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Research Paper

# How small green spaces cool urban neighbourhoods: Optimising distribution, size and shape

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## HIGHLIGHTS

- Green space design guidelines are generated based on four neighbourhood typologies.
- Inside green spaces, mean PET can vary up to 4 ℃ among different design scenarios.
- Grouping several small green areas cools neighbourhoods most effectively.
- Small green spaces scattered in a neighbourhood are the least effective strategy.

## ARTICLE INFO

*Keywords:*
Small park
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## ABSTRACT

How can green spaces smaller than 1 ha improve outdoor thermal conditions in urban neighbourhoods? Considering the variability of cooling effects based on the relevant urban design parameters of size, shape, and spatial distribution, this study entailed development of different design scenarios combining these parameters for four neighbourhood typologies and simulates the thermal sensation of these scenarios using ENVI-met. Three aspects of cooling effects — the inside and outside cooling as well as the Park Cool Island (PCI) effects of the green spaces are separately analysed. The study shows that inside the small green spaces, the mean Physiological Equivalent Temperature (PET) of different cases can vary up to 4 ℃. Larger green spaces with a squared shape lead to cooler PET inside. For a good cooling outside the green spaces, a configuration of grouped small green areas can reduce the PET by 1.3 ℃, with distribution of the green spaces being the most influential factor. The PCI effect is mainly determined by size and shape of the green spaces, where a bigger size and squared shape leads to better cooling effects. But for neighbourhoods with radial streets, it is more related to the spatial distribution, which can result in a reduction of 10.2 ℃ in PCI for linear green spaces next to narrow streets. Guidelines for effective design scenarios are generated from this research, providing urban designers and planners with practical reference in neighbourhood greening projects for cooler cities.

## 1. Introduction

### 1.1. Small green spaces as urban cooling interventions

In recent years, many cities worldwide experienced the highest summer temperatures on record, with significant impacts on the health of people (Tollefson, 2023). In Europe, the number of heat-related deaths is estimated at more than 60,000 in 2022 (Ballester et al., 2023). Due to climate change, temperatures are projected to further increase and affect urban populations' health, well-being and liveability of urban areas. To provide urban residents with better thermal environments, cooling design interventions are needed. Extensive studies have shown that green spaces are regarded as some of the most effective local cooling solutions through evapotranspiration and shading (Bowler et al., 2010; Wong et al., 2021). However, adding new large green spaces into dense cities can be challenging for local authorities and planners, as

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they compete for space with buildings and amenities for other urban functions (Gavrilidis et al., 2022).

To embed more green spaces in cities, small green spaces, such as tiny forests, or pocket parks, are gaining more and more attention as lower investments are needed and implementation is simpler than for large green spaces (Park et al., 2017; Park et al., 2021). A small green space is defined as a green space that is less than 1 ha (ha) (Gavrilidis et al., 2022). These outdoor areas can be close to urban resident's homes and integrated into their daily use of the city, providing more accessibility to nature and improving mental restoration and well-being (Ekkel & de Vries, 2017; Gavrilidis et al., 2022; Lin et al., 2019). However, when considering the cooling effects of such green spaces, studies have not reached a consensus, as some have shown small green spaces are cooler (Chang et al., 2007; Oliveira et al., 2011), while others show that they do not have a significant cooling effect (Cao et al., 2010) or they can be warmer (Chang et al., 2007; Motazedian et al., 2020). Thus, the cooling effects of small green spaces can vary and the underlying reasons need to be explored.

### *1.2. Spatial distribution, size, shape, and surrounding morphology*

Recent studies on small green spaces show that the main factors influencing their cooling effects include spatial distribution of green spaces in the city (Asgarian et al., 2015), their size (Fan et al., 2019; Yang et al., 2020), shape (Cao et al., 2010; Park et al., 2017; Xiao et al., 2018; Yang et al., 2020), and the surrounding urban morphology (Wong et al., 2021; Xiao et al., 2018). Although studies have started exploring the effects of the above-mentioned factors, the findings are not always consistent across the studies (Table 1).

Regarding the influence of small green spaces' spatial distribution on their cooling effects, Asgarian et al. (2015) mentioned that the more homogeneously dispersed the patches, the lower the Land Surface Temperature (LST) is in the areas studied. However, Zhang et al. (2017) mentioned that clustered green spaces improve cooling in the immediate vicinity while a scattered pattern enhances cooling over a broader area. Moreover, the cooling effects of adjacent parks may influence each other, complicating temperature estimation (Lin et al., 2015). Therefore, the spatial combinations of small green spaces still need to be explored considering the inconsistency and small number of previous studies.

Regarding the influence of small green spaces' size on their cooling effects, some studies in Asian and European cities with temperate, Mediterranean or subtropical climates show that the efficient size (threshold value of efficiency) is 0.5–0.96 ha (Fan et al., 2019; Yang et al., 2020; Yu et al., 2018). However, in the same regions, other studies show that green spaces under 2 ha do not have cooling effects or can even be warmer than the surrounding areas (Cao et al., 2010; Chang et al., 2007). Thus, it is still uncertain what size of small green spaces can be most effective in these contexts.

Regarding the influence of small green spaces' shape on their cooling effects, most studies concluded that squared or circular-shaped green spaces produced stronger cooling effects and larger cooling areas (Park et al., 2017; Yang et al., 2020; Xiao et al., 2018); irregular and belt-shape parks were found to have a low park cooling island intensity (Cao et al., 2010). However, some studies show that irregular shapes have a more obvious cooling effect as they contain more core areas that are away from the patch edge (Asgarian et al., 2015; Tan et al., 2021). The relationship between the shape of green space and cooling effects can thus vary among different contexts and is related to the synergy of other factors such as size and aggregation (Estoque et al., 2017).

The cooling effects of small green spaces are influenced by the surrounding urban morphology (Wong et al., 2021). Exploring typical neighbourhood typologies can help clarify the cooling effects of small green spaces in different urban morphologies. To analyse urban morphology impacts, it is essential to take the geographic regions, configurations of urban blocks and street patterns into consideration (Louf & Barthelemy, 2014). Given the rising heatwave-related mortality in Western Europe (Rousi et al., 2022), it is crucial to focus on cities in this region with a temperate climate. Wu et al. (2022) analysed combinations of street canyon's orientation and Height-to-Width ratio, street total length, building block's floor area ratio and shape factor in heat-prone Western European neighbourhoods, identifying four typologies most likely to experience heat stress. These typologies can be used to explore how specific surrounding morphologies affect the cooling potential of small green spaces.

**Table 1**
Existing research on the most effective spatial distribution, size, and shape of small green spaces to provide cooling.

| Research target | Effective distribution | Effective size | Effective shape | Climate | Heat-related index | Method | Reference |
|---|---|---|---|---|---|---|---|
| All green cover in a city | Homogeneously dispersed patches | – (not specified) | Complex | Hot dry desert | LST | Remote sensing | Asgarian et al., 2015 |
| 92 parks in a city | – | The bigger, the better | Compact | Humid subtropical | LST | Remote sensing | Cao et al., 2010 |
| 61 parks in a city | – | >2 ha | – | Humid subtropical | Ta | Measurement | Chang et al., 2007 |
| All urban green patches in seven cities | – | 0.60–0.96 ha | – | Hot-humid | LST | Remote sensing | Fan et al., 2019 |
| All urban parks in a city | – | The bigger, the better | Compact | Humid subtropical | LST | Remote sensing | Liao et al., 2023 |
| Six 1 ha small parks and six 6 ha large parks | Large park in an upwind area; several small parks spread evenly as far as possible | The bigger, the better | – | Humid subtropical | Ta | ENVI-met modelling | Lin & Lin, 2016 |
| Six blocks composing different shapes of small green spaces | – | – | Polygonal | Humid continental | Ta | Measurement | Park et al., 2017 |
| 41 parks with sizes from 0.17 to 3.5 ha | – | The bigger, the better | Complex | Humid subtropical | LST | Remote sensing | Wu et al., 2021 |
| 15 parks with sizes from 0.77 to 3.24 ha | – | The bigger, the better | The less perimeter, the better | Humid subtropical | Ta | Measurement | Xiao et al., 2018 |
| All urban green–blue spaces in a city | – | 0.69 ha | Compact (<1 ha), complex (>1 ha) | Temperate oceanic | LST | Remote sensing | Yang et al. 2020 |
| All urban tree/grass-covered green spaces in eight cities | – | 0.5 ha | – | Temperate Monsoon; Mediterranean | LST | Remote sensing | Yu et al. 2018 |

Evidence indicates that parameters such as distribution, size, shape, and surrounding morphology impact the cooling effects of small green spaces, yet their synergistic influence remains unclear (Yu et al., 2017; Wong et al., 2021; Liao et al., 2023). For instance, the comparative cooling efficacy of linear-shaped green spaces with grouped distribution versus square-shaped spaces with scattered distribution is not well investigated. Therefore, developing and analysing design scenarios that incorporate these parameters in combination is imperative.

