and reduce air temperature (Karimimoshaver et al., 2021; Lin and Lin, 2016). T3 follows, as its NE-SW street orientation, which is parallel to the prevailing wind direction, partially supports airflow but encounters more resistance due to narrower streets (Huang and Chen, 2023). T2 ranks third, as its narrow streets with N-S and E-W layouts significantly limit ventilation. This aligns with Kim and Brown's (2021) claim that a high H/W ratio street reduces the cooling rate of urban areas by restricting turbulent transport caused by wind and artificial heat emissions. T4 experiences the lowest wind speed due to its irregular layout and multiple street orientations, which disperse airflow and reduce overall ventilation efficiency. Therefore, although vegetation oriented parallel to the wind direction enhances evapotranspiration, effectively reducing air temperature (Atwa et al., 2020; Tan et al., 2016), the relatively low wind speed in T4 limits its ability to cool the air downwind and disperse the cooling effect efficiently.

For large tree scenarios, neighbourhoods with higher initial PET values experience greater cooling benefits. PET reduction follows the same order as the initial PET ranking (T4 > T1 > T2 > T3; Fig. 7), while wind speed plays a lesser role, as T4 achieves the greatest PET reduction despite having the lowest wind speed. This suggests that large trees consistently cool T4 more than T1, T2, and T3, indicating that PET reduction from large trees is more strongly influenced by neighbourhood morphology than by prevailing wind direction. Previous studies have noted that vegetation is less effective in canyons with higher H/W than in those with lower H/W, as narrow streets create strong building shading, reducing the additional shading provided by trees (Tan et al., 2016; Chen et al., 2023). Our study further shows that neighbourhoods with open areas, wide streets, and N-S or E-W street networks—where thermal sensation is higher—benefit more from large tree plantings than denser neighbourhoods with narrow NW-SE and NE-SW streets. These findings highlight the influence of initial thermal conditions shaped by neighbourhood morphology on the effectiveness of cooling strategies.

Additionally, neighbourhood typology appears to be more influential than planting strategy in scenarios involving small trees and grass (S5-S8). In these scenarios, percentage change in thermal sensation class remains consistent with the original typology order (S0), suggesting that the neighbourhood's physical structure has a greater influence on thermal performance than the specific planting strategy. This conclusion is based on the finding that scenarios S5–S8 have a limited impact on MRT (Fig. 2). Meanwhile, neighbourhood morphology affects MRT, which is often the most influential factor in PET variations, as it determines the amount of radiation received at the pedestrian level, significantly impacting overall thermal sensation (Li et al., 2024; Yin et al., 2019; Wu et al., 2025). However, when large trees are planted along wide N-S and E-W streets, the planting strategy can exert a greater influence than the neighbourhood's morphological characteristics.

Finally, although grass scenarios provided less cooling than the tree ones, they were found to be most effective in neighbourhoods with low H/W ratios, open spaces, and streets oriented with more direct sunlight. For example, with such scenarios, no change in the thermal sensation class percentage is observed in T3, as opposed to T4. This finding supports the claim by Lobaccaro and Acero (2015) that grass provides significant cooling benefits mainly in open-set urban areas. Consequently, planting grass is recommended in neighbourhoods with larger open spaces and streets exposed to direct sunlight. In contrast, it is not advisable for use in dense neighbourhoods, particularly those with streets oriented in NW-SE or NE-SW directions, where its cooling effect is limited.

4.3. Design recommendations

To provide urban planners and designers with practical guidelines for cooling specific neighbourhoods, we analysed the cooling rankings of each neighbourhood in detail. A comprehensive scoring system is presented in Table S4. The rankings were derived from simulations conducted during a heatwave period in European temperate climate cities, characterised by a prevailing south-western wind direction.

The final scores were calculated by summing the ranking scores for PET reduction, percentage change in thermal sensation class, and cooling efficiency (eff_delta and eff_pct). These combined scores are presented as an overall ranking in Fig. 10. All three indices were given equal weight in this process. However, urban planners and designers can adjust the weighting of these factors according to the specific needs of their projects to create a ranking tailored to their context.

