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Greening guidelines for cooling European neighbourhoods with temperate climate: A research-through-design approach

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ABSTRACT

Green infrastructure measures such as street tree planting and ground surface greening effectively mitigate urban heat. As heat stress intensifies, identifying effective spatial arrangements of these interventions becomes increasingly important. To provide actionable guidance for real-world projects, practical design and resource constraints must also be considered. However, studies that systematically balance cooling effectiveness with practical applicability remain limited. This study develops design guidelines on the size, amount, and spatial distribution of street trees and grass in urban neighbourhoods, focusing on applicability in urban design practice. Four neighbourhood typologies in temperate-climate European cities were used as case examples, for which multiple greening scenarios were generated. A research-through-design approach was adopted: focus group workshops with practitioners evaluated the scenarios in terms of visual experience, functionality, cost, and maintenance; then the refined designs were assessed using ENVI-met simulations. The refined scenarios reduced mean PET by 1.07–7.89 °C compared with the no-greening reference case, with the strongest reductions in wide-street typologies. However, greater green coverage did not necessarily lead to stronger cooling: in a narrow-street typology with diagonal street orientations, the tree-only scenario reduced mean PET by 1.79 °C, while the tree-grass scenario with higher tree and grass coverage reduced mean PET by 1.33 °C. For each typology, two recommended scenarios are identified: one maximising cooling capacity and one prioritising cooling efficiency under space and resource constraints. By translating thermally ranked scenarios into practitioner-refined greening guidelines, this study provides design support for neighbourhood-scale, morphology-specific heat mitigation through the strategic spatial arrangement of street trees and grass.

1. Introduction

1.1. Urban neighbourhood cooling using greening strategies

Urban heat has intensified over the past decade due to global climate change, increasing risks for cities worldwide (Kearl & Vogel, 2023; Tollefson, 2023). Urban designers, planners, and landscape architects (hereinafter referred to as "practitioners") are actively implementing green infrastructure, such as street trees and greening of ground surfaces, to mitigate urban heat. Green infrastructure plays a pivotal role in adaptation policy interventions by enhancing adaptation and

minimizing maladaptation (Kim et al., 2025). Street trees can significantly improve thermal sensation by blocking solar radiation and increasing evapotranspiration, which reduces air temperature (Taleghani, 2018). Greening of ground surfaces such as introducing lawns, meadows, beds with perennials or flowers, or low shrubs (hereinafter referred to as 'grass') in the streets, can decrease the albedo, increase the evapotranspiration, and thus cool surfaces (Armson et al., 2012; Lobaccaro & Acero, 2015). Additionally, street trees and grass provide important environmental and social benefits to residents (Roe & McCay, 2021).

Current studies have started to explore the effective designs of street

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trees and grass to enhance overall thermal sensation, yet few studies have developed comprehensive design guidelines that consider the amount and distribution of green measures at the neighbourhood level. Previous studies on street trees and grass either focused on providing design scenarios at the street level (Aboelata, 2020; Bartesaghi-Koc et al., 2021; Cui et al., 2023; Ojha & Mukherjee, 2024) or addressed the neighbourhood level by concentrating solely on overall greening quantity without offering specific design scenarios (Ouyang et al., 2020; Ziter et al., 2019).

Moreover, the impact of neighbourhood morphology on thermal sensation is an important factor in making street greening design decisions (Li et al., 2024; Yin et al., 2019). Neighbourhoods are complex combinations of different street orientations and Height-to-Width ratios (Wu et al., 2022), and it is therefore essential to take local spatial conditions into account when providing actionable guidance to practitioners to inform them about the design of street trees and grass within a neighbourhood for better microclimate considerations (Graça et al., 2022; Lobaccaro & Acero, 2015).

However, it remains unclear how greening strategies should be adapted and prioritised across different morphological contexts. Wu et al. (2025) developed design scenarios of different amounts and distributions of street trees and grass in four different neighbourhood types. Yet, given the limited space available for implementing greening in densely populated urban areas, it remains unclear how greening resources should be spatially prioritised across streets with different widths, orientations, and functional constraints within neighbourhoods.

1.2. From cooling effectiveness to practical applicability

Prioritising greening design strategies often involves responding to real-world constraints (Klemm et al., 2017). However, few studies have translated climate-based design knowledge into actionable guidelines that balance cooling effectiveness with real-world feasibility. The challenge for local governments is not only what cools, but what can be implemented and maintained within limited resources. According to Cortesão et al. (2020), visual experience, functionality, costs, and maintenance are also factors that influence decision-making in urban design practice. These factors are related to the spatial design of interventions involving street trees and grass, thereby also likely to influence their thermal effects. It is therefore crucial to add these factors into the design of street trees and grass when considering cooling to offer more practical guidance and recommendations.