To spatially understand the cooling effects of different scenarios, previous studies mostly used the Park Cool Island (PCI) effect indicator (Cao et al., 2010; Li et al., 2020; Liao et al., 2023; Xiao et al., 2023). The PCI effect measures temperature differences between the inside and outside buffer zones of green spaces (Motazedian et al., 2020). A high PCI effect typically indicates that the green space is cooler than its surroundings (Liao et al., 2023). However, this does not necessarily mean the green space cools its surroundings more effectively; it could also suggest that the surrounding areas are warmer. Thus, before focusing on the PCI effect, it is crucial to separately understand the inside cooling differences across various design scenarios and the outside cooling differences among these scenarios. This exploration will enable a deeper understanding of the thermal benefits small green spaces offer in urban neighbourhoods.

### 1.3. Aim and research questions

Where and how to add small green spaces should not rely on a single parameter. Literature indicates that the cooling effect of small green spaces varies significantly with size, shape, spatial distribution, and surrounding neighbourhood morphology. Urban design practitioners require guidelines integrating these aspects for optimal cooling effects and we aim to provide such guidelines by exploring different design scenarios. Considering that Western Europe has become a hotspot for heatwaves (Rousi et al., 2022), the rising intensity of urban heat stress requires more targeted urban design strategies in this region. Therefore, in this study we examine how the size, shape, and spatial distribution of green spaces influence the cooling effect in various neighbourhood typologies in European cities with temperate climate, considering the effect 1) inside the green space, 2) outside the green space, and 3) the park cool island (PCI) effect.

## 2. Methods

As a first step, four neighbourhood typologies (T1-T4) representing different urban morphologies were selected. For each typology, eight design scenarios (S1-S8) based on the size, shape, and distribution of small green spaces were generated. ENVI-met microclimate simulations were run for all design scenarios. Simulations were also run for each neighbourhood typology for a base case without green space, enabling comparison. Thermal sensation, expressed in Physiological Equivalent Temperature (PET), of spaces inside and outside the green space, was calculated for each scenario, and Park Cool Island (PCI) effect was derived. The cooling performance of the design scenarios in the four neighbourhood typologies was then ranked. The following subsections provide a detailed description of the methods.

### 2.1. Design scenarios of small green spaces in the neighbourhoods

Four neighbourhood typologies (T1, T2, T3 and T4) in heat-prone areas of European cities with temperate climate were used to represent different neighbourhood morphology. They were developed based on the analysis that clusters 656 neighbourhoods considering the different morphological combinations of street orientations, street Height-to-Width ratios, block shapes, block floor area ratios, etc. (Wu et al., 2022). Within these four typologies, each building block is consistently a courtyard with a height of 20 m and dimensions of 72 by 50 m. The differences between the typologies are defined by the percentage of street area occupied by each specific H/W ratio and street orientation (Table 2). The H/W ratios have three variations: H/W=0.83, H/W=1.25, H/W=2.5. While the height is consistently 20 m, the street widths are 24 m, 16 m, and 8 m, separately. The main streets are the widest streets in the centre of the neighbourhood, while the secondary streets are the second widest streets around the main streets.

To design scenarios for small green spaces, it is crucial to consider vegetation characteristics, including vegetation types and configurations, as their variations can affect cooling (Lai et al., 2023). The most effective vegetation types from existing studies to maximise cooling potential were selected. As large trees with high canopies and cylindrical shapes have proven effective for cooling (Wong et al., 2021; Park et al., 2019), 25 m high trees with a 12 m crown and cylindrical shape were suggested. Grass with a height of 25 cm was used as a standard for lawns and groundcover plants (Yang et al., 2021). To enhance the guidelines' applicability, we did not specify species but established a generalised tree and grass model. Regarding the vegetation configuration, the total grassland area was set at 1 ha, representing small green spaces. To understand the cooling effects of varying sizes, shapes, and distributions, all scenarios involved arranging four identical 2500 $m^2$ green spaces that add up to 1 ha in each design scenario. For each 2500m 2 green space, trees provide shade around the perimeter, leaving open areas in the centre for residents' outdoor activities. This configuration, developed in consultation with urban designers, is common for small green spaces. The spacing of each tree equals the crown size, which has been found effective for cooling (Park et al., 2019). Therefore, each scenario includes 48 trees to maximise cooling effects. Based on collaboration with urban designers, eight design scenarios (S1-S8) for the size, shape and distribution of small green spaces were developed (Table 1). In this research, the shape of the green spaces is represented using a shape index (Cao et al., 2010). A value of 1.13 indicates that the green space is a square shape. As the value increases, the green space becomes more linear.

As there were eight design scenarios for each neighbourhood typology, and there were four neighbourhood typologies, this resulted in a total of 32 cases with greening. These were compared against four S0 in which no greening is present. Therefore, 36 cases were simulated. Virtual abstracted representations of these typologies serve as the environment in which eight different design scenarios (S1-S8) were inserted (see Fig. 1).

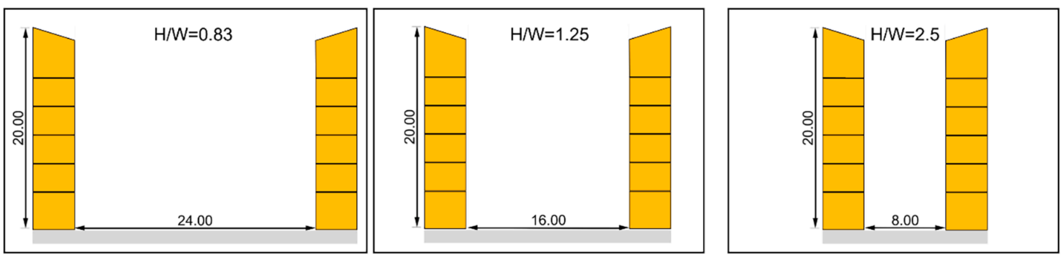
### 2.2. Simulation method

To understand the cooling effect of small green spaces, the simulation tool ENVI-met V5 was employed. ENVI-met is a CFD-based 3D microclimate simulation software that models heat and moisture transfer between building materials, soil surfaces, vegetation, and the atmosphere (Simon et al., 2018). Extensive studies have verified ENVI-met's reliability and accuracy in simulating the thermal effects of vegetation, buildings, and streets in Amsterdam, London, and Paris (Guo et al., 2019; Kleerekoper et al., 2015). Additionally, published studies have used ENVI-met simulation results to quantitatively compare various design scenarios (Zölch et al., 2016; Lobaccaro & Acero, 2015; Tseliou et al., 2022; Semeraro et al., 2023).

To generate the weather profile of a representative heatwave day, data from meteorological stations in De Bilt, London, and Paris for the years 2002–2021 were used, focusing on European cities with temperate climates and heat-prone neighbourhood typologies developed from Amsterdam, London, and Paris. According to the meteorological institutes in the three cities, heatwave days are defined as having a maximum day temperature above 30 °C (RIVM, 2023; McCarthy et al., 2019; Besancenot, 2002). Sixty-nine such days were identified for De Bilt, 83 for London, and 206 for Paris. Using these data, weather conditions for a typical heatwave day were determined and used as inputs for the simulations. The prevailing wind direction during heatwave days is East with a speed of 3 m/s. The detailed weather data and wind

**Table 2**
Total street area as a percentage of the neighbourhoods, with H/W ratios and orientations as percentages of the total street area; visual representation of three H/W types for street widths of 24, 16, and 8 m.; description of small green space design scenarios considering size, shape, and distribution.

| 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 | Single patch size (ha) | Number of patches | Shape index | Green patch distribution |
|---|---|---|---|---|
| S1 | 0.25 | 4 | 1.13 | Grouped next to wide streets |
| S2 | 0.25 | 4 | 1.13 | Scattered next to narrow streets |
| S3 | 0.5 | 2 | 1.20 | Grouped next to wide streets |
| S4 | 0.5 | 2 | 1.20 | Scattered next to narrow streets |
| S5 | 1 | 1 | 1.41 | Next to wide streets |
| S6 | 1 | 1 | 1.41 | Next to narrow streets |
| S7 | 1 | 1 | 1.13 | In the upwind area |
| S8 | 1 | 1 | 1.13 | Across wide streets |

Note: $Shape\,index = perimeter / 2\sqrt{\pi \times Area}$.

profiles are presented in Fig. S1. A full list of simulation inputs can be found in Table S1.

To understand how pedestrians experience the thermal environment, further exploration of thermal sensation, which considers air temperature (Ta), Mean Radiant Temperature (MRT), wind speed (WS), and relative humidity (RH), was necessary (Liu et al., 2020). We adopted the Physiological Equivalent Temperature (PET) in this study to quantify the pedestrian-level thermal environment. PET is widely used in urban climate studies, providing a basis for fair comparisons across multiple studies, climates, and regions (Liu et al., 2021). A higher PET indicates a hotter sensation. For Western Europeans, a high PET (>41 °C) signifies feeling "very hot", while a medium PET (18–23 °C) indicates "comfortable" conditions (Matzarakis et al., 1999). PET considers MRT, Ta, RH, WS, as well as human parameters (e.g., clothing level, age, sex, metabolism rate). In this study, PET was calculated using the ENVI-met module Biomet, at a height of 1.5 m above ground, representing a typical pedestrian experience. We focused on PET from 13:00–15:00, corresponding to the hottest part of the day, when cooling interventions are most beneficial. The PET differences in time series are presented in Fig. S2.