These design guidelines aim to support urban designers, planners, and landscape architects in prioritising planting strategies, especially when resources are constrained. By incorporating these recommendations, practitioners can adopt climate-responsive design strategies more effectively.

4.4. Novelty of this research

First, this research is grounded in four distinct neighbourhood typologies, each characterised by different combinations of street orientations and height-to-width ratios, both of which significantly influence the microclimate. While previous studies have predominantly focused on green strategies within a single neighbourhood street pattern (Acero et al., 2021; Ouyang et al., 2020), our study broadens the scope by examining how variations in neighbourhood morphology can affect the cooling effects of street trees and grass. By employing generic neighbourhood typologies, we address the need of site-specific research (Wu et al., 2025), offering clearer comparisons and more comprehensive recommendations for urban planners and designers.

Secondly, this research investigates the placement of street trees and grass within the neighbourhood, considering factors such as street hierarchy and the orientation of planting. In an innovative approach, street grass was modelled to cover entire street areas, taking into account the potential for future autonomous mobility. Our findings demonstrate that the cooling effects of street grass are limited, even when it fully covers the street surface. While most existing studies focus on tree canopy coverage and the thresholds for effective cooling (Lee et al., 2016; Ziter et al., 2019), we add another dimension to the analysis by exploring their spatial distribution. This approach allows us to identify optimal tree placement strategies to achieve efficient cooling.

Finally, this research evaluates cooling effects using three indices: PET reduction, percentage change in thermal sensation class, and cooling efficiency, and proposed design recommendations. Our analysis reveals that the same scenario can exhibit markedly different cooling effects depending on the chosen index. For instance, scenario S1, with the highest coverage of large trees, shows the greatest PET reduction and significantly reduces areas classified as "Very Hot" throughout the neighbourhood. However, when evaluated in terms of cooling efficiency, S1 ranks among the least effective scenarios. This finding suggests that researchers should consider multiple assessment indices when offering cooling recommendations, enabling urban designers and planners to select the most relevant indices for specific projects.

4.5. Limitations and future research

In our investigation into the cooling effects of green infrastructure in urban neighbourhoods, this research encounters several key limitations that require detailed discussion. The first limitation relates to the study's use of an abstract design framework, particularly the application of grass across entire street surfaces. The real-world implementation of such green infrastructure would likely face many physical, economic, and social constraints not considered in our model.

Moreover, since neighbourhood morphologies were derived from comprehensive datasets rather than customised for a specific

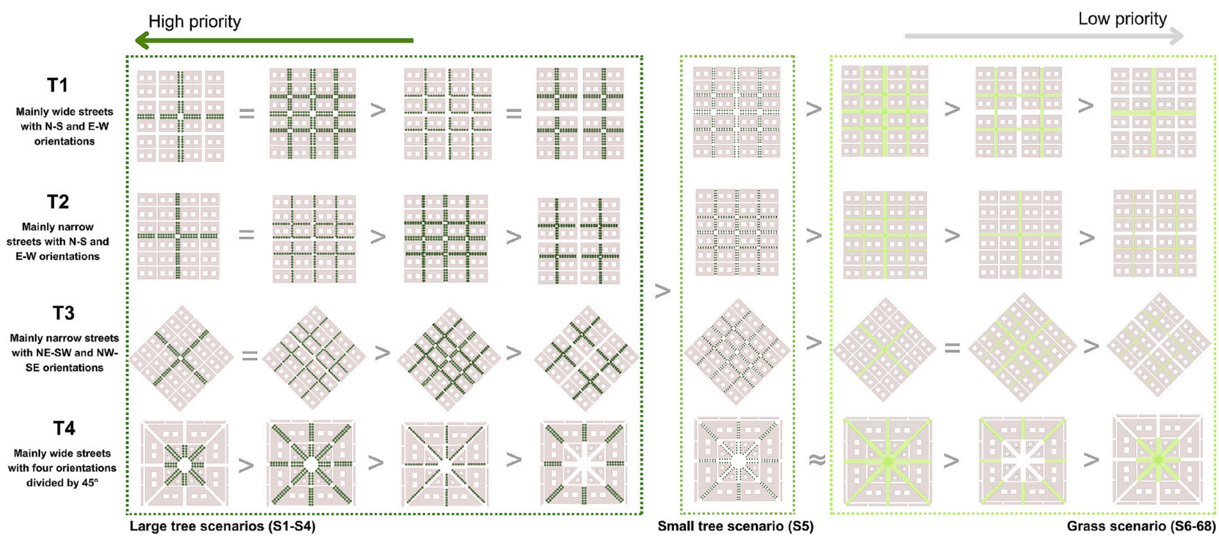


Fig. 10. Ranking of effective thermal sensation performance of each neighbourhood.