Urban greening for heat mitigation is therefore not only a question of identifying which spatial configurations cool most effectively, but also of translating climate evidence into design options that can be implemented, maintained, and prioritised under local conditions. Nature-based solutions research emphasises that urban climate adaptation requires stronger links between science, policy, and practice communities to support evidence-based decision-making (Frantzeskaki, 2019). Existing urban climate design studies have linked microclimate simulation and design practice in different ways: some test researcher-defined design scenarios in ENVI-met (Aboelata, 2020; Banerjee et al., 2024; Darbani et al., 2023), while others involve designers or planners in scenario generation before simulation (Lenzholzer et al., 2012).

In design disciplines, research-through-design (RTD) provides a way to generate knowledge through iterative design processes, spatial experimentation, and reflective evaluation (Lenzholzer et al., 2013; Shen & Lin, 2019; Cortesão & Lenzholzer, 2022). RTD can lead to actionable design guidelines through the involvement of design practitioners (Cortesão & Lenzholzer, 2022). This approach is a question-driven, iterative process in which design activities are continuously evaluated, refined, and further developed based on study, observation, and analysis (Lenzholzer et al., 2013). Lotfata et al. (2024) used the RTD approach to examine cooling strategies for different streetscape designs, where experts assessed design prototypes across

seven feasibility criteria in an RTD process, followed by interdisciplinary discussion to identify aspects requiring improvement in the next iteration. Cortesão et al. (2020) applied the RTD approach, engaging designers in evaluating various design solutions to address visual experience, functionality, cost and maintenance for water bodies. This approach facilitated the creation of design guidelines that effectively balance scientific and practical considerations.

1.3. Applicability criteria for practitioner assessment

The applicability of urban greening strategies for cooling refers to whether a strategy can be realistically integrated into urban design practice. Four applicability criteria are particularly relevant: visual experience, functionality, cost, and maintenance. These criteria provide a conceptual basis for involving practitioners in the RTD process, helping to identify where thermally promising scenarios may require spatial refinement before they can become usable design guidelines.

- 1) **Visual experience** is a primary criterion for assessing streetscape quality in urban design, referring to how visual aspects of the environment influence user perception. It can be understood through two key spatial dimensions: openness in the street and visibility of greenery from home. These aspects shape how people perceive and relate to their immediate surroundings and have been widely recognised as important in urban design practice (Fang et al., 2024). Openness describes the degree of spatial freedom or enclosure experienced at pedestrian level, shaped by street height-to-width ratio and vegetation arrangement (Asgarzadeh et al., 2012; Ewing & Handy, 2009). High-canopy trees can maintain openness while providing shade, whereas smaller or denser trees may obstruct views and create visual barriers (Arnold, 1993; Hu et al., 2022). Visibility from home refers to the extent to which green elements are visible from residential windows, contributing to perceived naturalness, aesthetic appreciation, and well-being (Ewing & Handy, 2009; Konijnendijk, 2023). These visual dimensions are also related to microclimatic performance, as vegetation configuration affects radiation exposure, airflow, and shading conditions (Ng et al., 2015; Zhu et al., 2024).
- 2) **Functionality** in urban design refers to ensuring that a space is fit for its intended use, addressing both physical and social aspects, with the ultimate aim of enabling various activities and uses (Carmona, 2021). The physical dimension includes factors such as daylighting, overshadowing, traffic flow, access, and circulation (Carmona, 2021). The social dimension refers to how effectively a space is used by people, supporting essential social activities and fostering a sense of community among residents (Gehl, 2006). To achieve this, each streetscape must be responsive to the needs of both motorised and non-motorised users, ensuring comfort and safety for all, including pedestrians, drivers, and others (Rehan, 2013). Patterns and volumes of car use influence streetscape design through lane allocation, traffic calming measures, and parking provisions, while streetscape design in turn affects travel behaviour (Liu et al., 2023; NACTO, 2019). Additionally, functionality is influenced by surface materials that have different albedos, thus designing different portions of the transportation and greenery considering functionality in the streetscapes affects the microclimates (Taleghani, 2018).
- 3) **Cost** as a design criterion refers to the financial investments required for establishing urban vegetation including expenses related to tree procurement, soil preparation, and irrigation infrastructure (Mullaney et al., 2014). Beyond initial installation, long-term costs are significant, encompassing costs of watering, pruning, and pest control. These expenses can increase further due to extreme climatic events, which cause canopy damage and necessitate additional restoration efforts (Tabassum et al., 2021). Given budget constraints, cities must carefully evaluate the cost-effectiveness of different

planting strategies to determine the most viable approaches for urban greening.