### *2.3. Analysis of thermal sensation in the neighbourhood*

To analyse the underlying reasons for the performance of different design scenarios and neighbourhoods, and to address the research questions in section 1.3, three metrics based on thermal sensation were calculated (Table 3): *Inside* ($PET_{in}$), *Outside* ($\Delta PET_{out}$), and Park Cool Island (*PCI*). "*Inside*" refers to the mean PET within small green spaces, measuring the thermal sensation experienced directly within these areas. The "*Outside*" metric measures the impact of green spaces on the surrounding neighbourhood by calculating the difference between the mean PET in streets outside the green spaces with and without greenery. This approach ensures the comparison not being influenced by varying environmental factors, allowing for a clear understanding of how adding green spaces influences thermal comfort in surrounding areas. "*PCI*" quantifies the mean PET difference between inside and outside the green spaces.

We also used local values of MRT, Ta, and WS, each affecting PET, to better understand the variations in the thermal environment within and between scenarios. Our simulation results showed that the cooling effect of green spaces in the neighbourhood extended up to 350 m. Therefore, only the central 350 m x 350 m area (at a height of 1.5 m) was the focus of analysis. All spatial analysis was conducted and visualised in ArcGIS Pro 3.1.

A One-Way Analysis of Variance (ANOVA) was conducted to determine if there are significant differences between the cooling effects of different design scenarios (Masoudi et al., 2021). Tukey's HSD post-hoc test identified specific design scenario pairs that differed significantly. All statistical analysis was conducted and visualised using R 4.3.1. A hierarchical cooling ranking was established for each neighbourhood typology, arranging scenarios from most to least effective based on increasing PET values. For each neighbourhood typology, three distinct rankings were established for Inside, Outside, and PCI metrics. A scoring mechanism awarded the top rank 8 points, decreasing to 1 point for the

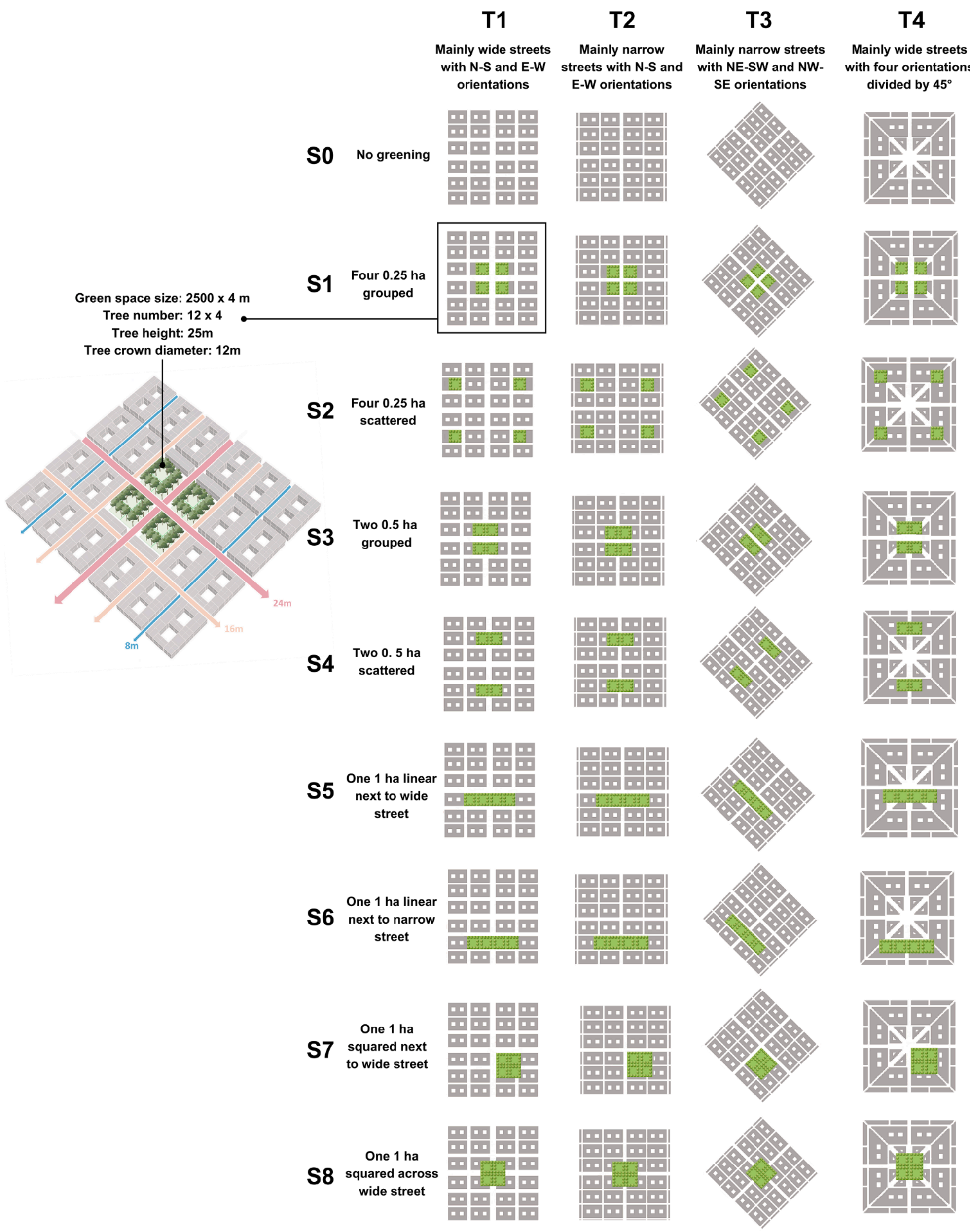



**Fig.1.** Design scenarios of small green space (S1-S8) in different neighbourhood typologies (T1-T4); an example of Scenario 1 for Typology 1 (T1S1).

eighth rank. The final ranking for cooling efficiency in design guidelines was determined by aggregating scores from each ranking to derive a cumulative score.

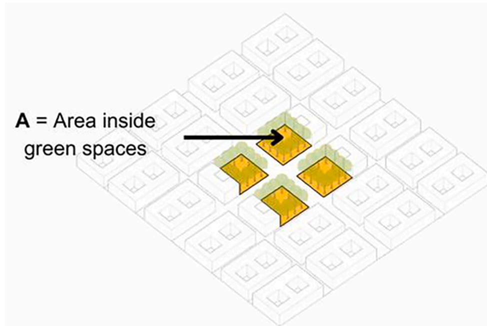
## 3. Results

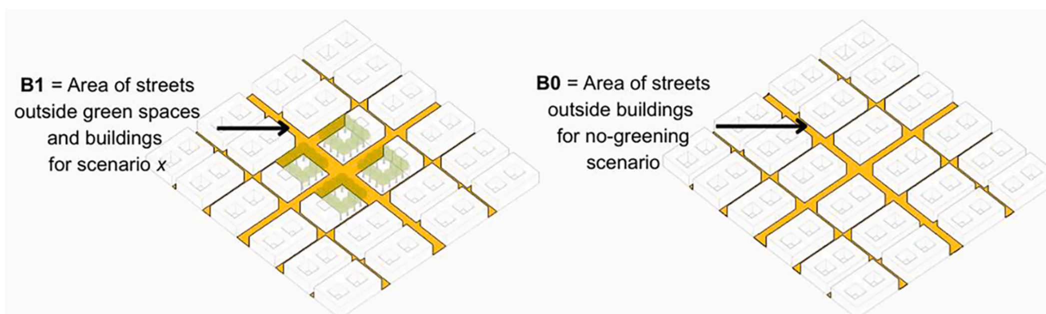
The cooling effects observed for different greening design scenarios vary for different neighbourhood typologies. The contributing parameters – MRT, Ta and WS – are shown for all scenarios, both inside and outside the green spaces, in Fig. 2. These values explain the differences in mean PET for each scenario in different neighbourhood typologies. According to the one-way ANOVA analysis results, there were significant differences in the cooling effects between the design scenarios (also see Table S2) and between the neighbourhood typologies (also see Table S3). In the following sub-sections, the results for each cooling metric (*Inside, Outside and PCI*) are described separately for each neighbourhood typology (T1-T4) and for each scenario (S1-S8).