case, it was not possible to directly measure temperature variations and cooling effects within real urban environments. This methodological choice limits our ability to validate the model's predictions with real-world measured thermal sensation data. Our approach, therefore, focuses on providing a comprehensive analysis and comparison of different design options, aiming for broad relevance rather than precise accuracy for specific locations.

A further limitation is the study's focus exclusively on temperature dynamics during the hottest hour of the hottest day in summer. While this allows for a targeted analysis of peak cooling effects, it does not account for the broader temporal context, such as the cooling potential during nighttime or other seasons. Urban heat dynamics are not limited to daytime temperatures in summer; nighttime temperature regulation and winter conditions also significantly impact urban thermal comfort and energy consumption (He et al., 2021; Zhu et al., 2022).

Despite these limitations, this research provides recommendations for developing design strategies centred on the amount and spatial distribution of street trees and grass in urban neighbourhoods. These insights can guide urban designers and landscape architects in making decisions to enhance urban climate resilience. To develop more comprehensive design guidelines, future research should explore cooling effects across the entire diurnal and seasonal cycle and in different climate types and local climate zones with varying neighbourhood morphologies. Additionally, future studies should investigate scenarios that combine both street trees and grass to present a more complete picture of their potential to mitigate urban heat island effects. As the effects of prevailing wind and typology are interconnected and jointly influence thermal sensation, future studies could isolate these factors by designing a consistent buffer area around the inner region with different typologies or by examining the impact of varying wind directions for each greening scenario.

5. Conclusion

This research explored the spatial design scenarios of street trees and grass in different neighbourhoods. In answer to the study's research question 1 "What are the impacts of spatial design on cooling effects of street tree and grass planting?", the results indicate that scenarios involving large trees consistently provide the most significant PET reduction across all typologies, primarily due to the extensive shading from large tree canopies. Small trees provide more PET reduction than all grass scenarios. Grass scenarios generally have the least impact on cooling. They can reduce air temperature through evapotranspiration to a larger extent than small tree scenarios in some neighbourhoods, yet with negligible effect on radiation, their cooling effect is less without the shading effect of trees. Placing two rows of large trees on main streets is more cooling-efficient than a single row on both main and secondary streets on the high-radiation side.

In answer to the study's research question 2 "How do these impacts vary across the neighbourhoods with different morphologies?", the results indicate that the cooling effects of each design scenario are influenced by neighbourhood morphological characteristics. Neighbourhoods that have higher initial thermal conditions, for instance with radial-oriented and wide (low H/W ratio) streets and open areas, experience more substantial cooling when large tree interventions are involved. Neighbourhood typology generally exerts a stronger influence than planting strategy in scenarios involving small trees and grass. For scenarios with large trees planted along wide N-S and E-W streets, the planting strategy becomes more influential, enhancing airflow and reducing PET more effectively.

Overall, the findings indicate that introducing neighbourhood-specific greening interventions, while considering the interaction between vegetation type, arrangement, and neighbourhood morphology, is essential for optimising thermal comfort in urban areas. Urban designers and planners can refer to our developed planting recommendations for street trees and grass in specific neighbourhood types within their projects, contributing to climate resilience in future urban developments.

CRediT author statement

Yehan Wu: Conceptualization; Data curation; Formal analysis; Methodology; Software; Visualization; Writing - original draft; Writing - review & Editing.

Bardia Mashhoodi: Conceptualization; Methodology; Supervision; Writing - review & Editing.

Agnès Patuano: Conceptualization; Methodology; Supervision; Writing - review & Editing.

CRediT authorship contribution statement

Yehan Wu: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Bardia Mashhoodi:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Agnès Patuano:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2025.102376.

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