- 4) **Maintenance** refers to the ongoing management efforts necessary to sustain healthy urban greenery. Limited space and poor soil quality complicate tree establishment, requiring more intensive management (Egerer et al., 2024). Many planting sites consist of small, shallow areas with compacted or nutrient-deficient soil, which restricts root growth and weakens tree stability. These constraints often lead to conflicts with urban infrastructure, as roots compete for space with underground utilities and pavement, increasing the risk of physical stress on trees (Shi et al., 2023; Torres et al., 2017). Ensuring the long-term health of urban greenery requires appropriate site selection, soil improvement measures, and routine maintenance to mitigate these challenges.

1.4. Aim and research questions

To address the limitations of previous studies on the effective distribution of trees and grass at the neighbourhood level, as well as the lack of consideration for practical factors, this research aims to develop street greening design guidelines that translate urban climate evidence into implementable street designs that fit realities at the neighbourhood scale.

The study focuses on European neighbourhoods with temperate climate, where heatwaves have intensified and record-breaking temperatures above 40 °C have been observed in recent years (Beck et al., 2018; Rousi et al., 2022; Witze, 2022). Using European neighbourhoods with temperate climate as case examples, these guidelines integrate empirical simulation findings with input from practitioners to ensure both effectiveness and real-world applicability. Specifically, two sub-research questions were addressed:

- 1) What are the street greening scenarios for cooling neighbourhoods, and how can these scenarios be improved integrating practical design considerations?
- 2) How do the improved design scenarios affect the thermal sensation performance of the neighbourhood?

2. Methods

This study used the RTD approach with an iterative design process that combines qualitative designer feedback and quantitative thermal

comfort simulations to evaluate street tree and grass distribution. Two main steps were conducted (Fig. 1). In Step 1, focus group workshops were conducted with practitioners to evaluate aspects of visual experience, functionality, cost and maintenance of several cooling design scenarios. The design scenarios were then further improved based on their assessments. In Step 2, ENVI-met simulations were conducted for the new scenarios to ensure that their cooling effects had not been compromised by the practitioners' decisions. The final design guidelines were then developed from the results of these simulations.

2.1. RTD Step 1: selection and refinement of design scenarios

2.1.1. Selection of design scenarios

Developing guidelines requires connected steps from identifying relevant neighbourhood typologies to testing greening scenarios and translating the results into implementable design guidance. This study builds on two preceding steps in this process. First, four neighbourhood typologies representing heat-prone compact mid-rise areas in temperate European cities were developed from 656 heat-prone neighbourhoods, based on combinations of street orientation, street height-to-width ratio, block shape, and block floor area ratio (Wu et al., 2022). Second, eight preliminary greening scenarios (S1–S8) with varying configurations of street trees and grass were generated for these typologies and thermally ranked through ENVI-met simulations using PET reduction, percentage change in thermal sensation class, and cooling efficiency (Wu et al., 2025).

Building on these steps, the present study focuses on translating the initially high-performing greening scenarios into practical design guidelines by converting them into street-scale design profiles, refining them through practitioner assessment, re-simulating the revised neighbourhood scenarios, and formulating morphology-specific greening recommendations. The preliminary S0–S8 scenarios used for selection in this study are identical to those in Wu et al. (2025), and are used here as the starting point for selecting the initially best-performing street-tree and grass configurations.

To improve the design of the most effective greening scenarios, the two highest-ranked scenarios for each neighbourhood typology were selected for further assessment in this research (Fig. 2). In T1, the most effective scenarios are S3 and S1. In T2 and T3, S3 and S4 were identified as the best-performing scenarios. In T4, S3 ranked highest, followed by S4. Grass was not considered a sole greening strategy in the new streetscape designs due to its limited daytime cooling capacity and high