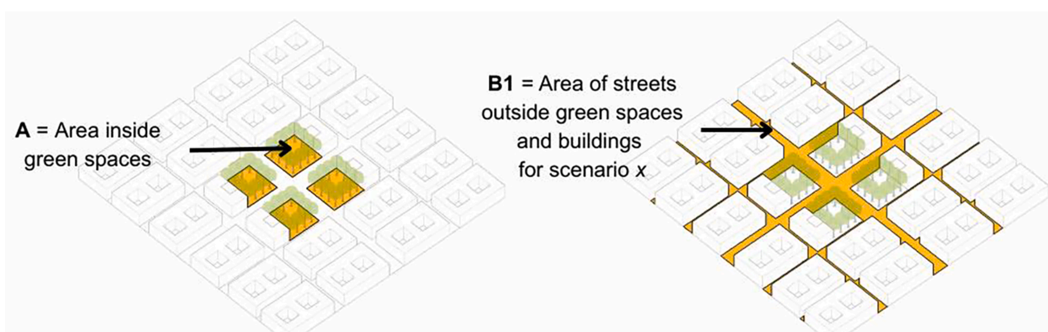
### 3.1. Thermal sensation impacts inside the small green spaces

When comparing scenarios within the same typology (Fig. 3), in typology T1, scenario S8 is the coolest, with a mean PET of 31.1 °C, the lowest MRT at 27.6 °C, and a relatively low Ta of 28.5 °C. In contrast, S1 and S2 have the highest PET (34.4 °C and 34.8 °C), driven by higher MRT and, in S2, lower wind speed. T2 and T3 show similar cooling patterns. T3S8 has the lowest PET (30.7 °C) across all the scenarios, which is 4.1 °C cooler than T1S2. For T1, T2 and T3, S5-S8 with 1 ha single patch provide generally better cooling effects than S3-S4 with 0.5 ha single patches, followed by S1-S2 with 0.25 ha single patches. Additionally, square-shaped patches in S7-S8 offer more cooling than the linear-shaped patches in S5-S6. For T4, the lowest PET (30.9 °C) is observed at S6, which has a linear 1 ha green space next to narrow streets. The lower MRT is related to the presence of buildings on the south side of T4S6 (also see Fig. S3). Since the green space is directly adjacent to the buildings (Fig. 1), the shadows cast by the buildings fall entirely within the green space. S6 also has the lowest air temperature

**Table 3**
Cooling indices analysed for each research question (yellow-coloured areas are calculated for each index).

<table>
<tr><th>RQ</th><th>Illustration</th></tr>
<tr><td>1. Inside (PET<sub>in</sub>): Mean PET within area A</td><td>

$PET_{in}$ = mean ($PET_A$)</td></tr>
<tr><td>2. Outside (ΔPET<sub>out</sub>): Difference of Mean PET between street area B1 (with greening) and B0 (the same area without greening)</td><td>

$\Delta PET_{out}$ = mean ($PET_{B1}$) − mean ($PET_{B0}$)</td></tr>
<tr><td>3. Park Cool Island (PCI): Difference of Mean PET within area A and Mean PET of area B1)</td><td>

$PCI$=mean ($PET_A$) − mean ($PET_{B1}$)</td></tr>
</table>

(Ta) at 27.9 °C, which is 1.1 °C cooler than T1S1. Similarly, in T1, T2 and T3, S6 also records the lowest air temperature, indicating that linear green spaces aligned with narrow (high H/W ratio) E-W streets result in cooler air temperatures.

When comparing the same scenario across different neighbourhood typologies (see also Fig. S4), S1 and S3, which have grouped green spaces of 0.25 or 0.5 ha, display the same cooling ranking, with T3 being the coolest with its highest wind speed and lowest air temperature. Similarly, S2 and S4, which have scattered green spaces of 0.25 or 0.5 ha, share the same cooling ranking, with T4 being the coolest. In particular, T4S2 exhibits an MRT that is 9.5 °C lower than that of T1S2 (Fig. 2). Fig. 1 shows that many edges of the green spaces are directly adjacent to the surrounding buildings, with the shadows cast by these buildings falling entirely within the green spaces (also see Fig. S3). The lower MRT is related to the presence of buildings on the south side of T4S6 (see Fig. 1 and Fig. S3). For S5 and S6, T4 is the coolest, whereas for S7 and S8, T3 is the coolest, followed by T2. Notably, the lowest PET is observed in T3S8 at 30.7 °C. It can be found that T3, where 71 % of street areas have a H/W ratio of 2.5 in NE-SW and NW-SE orientations (Table 2), provides cooler conditions in most scenarios.

The above results show that, in general, larger, square-shaped green spaces, especially in neighbourhoods with narrow NE-SW and NW-SE streets, or linear green spaces aligned with narrow E-W streets, are good at producing a cooler local microclimate inside the green spaces.

### 3.2. Thermal sensation impacts outside the small green spaces

Fig. 4 shows the spatial distribution of PET differences across the neighbourhood, comparing the situation with and without greenery for each design scenario. Negative values of PET change are indicated in blue. The figure demonstrates that replacing buildings with green spaces consistently lowers neighbourhood temperatures, highlighting that green spaces provide more effective cooling than buildings alone. It also shows the spatial pattern of how the cooling effect extends beyond the green spaces. For example, the street area between the green spaces is cooler in T1S1, while in T1S2, the cooled area outside the green spaces is

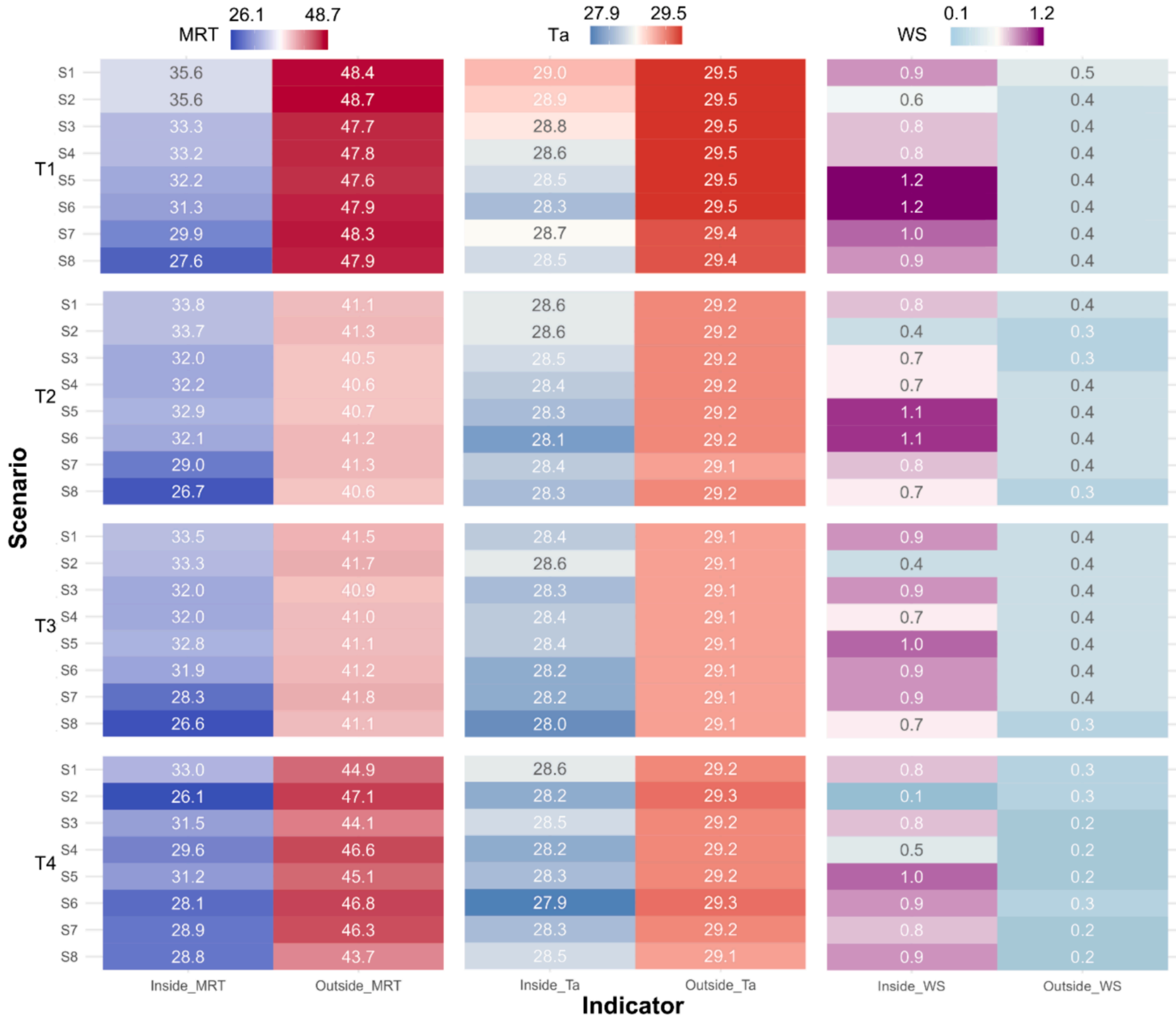



**Fig.2.** Spatially averaged MRT, Ta and WS values inside and outside of the green spaces for all simulated scenarios.

more limited. Fig. S5 shows the percentage of area under a certain PET difference threshold.

When comparing scenarios within the same typology (Fig. 5), T1′s cooling ranking for areas outside green spaces shows that S1 is the coolest design scenario, with an average of 0.7 °C PET cooling outside green spaces, whereas S8 provides the least cooling. This order is the reverse of the PET cooling order inside green spaces as shown in Fig. 3. T2 has slightly less cooling across all scenarios. T3 exhibits less cooling than T2, and S3 is the coolest, followed by S1. For T4, S1 produces the largest cooling effect of all scenarios studied (1.3 °C), followed by S3. It can be found that S1, with grouped small green spaces, demonstrates the best outside cooling performance across all typologies.

When comparing the same scenario in different neighbourhood typologies (also see Fig. S4), for S4 and S6, it follows the rank that T1 is the coolest, followed by T2, T4, and T3. For all the other scenarios, T4 has the lowest PET difference, followed by T1, T2, and T3. In T4 and T1, which have a higher proportion of wide streets (34–35 % with H/W=0.83, Table 2), the outside areas are cooler. In contrast, T2, with predominantly narrower streets (71 % with H/W=2.5), is less easily cooled, while T3, with NE-SW and NW-SE street orientations, experiences the least cooling in outside areas.

These results indicate that the spatial distribution and the surrounding morphology of small green spaces are the most important factors influencing their capacity to cool the surrounding areas in the neighbourhood. The most effective cooling occurs for small green spaces, grouped together and next to wide streets.

### 3.3. Park cool island effects in the neighbourhood

When comparing scenarios within the same typology (Fig. 6), the PCI rankings for T1, T2, and T3 follow a similar pattern, consistent with the cooling performance inside green spaces discussed in Section 3.1, where larger, square-shaped green spaces perform better. Conversely, the rankings are roughly in reverse order for cooling outside the green spaces, as discussed in Section 3.2. It is worth noting that the PCI effect is greater for T1 than for T2 and T3, even though it experiences the highest PET inside parks among the three typologies (Fig. 3). For T4, the PCI ranking follows a unique order compared to the cooling inside, where S6 with linear green spaces next to narrow streets S2 with 0.25 ha green spaces scattered produce the greatest PCI effect.

When comparing the same scenario in different neighbourhood typologies (also see Fig. S4), it was found that for all the scenarios, T1 and

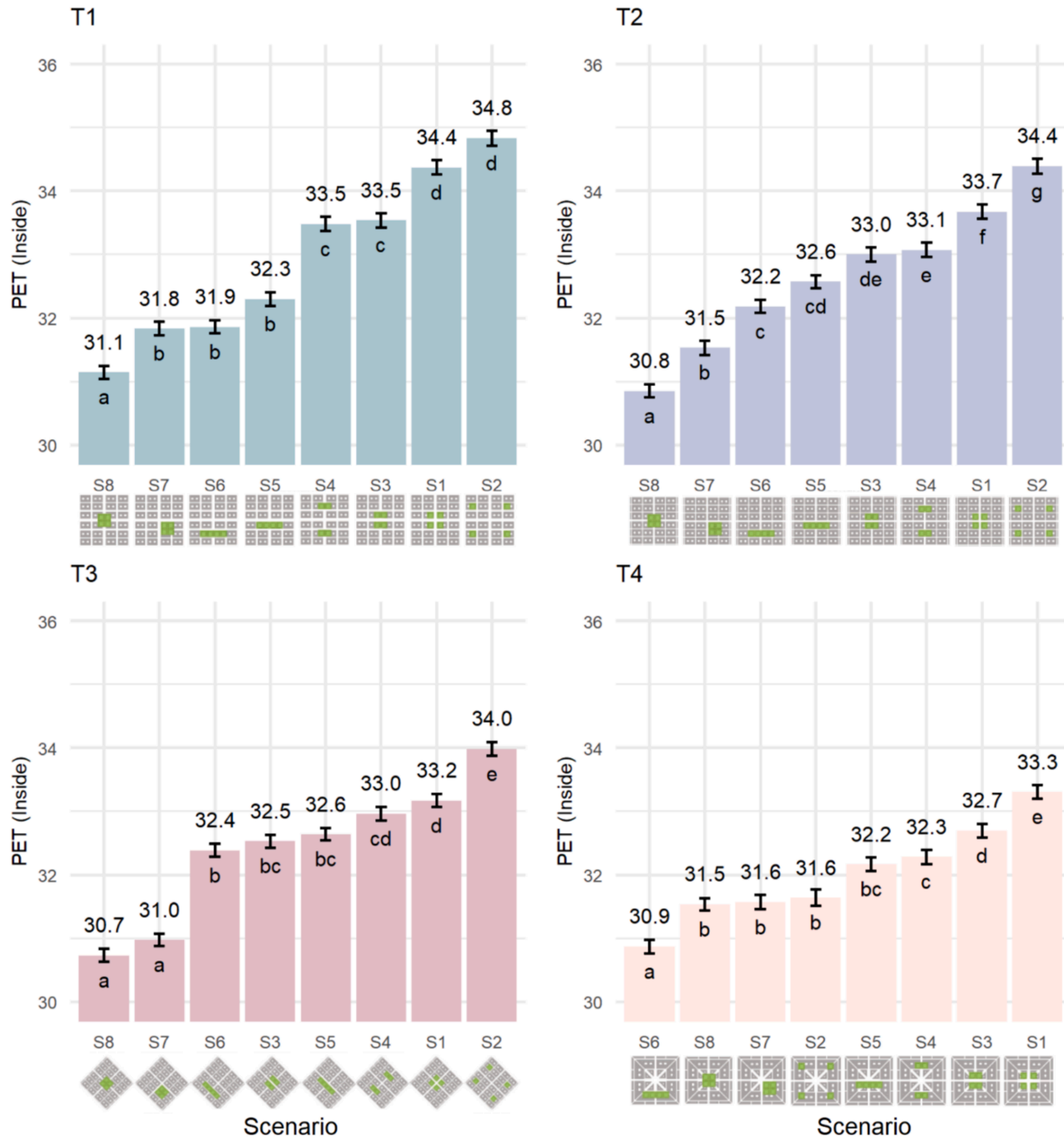



**Fig.3.** PET inside small green spaces during the hottest period (13:00–15:00). Design scenarios are ranked from the coolest (left) to warmest (right). Error bars denote standard error, with different letters indicating significant differences between design scenarios, using a one-way ANOVA test and Tukey's HSD post-hoc test.

T4 with wide streets are cooler than T2, followed by T3. For S1, S3, S5, S7, and S8, the PCI ranking is the same: T1 > T4 > T2 > T3. All these scenarios have green spaces next to wide streets in T1. Compared to T4, the green spaces inside are less cool in T1 and the outside is warmer, so the PCI (inside PET minus outside PET) is lower; meanwhile, T4 has a lower Ta outside (Fig. 2). For S2, S4, and S6, which are all next to narrow streets, the PCI value is T4 > T1 > T2 > T3. T4 has stronger PCI effects than T1.

These results show that for neighbourhoods with regular street grids, when small green spaces have square shapes and are grouped together, the PCI effect is stronger. However, for neighbourhoods with radial streets, the PCI effects are stronger when green spaces are next to narrow streets. Neighbourhoods with higher coverage of wide streets (low street H/W ratios) have stronger PCI effects.

## 4. Discussion

### *4.1. Influence of green space design parameters and neighbourhood typology on cooling effects*

Our results reveal that for cooling effects inside green spaces, size is the most influential parameter, followed by shape and spatial distribution; regarding the outside, spatial distribution is the most influential, while there is no distinct difference in the influence of size and shape. Regarding PCI, a similar order to the rankings for cooling inside green spaces occurs. This similarity can be attributed to the fact that the variation in temperatures outside the green spaces is considerably less than inside. Consequently, the PCI is predominantly determined by the PET inside the green spaces. While many previous studies use PCI to analyse the cooling effects of (mostly large) green spaces (Feyisa et al., 2014; Shah et al., 2021), our study shows that when small green spaces are the research target, the cooling effects inside and outside the green spaces should be the focus rather than PCI. To delve deeper into the