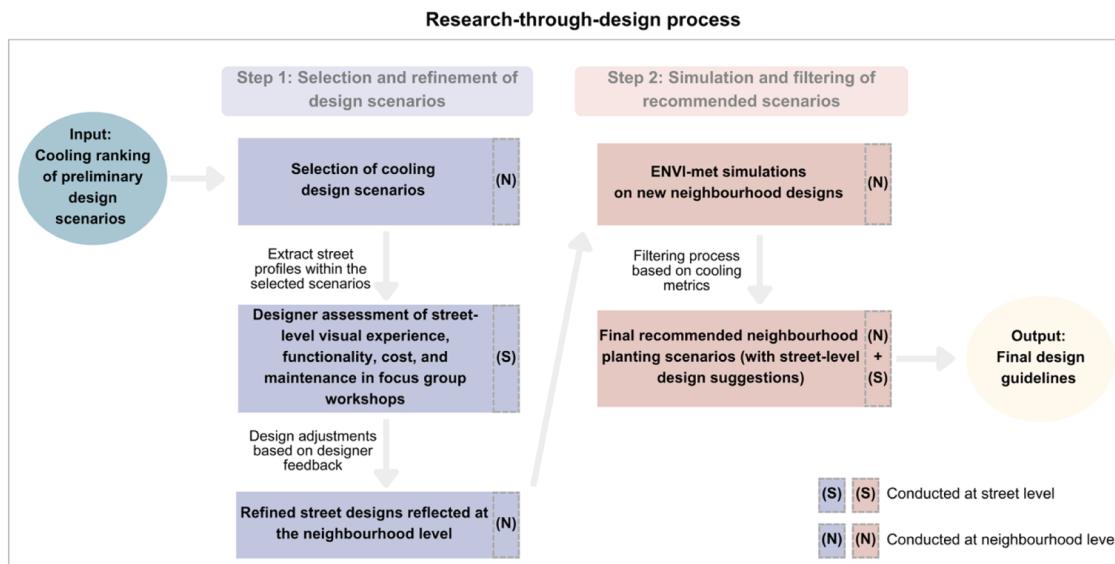


Fig. 1. Methodological flowchart.

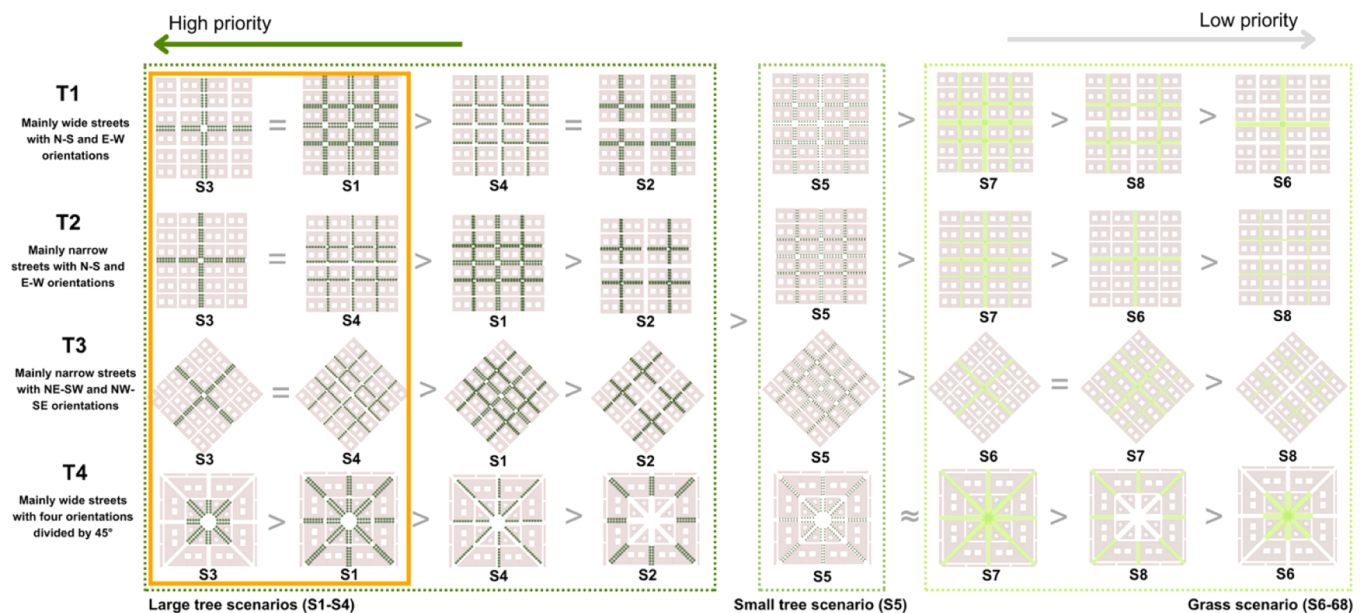


Fig. 2. Cooling effectiveness ranking of the preliminary greening scenarios from Wu (2025). The two initially best-performing scenarios for each neighbourhood typology are highlighted in the orange box.

maintenance demands in resource-limited areas (Ligtermoet et al., 2022; Wu et al., 2025). Nonetheless, studies have highlighted its thermal benefits during nighttime (Aboelata & Sodoudi, 2019; Fu, 2022) and in winter (Zhang et al., 2024). Therefore, grass was included only as a supplementary element in the new designs.

2.1.2. Refinement of design scenarios

2.1.2.1. Designer assessment form. The top two neighbourhood-scale greening scenarios identified above were converted into street-scale designs to ensure their relevance to typical urban design projects aligning with the most common scale of urban design projects, since design practitioners typically operate at the street scale within neighbourhoods. The three street widths were derived from prior typology research. In [Wu et al. \(2022\)](#), street width and street-canyon height were

calculated from empirical street and building data in 656 heat-prone neighbourhoods, and the resulting H/W values were grouped into three categories. In the generic typology models, these categories were represented by 24 m, 16 m, and 8 m street profiles, using a 20 m building height to represent compact mid-rise neighbourhoods. Detailed typology parameters are reported in [Wu et al. \(2025\)](#).