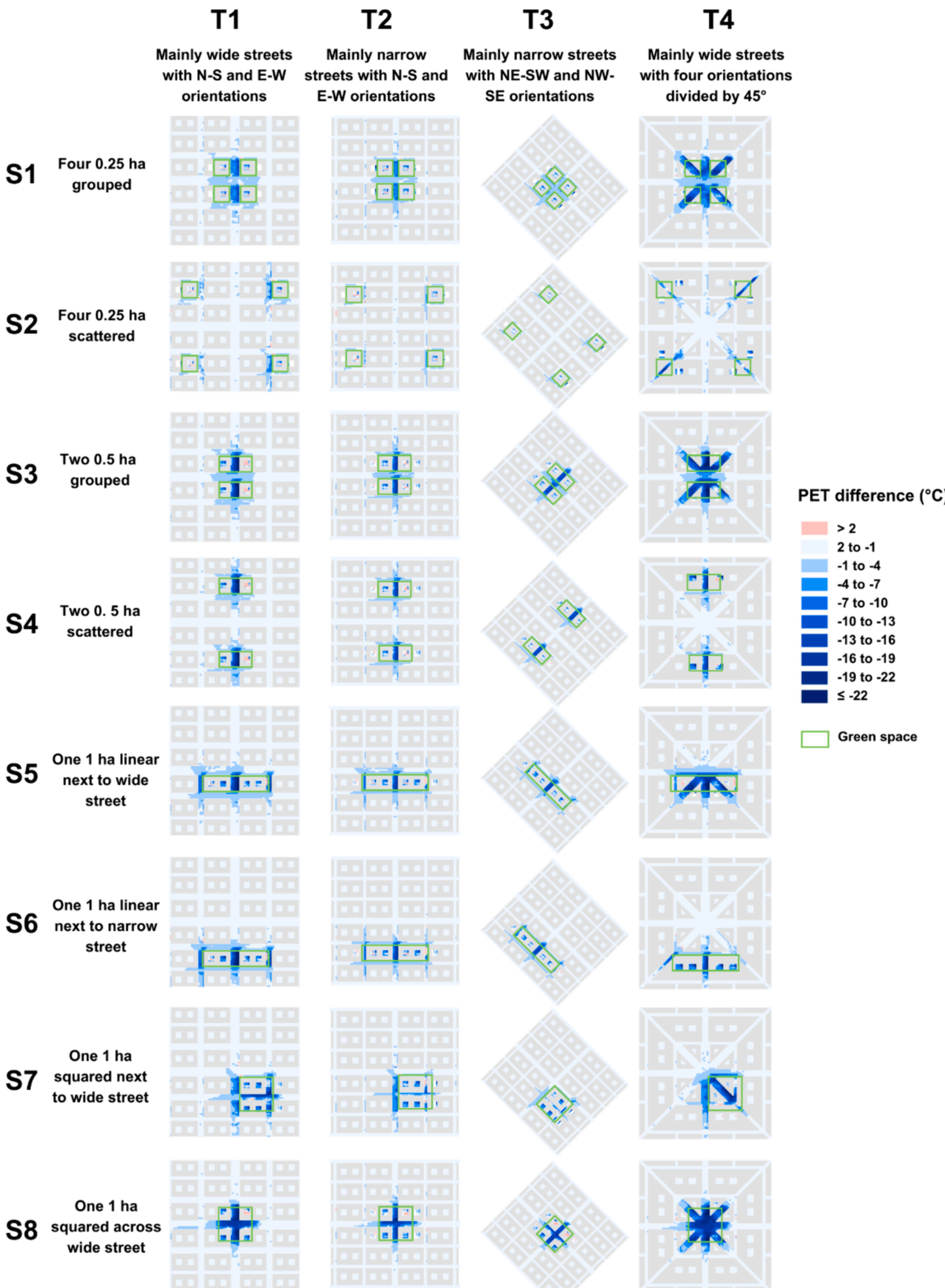



**Fig.4.** Visualisation of ENVI-met model results, showing reduction in PET due to adding greenery (comparing each design scenario with and without greenery).

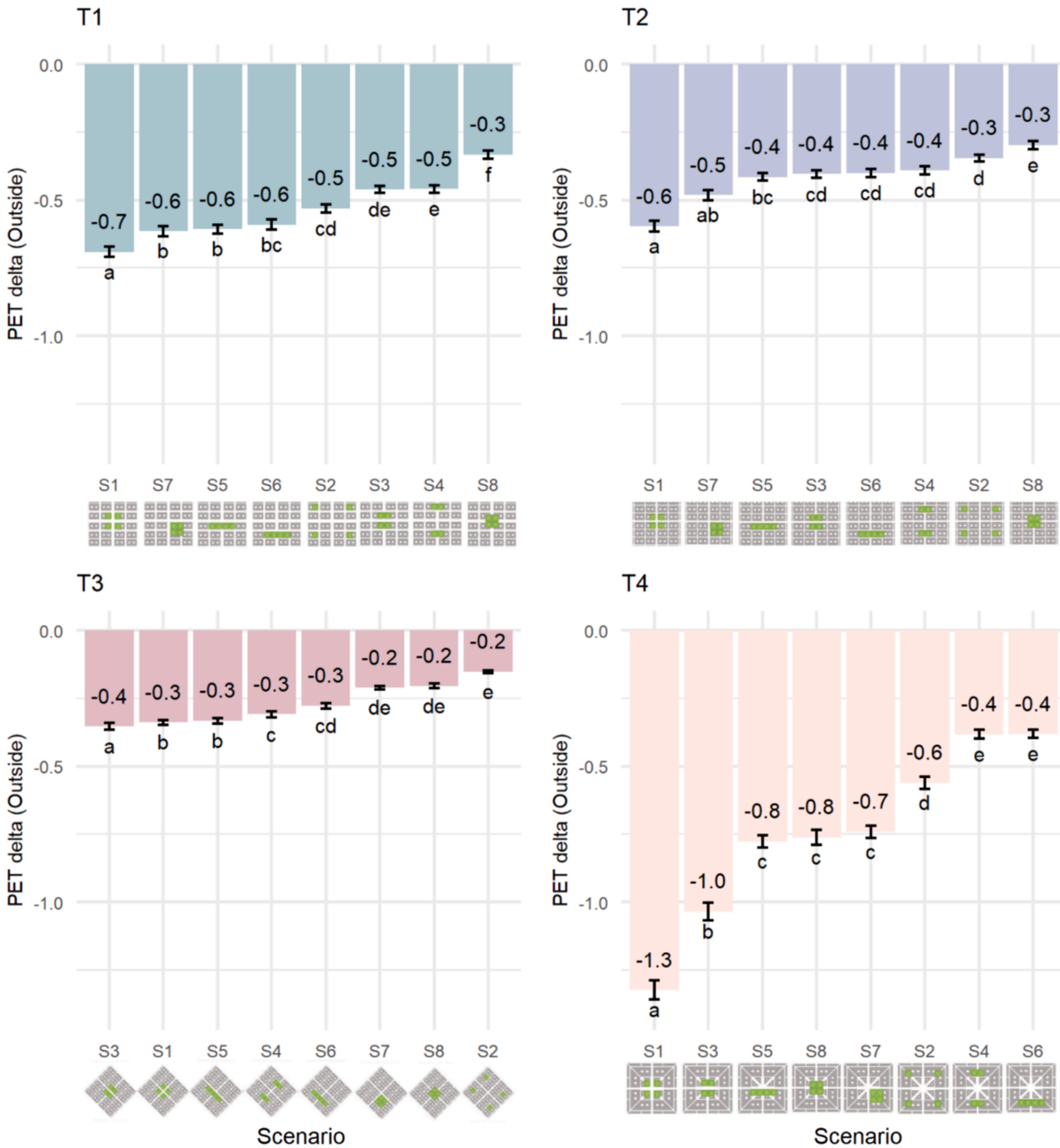



**Fig.5.** PET reduction outside small green spaces during the hottest part of the day (13:00–15:00), showing the difference in spatially averaged PET with and without greenery for each design scenario.

influence of distribution, size, shape, and neighbourhood typology on cooling effects, the following discussion elaborates on these four aspects separately.

#### 4.1.1. *Spatial distribution*

Although many studies analysed the spatial distribution of green spaces on cooling effects, their results are contradictory: some claim that scattered distribution is more effective at lowering temperatures, as it enhances energy flow and exchange between green spaces and their surrounding areas, thereby decreasing the temperature (Lin & Lin, 2016; Zhou et al., 2011), while others have shown that clustered distribution is cooler due to the use of different types of data and units of analysis (Li et al., 2012; Zhang et al., 2009). Our study shows that there is no clear pattern indicating whether a scattered or clustered distribution is better for cooling inside green spaces. Instead, cooling effectiveness is more closely related to the surrounding urban morphology and the configuration of shadow-casting elements. When green spaces are located adjacent to buildings and are mostly shaded, they tend to be cooler, even in the smallest parks (e.g., T4S2), supporting Wong et al. (2021) that small green spaces are sensitive to urban geometry. This also explains the low PET in T4S6, where the linear green space is oriented in E-W direction and is directly adjacent to buildings. During the hottest hours, when Western European cities receive the strongest sunlight from the south to southwest, most shadows from the buildings are cast within the green spaces, thereby reducing MRT. Green spaces with shorter perimeters next to wide streets create cooler environments (S8 > S7, S6 > S5), consistent with Lin et al. (2017) on building shading reducing daytime temperatures. MRT is mainly influenced by shading, which can be improved by planting more trees or adding artificial shading. Our results are based on tree rows around the perimeter, but different vegetation configurations or denser shading could yield other effects (Lai et al., 2023).

For cooling the outside areas of green spaces, spatial distribution is crucial. Clustered small patches optimally cool surroundings, likely due to increased adjacent open space (streets), supported by Zhou et al. (2011) and Maimaitiyiming et al. (2014) who found increased edge

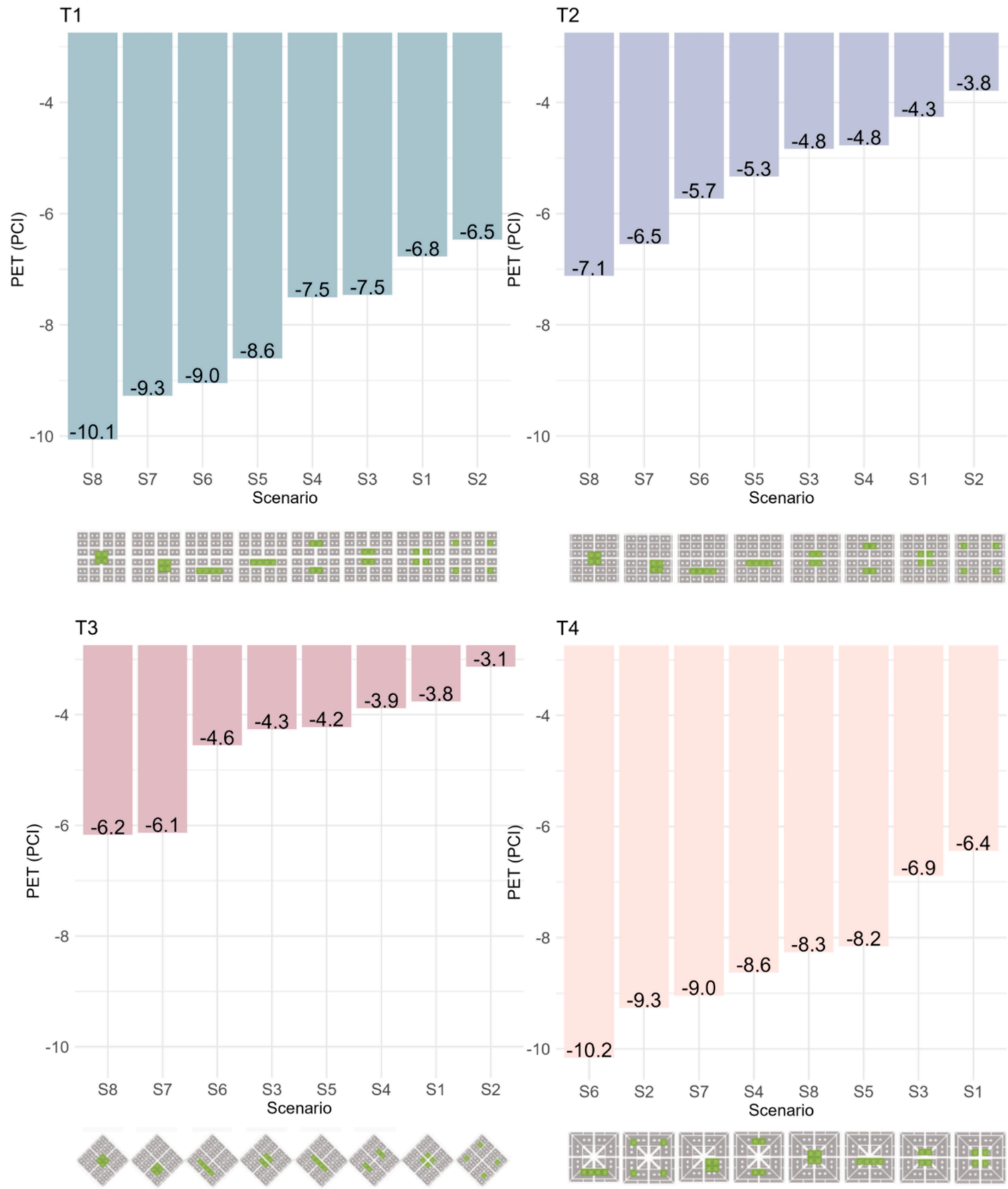



**Fig.6.** PET for the Park Cool Island effect of small green spaces at the hottest period.

density of green spaces enhances energy exchange with built-up areas, cooling surroundings. The smallest grouped scenario also cools streets between small green spaces. Thus, while S8 achieves better local cooling, S1 cools a larger area.

#### *4.1.2. Size*

Regarding the cooling inside the green spaces, our results reveal a consistent pattern across all typologies: given the same total area, larger single patch sizes result in cooler PET than several smaller patches (S5-S8 > S3&S4 > S1&S2). This aligns with previous studies, which found that increased patch size can mitigate UHI effects (Li et al., 2012). The primary reason for this is the reduction in MRT. In larger green space patches, their tree shadows predominantly fall within the green spaces themselves, providing significant shade and cooling. In contrast, smaller patches cast shadows on surrounding streets, which have more exposed edges and offer less shading and cooling within the green spaces (Greene & Kedron, 2018). Moreover, air temperature is lower in most large patches. This can be attributed to the fact that more vegetation within an area leads to higher rates of evapotranspiration, a process that absorbs solar energy to transform liquid water into water vapour, replacing sensible heat with latent heat, thereby cooling the air to a greater extent (Bowler et al., 2010; Oke et al., 2017; Wong et al., 2021). This study supplements existing research by showing that green space size is the most influential factor, compared to shape and distribution, in influencing thermal sensation inside small green spaces. Conversely, our study shows that cooling outside is not associated with changes in green space sizes, indicating that external cooling depends more on surrounding morphology than on green space characteristics.

#### 4.1.3. Shape

For cooling effects inside green spaces, shape is the second most influential parameter. The ranking of [S7, S8] > [S5, S6] across typologies indicates that a square shape is more effective than a linear one in influencing thermal sensation. Park et al. (2017) attributed this to plant selection, with small trees and shrubs in square parks trapping cooled air, while linear parks mostly have identical trees. Our study shows that even with the same tree distribution, square parks are cooler than linear parks. This is mainly due to the reduced MRT from the shorter perimeter exposed to direct sunlight. Less edge complexity leads to cooler conditions, aligning with studies by Yu et al. (2017), Park et al. (2017), and Chen et al. (2014). Linear green spaces aligned with high H/W ratio E-W streets tend to have cooler air temperatures. This is likely due to their alignment being parallel to the prevailing wind direction, allowing air to travel over longer distances within these E-W oriented green spaces, enhancing the cooling effect. As for the cooling outside, again, there is no clear pattern that is associated with changes in shape.

#### 4.1.4. Neighbourhood typology

Regarding the influence of neighbourhood typologies on cooling inside green spaces, our results indicate that neighbourhoods with NW-SE and NE-SW streets are generally cooler. This is due to the sun angle during the hottest periods of the day being perpendicular to the buildings, resulting in most areas of the green spaces being shaded (Acero et al., 2021). However, for linear green spaces, when their orientations are parallel to the wind direction, they are cooler in neighbourhoods with N-S and E-W streets. This aligns with previous studies showing that plants parallel to the wind direction enhance evapotranspiration, decreasing air temperature (Lin & Lin, 2016).

Regarding cooling outside green spaces, in most design scenarios, T2 and T3 are less effective in cooling when adding green spaces, as these two typologies have more narrow streets, which already provide good shading and lower PET across the neighbourhood without green space. This supports the claim that tree shade becomes less effective at reducing temperature when it overlaps with building shade (Thom et al., 2016; Wong et al., 2021). Lin et al. (2017) also highlighted the importance of building shading in reducing daytime temperature. As the original PET is comparatively low, it reduces the potential cooling benefit of green spaces. The wider streets in T1 and T4 experience higher temperatures, so greening has a greater cooling effect here. Typologies T1, T2, and T3 all reduce PET by 2 °C or more across 2–10 % of the neighbourhood (also see Fig. S5). For T4, this area increases to 5–18 % of the neighbourhood, indicating that radial, wide streets facilitate a more effective spread of cooling into surrounding areas.

### 4.2. Design guidelines

To provide urban planners and designers with clear design guidelines for cooling specific neighbourhoods, the cooling rankings for each neighbourhood were analysed. A detailed scoring system is presented in Table S4. The rankings are based on the simulations that focus on the heatwave period in European temperate climate cities, with a prevailing Eastern wind direction.

As the ranking for cooling inside green spaces and the PCI effect follow very similar patterns, to avoid result duplication, the final scores have been calculated by adding together ranking scores for inside and outside the green spaces only (excluding the PCI effect). The resulting overall ranking is shown in Fig. 7. The same weight was assigned to both Inside and Outside. Urban designers and planners can assign the weight of importance to the Inside and Outside considering their specific cases to obtain a ranking adapted to their needs.