Distinct street profiles were developed for the assessment, reflecting varying greening types and configurations from the most effective scenarios identified in [Wu et al. \(2025\)](#). Within the top two effective scenarios, the following were the street profiles that practitioners were invited to assess for the practical considerations: two rows of large trees in 24 m, 16 m, 8 m streets; one row of large trees in 16 m and 8 m streets. Among the grass scenarios, covering the 24 m, 16 m, and 8 m streets with grass were tested as well. A pilot test of the assessment form was done with two landscape architects and one urban designer with project experience in Amsterdam, London, and Paris, all cities from where the

(a)

Two rows in 24m-width street

To what extent do you agree with the following statements about the green infrastructure?

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
They are aesthetically pleasant, considering:				☒	☐
Openness in the street	☐	☐	☐	☒	☐
Visibility from home	☐	☐	☐	☒	☐
They are compatible with other infrastructure, including:					
Vehicle	☐	☒	☐	☐	☐
Cycling	☐	☒	☐	☐	☐
Walking	☐	☐	☐	☒	☐
They are costly			☒	☐	☐
They are easy to maintain	☐	☐	☒	☐	☐

Suggestions for improvement?

- Good coverage over pedestrian and cyclist paths, but trees planted unsuitable.
- Good for both sides of the street to lower tree canopy views.
- Tree height too low for better view of road.
- Trees too close to buildings and cars parked along the side of the road.
- Reduce a little bit more of all trees, especially those close to the road.
- Less planting of trees by the houses.

Other aspects for improvement?

- Green zone needs to be suitable for the street width.

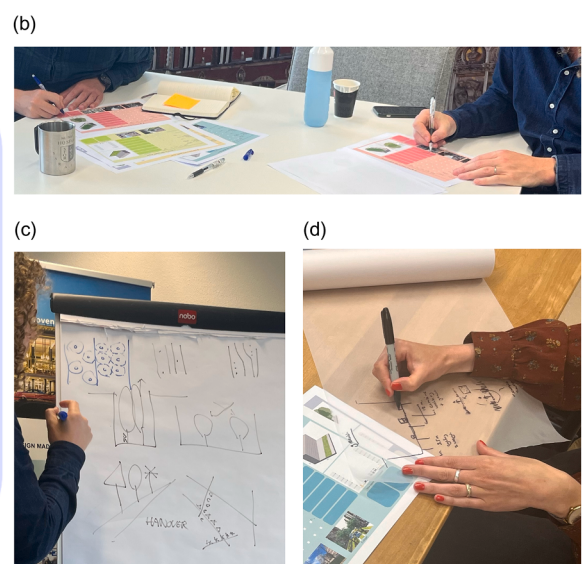


Fig. 3. Example assessment form showing two-row tree distribution on a 24 m-wide street (a). Designers completed the forms during the workshop (b) and explained suggestions using sketches (c, d).

neighbourhood typologies of Wu et al. (2022) were derived.

The final version of the assessment form (Fig. 3 as an example for two rows in 24 m streets) was divided into four parts. The four parameters visual experience, functionality, cost, and maintenance of the scenarios were assessed using statements: *"They are aesthetically pleasant, considering 1) Openness in the street; 2) Visibility from home. They are compatible with other infrastructure, including 1) vehicle, 2) cycling, 3) walking. They are costly. They are easy to maintain."* The four criteria were selected based on the applicability framework introduced in Section 1.3 and previous RTD climate-responsive design research (Cortês et al., 2020). Since thermal performance was assessed separately through ENVI-met simulations, the practitioner assessment focused on non-thermal applicability criteria: visual experience, functionality, cost, and maintenance. These criteria were used to evaluate whether initially cooling-effective scenarios could also be integrated into urban design practice. Designers responded to each statement using a 5-point Likert scale, from *strongly disagree* to *strongly agree*, and could add comments for improvement. Each form included a visual representation of street conditions, showing variations in street width (8 m, 16 m, 24 m), with a fixed building height of 20 m. Tree spacing, lane allocation, and reference images from Google Street View were included to support the evaluation. A final comment box allowed for additional suggestions. The assessment forms for all eight street profiles are included in Fig. S1.

2.1.2.2. Workshops with designers. Focus group workshops were organised to engage practitioners in evaluating each street profile based on practical factors related to visual experience, functionality, cost, and maintenance. The workshops also aimed to gather recommendations for improving the designs. The workshops followed an expert-based RTD format, in which professional judgement was used to support design refinement. This format is consistent with related RTD studies. For example, Cortês et al. (2020) involved eight experts from urban design and landscape architecture offices, consultancies, and municipalities in design workshops for prototype evaluation and design refinement feedback. Similarly, Lotfata et al. (2024) used seven experts in the fields of climate adaptive design, urban climate, land use planning, equity, urban finance, mobility, and architecture in RTD prototype assessment and subsequent refinement discussions.

Practitioners were recruited using the purposive sampling method. The workshops were intended to gather professional judgement for design refinement rather than statistically representative practitioner preferences. Participants were selected based on three criteria: (1) professional background in landscape architecture and/or urban design; (2) experience with urban climate adaptation or urban greening projects; and (3) practical project experience in Amsterdam, London, and/or Paris, which are the urban contexts from which the neighbourhood typologies were derived. Six practitioners participated in the workshops, including four landscape architects and two urban designers based in the Netherlands and the UK, all with project experience in Amsterdam, London, and Paris.

The workshops were conducted between May and June 2023 and were organised into three smaller subgroup sessions according to the practitioners' locations to facilitate scheduling and participation. Each practitioner attended one workshop only, and the three workshops together involved six distinct participants. To ensure consistency across the sessions, all workshops followed the same structure, used the same assessment forms and design materials, and applied the same evaluation criteria. Each workshop lasted approximately 1.5 h, which began with an introduction outlining the relationship between street profiles, heat-prone neighbourhood typologies, and the corresponding planting strategies. Participants then completed the assessment form and further elaborated on their evaluations through sketches (Fig. 3).

2.1.2.3. Scenario refinement following designer assessments. The scenario refinement process translated practitioner assessments into spatial

design revisions. The Likert-scale results were first summarised as percentages for each of the five response categories, ranging from "strongly disagree" to "strongly agree". Given the small expert sample and the RTD purpose of the workshops, the Likert-scale assessment was used as a structured way to collect practitioners' initial views, rather than as a basis for statistical inference. These results were used to identify general tendencies and differences in practitioners' views.

Then, written comments and sketches were used to interpret the reasoning behind the ratings and to identify design concerns and possible improvements. The written comments from the assessment forms were transcribed and grouped according to the four evaluation criteria: visual experience, functionality, cost, and maintenance. Similar suggestions within the same criterion were synthesised and merged, while different opinions were incorporated into the revised designs where spatially feasible, rather than prioritising only one view.

This was followed by identifying feedback with clear spatial implications, such as tree size, planting layout, mobility space, maintenance feasibility, or sun exposure. Such feedback was incorporated into the revised designs. Practitioners' sketches were analysed alongside the written feedback to support the spatial interpretation of these revisions.

Finally, revised design options were developed for each street width based on this combined review. These updated street profiles were then integrated into neighbourhood-scale layouts. For each neighbourhood typology, a set of new planting scenarios was created by inserting the refined street-level designs into the corresponding street widths within the neighbourhood structure.

2.2. RTD Step 2: thermal sensation simulation for the improved scenarios

Step 2 quantified the cooling effect value of the new design scenarios. ENVI-met V5 was used as the simulation tool. Its capacity to accurately represent thermal dynamics in urban settings has been thoroughly validated in cities like Amsterdam, London, and Paris, particularly concerning the impact of vegetation, streets, and buildings on local microclimates (Guo et al., 2019; Kleerekoper et al., 2015). A representative heatwave weather profile was selected because the study aims to evaluate greening strategies during periods when outdoor cooling is most needed. Meteorological data from De Bilt, London, and Paris for 2002–2021 were used to identify observed heatwave days with maximum daily temperature above 30 °C. The hourly meteorological conditions from these heatwave days were then averaged to construct a representative heatwave-day profile for the ENVI-met simulations. The wind rose, air temperature, and relative humidity profiles are provided in Fig. S3. The complete ENVI-met simulation inputs are available in Table S1.

To analyse cooling performance, both the metrics cooling capacity and cooling efficiency were used (Wu et al., 2025). Cooling capacity refers to the absolute cooling effect of a greening scenario compared with the no-greening reference case, while cooling efficiency refers to the cooling benefit achieved per unit of green coverage. This distinction allows scenarios that maximise total cooling to be compared with those that use greening resources more efficiently. Cooling capacity was assessed using mean PET reduction and the percentage change in thermal sensation class. PET reduction was calculated as the average PET difference between each greening scenario and the no-greening reference case. Changes in thermal sensation class were assessed by comparing the percentage of neighbourhood area classified as Warm (<35 °C), Hot (35–41 °C), and Very Hot (≥41 °C). Cooling efficiency was evaluated using two indicators: *eff_delta*, the ratio of PET reduction to green coverage, and *eff_pct*, the ratio of the percentage decrease in Very Hot areas to green coverage.