These design guidelines can support urban designers, planners and landscape architects in making design decisions for both new designs and regeneration projects:

- in the creation of new designs or masterplans, they can ensure that new designs are adapted to specific climatic and urban settings from the very beginning;
- for regeneration projects or tactical urban interventions, the guidelines ensure that interventions are integrated into the existing urban fabrics.

Utilising these guidelines enables practitioners to effectively address climate-responsive design, making it more accessible and applicable. They contribute to creating cooler, more liveable, and sustainable urban environments.

### 4.3. Originality

This study develops a novel framework for green space design

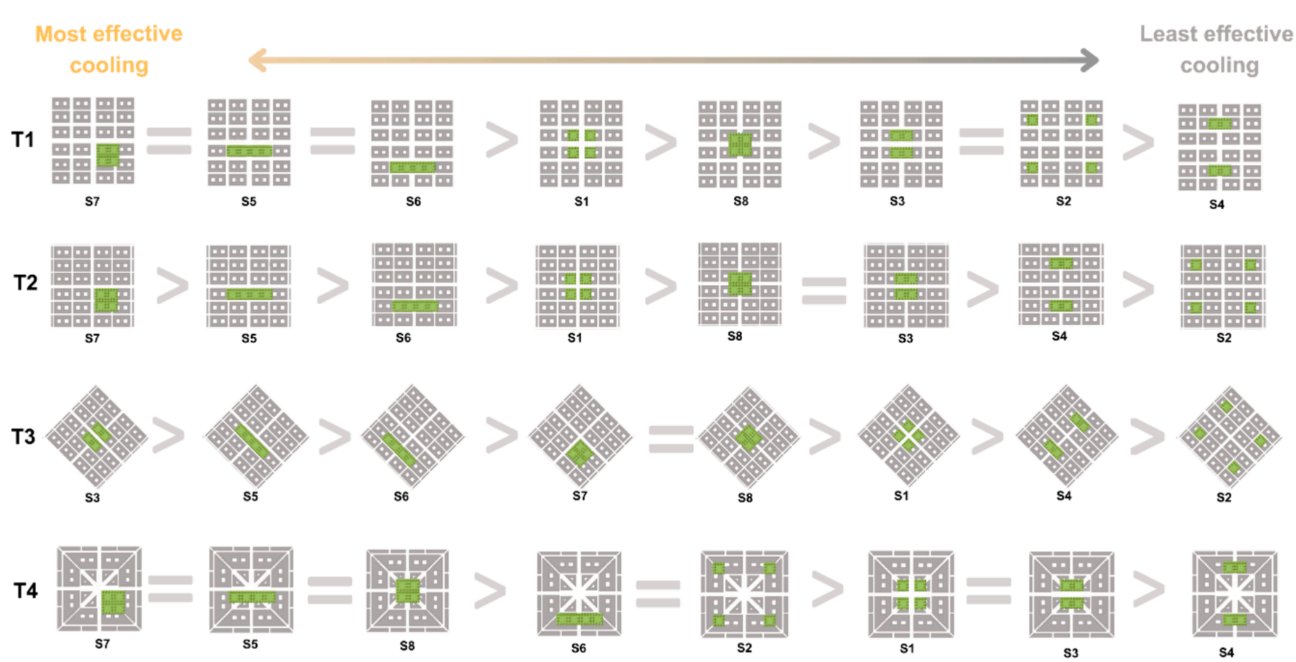



**Fig.7.** Ranking of overall thermal sensation performance of each neighbourhood.

guidelines to enhance the outdoor thermal environments of urban neighbourhoods during the day. Previous studies often focused on a single neighbourhood or considered multiple neighbourhoods without consistent factors such as size and surrounding morphology (Lin & Lin, 2016; Wong et al., 2021). To provide clear guidelines to urban planners and designers, this study uses generic neighbourhood typologies, overcoming the limitations of site-specific studies. It uniquely explores the combined effects of critical urban design elements — spatial distribution, size, and shape — in different green space design scenarios. Thermal sensation performance is simulated using generic weather profiles for these typologies.

Most previous studies use LST to indicate the thermal effect of different sizes, shapes, and distributions of green space (Asgarian et al., 2015; Cao et al., 2010; Liao et al., 2023; Yu et al., 2018). However, for urban neighbourhood designs, it is crucial to understand the human thermal experience at the pedestrian level. Therefore, this study uses PET to quantify the thermal environment, combining physical parameters (Ta, MRT, RH, and WS) and human factors (clothing, activity level, etc.).

The thermal sensation effects of inside, outside, and PCI of small green spaces are investigated separately. Prior studies predominantly used PCI as the main indicator to measure cooling effects (Cao et al., 2010; Liao et al., 2021). This study reveals:

i) A high PCI might indicate a cool refuge inside the green space but not significantly impact the broader neighbourhood;
ii) Cooling inside green space and PCI effects follow similar trends, constituting similar measures of local cooling;
iii) Cooling outside green spaces provides a separate metric, showing the potential of small green spaces to extend cooling beyond their boundaries and interact with surrounding urban morphology.

Consequently, the guidelines from this study view green spaces not as isolated cool air pockets but as key components contributing to overall thermal comfort in urban neighbourhoods.

### 4.4. Limitations and future research

It should be noted that this study has various limitations. Firstly, the vegetation characteristics, including types and configurations within green spaces, remain consistent across the design scenarios, but we are aware of the fact that vegetation characteristics are crucial design elements, and their variations can influence thermal sensations (Lai et al., 2023). Future research should select the most effective scenarios from our guidelines and test different vegetation characteristics inside green spaces for each neighbourhood typology. This workflow can minimise simulations and computational demand, targeting the most effective scenarios.

Secondly, the total street area is not the same across all design scenarios: some small green spaces replace buildings (S1 and S2), or green spaces replace both streets and buildings (S3-S8). The decrease in street area may affect simulated cooling effects. Future research should focus on larger neighbourhood sizes and distribute green spaces in different locations based on block size, so that street areas remain consistent.

Thirdly, our approach emphasises proposing guidelines through comparative analysis of design scenarios, excluding onsite measurements. Given that neighbourhood morphology and weather data were generalised from extensive datasets rather than tailored to a specific case, finding real-world neighbourhoods that precisely match our scenarios for a single weather day is not feasible. Our approach allows a broader evaluation and comparison of design possibilities, focusing on generalised applicability rather than specific, localised precision.

Lastly, this study focuses on the cooling effects of green space during the hottest daytime period of a heatwave. Daytime MRT (and thus PET) can be adjusted through shading, but spatial interventions can also result in nocturnal heat-trapping. Night-time air temperatures are altered less easily. Considering the temporal variability of thermal comfort throughout the year (Acero et al., 2021), the role of green spaces in cooling surrounding areas during temporal and seasonal timescales becomes important, highlighting the need for future research.

## 5. Conclusion

This study aimed to establish guidelines for optimising small green spaces for urban cooling. It used ENVI-met microclimate simulations of 32 design scenarios with varying sizes, shapes, and spatial distributions of green spaces within four generalised neighbourhood typologies. Specifically, it explored the impact of green space size, shape, and distribution on thermal comfort 1) inside green spaces, 2) outside green spaces, and 3) considering the Park Cool Island (PCI) effect.

1) **Thermal sensation inside green spaces:** Larger, squared green spaces provide cooler local PET due to the agglomeration effect. Linear parks aligned with prevailing winds also cool effectively, especially with shading from buildings. Size is the most influential factor, followed by shape, then distribution. Across the 32 simulations, the variety in greening and urban morphology produced a 4 °C difference between the hottest and coolest scenarios.
2) **Thermal sensation outside green spaces:** Cooling effects outside green spaces relate more to spatial distribution than size or shape. Grouped green spaces or large ones adjacent to wide streets offer more cooling. Green spaces cool neighbourhoods with wider streets more effectively. The maximum spatially averaged PET reduction, comparing greenery with no greenery, was 1.3 °C.
3) **PCI effect:** The PCI effect aligns with PET results inside green spaces, with squared and grouped green spaces showing stronger PCI effects. The green space location relative to the urban context causes variation across neighbourhood typologies. Scattered small green spaces are generally less effective, except when well-shaded and sheltered from wind. A range in PCI effect of −3.1 °C to −10.2 °C was observed.

Small green spaces are effective for urban cooling over day, but their effect depends on design and neighbourhood morphology. Neighbourhood-specific guidelines are essential to maximise cooling benefits. This study provides a novel framework for developing design guidelines for small green spaces in urban neighbourhoods with regard to the key urban design aspects of spatial distribution, size, and shape of green spaces.

## CRediT authorship contribution statement

**Yehan Wu:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Agnès Patuano:** Writing – review & editing, Supervision, Methodology. **Bardia Mashhoodi:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Sanda Lenzholzer:** Writing – review & editing, Supervision, Software, Project administration, Methodology, Funding acquisition, Conceptualization. **Andy Acred:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Laura Narvaez Zertuche:** 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.landurbplan.2024.105224.

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