2.3. Generating the design guidelines

To generate the final guidelines, we calculated the cooling effect of each new design scenario using PET reduction, difference in thermal

sensation class, and cooling efficiency. For each metric, scenarios were ranked within each typology, and scores were assigned accordingly. Scenarios with higher ranks received higher scores. The overall ranking (Final_rank) for each scenario was then determined by summing its scores (Sum_score) across all metrics. Guidelines were generated by providing detailed descriptions of the highest-ranking scenarios for each neighbourhood typology, and their spatial arrangements of greenery, including tree size, canopy coverage, grass coverage and distribution. The guidelines also included specific recommendations from the practitioners and illustrated the updated designs, showcasing their applicability to various functional contexts.

3. Results and discussion

Sections 3.1–3.3 present and discuss findings related to research question 1, including designer assessments, street design revisions, and new neighbourhood scenarios. Section 3.4 addresses research question 2 by analysing and interpreting the thermal performance of the new neighbourhood scenarios. Section 3.5 presents the resulting design guidelines, followed by Sections 3.6 and 3.7, which discuss the novelty of this research and directions for future study.

3.1. Designer's assessment by street type and criteria

This section presents designers' feedback on various street planting strategies. The Likert-scale results were used to identify general tendencies (Fig. S2), while written comments, sketches, and workshop discussions were used to explain the reasoning behind these responses and identify spatial refinement suggestions for each street profile. Street profiles of 24 m, 16 m, and 8 m were evaluated across scenarios involving two rows, one row of trees, or grass-covered streets. Practitioner feedback is summarised in Table 1, with full details in Table S2. Within this synthesis, cost refers to practitioners' comparative judgement of the relative implementation burden of each design option.

3.2. Street-level design revisions based on feedback

Revised street greening strategies were developed to address designers' concerns about visual experience, functionality, cost, and maintenance. Some changes reflected direct workshop suggestions (e.g. tree height, crown size, planting layout), while others responded to recurring issues across criteria to retain valued aspects of the original schemes while enhancing practical feasibility. Table 2 presents the initial and revised options for each street type. Option 1 proposes extensive greening where feasible; Options 2 and 3 address space or resource constraints.

Design decisions prioritised spatial feasibility. Suggestions that conflicted with core movement functions or offered marginal benefits in narrow configurations were not retained. For example, a grass median between pedestrian and cycling paths was proposed but excluded, as its cooling and visual contributions were considered minimal in limited-width applications (Lobaccaro & Acero, 2015). Other feedback related to non-spatial elements, such as paving materials or surface texture, was recorded and incorporated into final design guidelines (Section 3.5).

Revisions for 24m streets: dense high-canopy trees were retained, as designers found them effective for maintaining openness and providing shade. Option 1 (Table 2) keeps two rows of large trees and 20 m width of grass, with 4 m width of hardscape for pedestrians and cyclists. This option responds to the divergent views on grass by retaining substantial grass-covered areas for ecological and visual benefits while maintaining hardscape pedestrian and cycling paths for functional accessibility. Suggested features like a grass strip between pedestrian and cycle lanes were excluded because their additional visual and cooling value was considered limited relative to the added maintenance and spatial complexity. Option 2 keeps the original large trees and placement.

Table 1

Synthesised practitioners' feedback on street-level greening options across the four evaluation criteria.

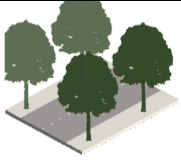
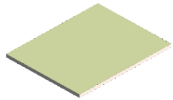
Criteria	Option	24 m street	16 m street	8 m street
Visual experience	Two-row trees	High canopies created 'green tunnel effect'; require foliage management to avoid obstruction	Crowns too large relative to width	Somewhat full but not overwhelming
	One-row trees	–	More balanced and visually fitting.	Preferred in narrow streets, especially with building shade.
	Grass	Added openness but lacked vertical depth, appeared flat	Greener due to narrow scale, but still lacked vertical depth	Strongest visual impact but still lacked vertical depth
Functionality	Two-row trees	Compatible with pedestrians/cycling, but required reducing car lanes	Hindered car movement; walking/cycling prioritized; cycling lanes essential	Caused congestion in limited space
	One-row trees	–	Better balance for width	Reduced congestion, more suitable
	Grass	Low vehicle/cycling compatibility when wet; some saw ecological corridor potential	Unsuitable for heavy traffic; walking paths lacked durability	Impractical for vehicles, slippery for cycling when wet
Cost	Two-row trees	Acceptable long-term investment with ecological/visual benefits	Justified as long-term value	Additional green infrastructure costs
	One-row trees	–	Reasonable long-term value	Lower additional cost than two-row
	Grass	Costly, limited multifunctional value	Costly, low resilience under frequent use	Costs difficult to justify given existing pavement/sewage investment
Maintenance	Two-row trees	Pruning manageable	More difficult with limited sunlight	–
	One-row trees	–	Manageable	Easier than grass
	Grass	Demanding: mowing, irrigation, access harder with large areas	More effort due to light sensitivity and wear	Hard to maintain with low sunlight and intensive use

Revisions for 16m streets: feedback noted that tree crowns were oversized relative to street width. Revised options use medium-sized trees (16 m height, 8 m crown). In Option 1, trees are arranged in two rows, with grass added only on the sunlit side due to concerns over shaded maintenance. Hardscape zones remain for pedestrians and cyclists. Option 2 applies a staggered layout to improve space efficiency and accommodate cycling and parking. Option 3 offers a simplified one-row tree without grass, suitable for narrow or resource-limited streets. Trees are placed on the sunlit side—north for E–W streets, east for N–S, northeast for NW–SE, and northwest for NE–SW.

Revisions for 8m streets: due to limited space, 8 m street designs were simplified. Designers raised concerns about mobility conflicts and maintenance. Tree size was reduced to small canopies, with only one-row layouts retained where space and sunlight permit. In Option 1, a

Table 2

Visual representation of street-level planting strategies for 24 m, 16 m, and 8m-wide streets.

Street width	Preliminary models and design options for each street width					
24m	Preliminary tree-based model	Preliminary grass-based model	Design option 1: mixed greening	Design option 2: high canopy trees		
24m						
16m	Preliminary two-row tree-based model	Preliminary one-row tree-based model	Preliminary grass-based model	Design option 1: mixed greening with medium trees	Design option 2: two rows of medium trees, staggered or parallel	Design option 3: one-row medium trees
16m						
8m	Preliminary two-row tree-based model	Preliminary one-row tree-based model	Preliminary grass-based model	Design option 1: one-row small trees		
8m						

single row of small trees is placed on the sunlit side. Grass was excluded as unsuitable for vehicles or cyclists and difficult to maintain under high-traffic conditions.

3.3. New neighbourhood design scenarios

Building on the revised street typologies from Section 3.2, a set of neighbourhood-scale greening scenarios was developed to test cooling performance. Each scenario integrates different combinations of 24 m, 16 m, and 8 m street designs based on the spatial layout presented in Section 2.1.2. For the four typologies (T1–T4) composed of different street compositions, each of them includes multiple design scenarios

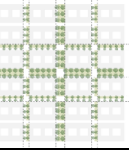
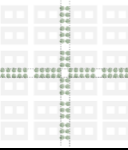
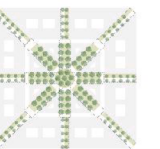
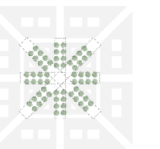
(NS1–NS4) with varying greening designs. Table 3 summarises the neighbourhood designs used for ENVI-met simulations.

For T1, NS1 includes two rows of large trees with 20 m-wide grass on the east and north sides of 24 m streets (Option 1); two rows of medium trees with 8 m grass in 16 m (Option 1), resulting in the highest green coverage. NS2 retains two rows of large trees but removes grass from 24 m streets (Option 2) to improve feasibility and reduce maintenance.

For T2, NS1 includes two rows of medium trees and grass on the east and north sides of 16 m streets (Option 1) and one row of small trees in 8 m streets (Option 1). NS2 only keeps two rows of medium trees in 16 m streets (Option 2). NS3 simplifies NS1 to one row of trees in 16 m streets (Option 3) and 8 m streets (Option 1). NS4 includes a two-row tree

Table 3

New simulation models at the neighbourhood level with planting descriptions for each design scenario.

Scenario	T1-NS1	T1-NS2	T2-NS1	T2-NS2	T2-NS3	T2-NS4
Model visualisation						
Scenario	T3-NS1	T3-NS2	T3-NS3	T4-NS1	T4-NS2	
Model visualisation						

layout in 16 m streets to enhance space utilisation while retaining greenery (Option 2).

For T3, NS1 includes two rows of medium trees and 8 m grass on the sunlit northwest and northeast sides of 16 m streets (Option 1); one row of small trees in 8 m streets placed for sun exposure (Option 3). NS2 includes two rows of medium trees in 16 m streets (Option 2). NS3

applies one-row layouts: medium trees in 16 m (Option 3) and small trees in 8 m streets (Option 1), both on sunlit sides.

For T4, NS1 includes two rows of large trees with 20 m-wide grass in 24 m streets (Option 1), two rows of medium trees with 8 m grass in 16 m streets (Option 1), and a 40 m diameter green roundabout at the main crossing. NS2 simplifies to only two rows of large trees in 24 m streets

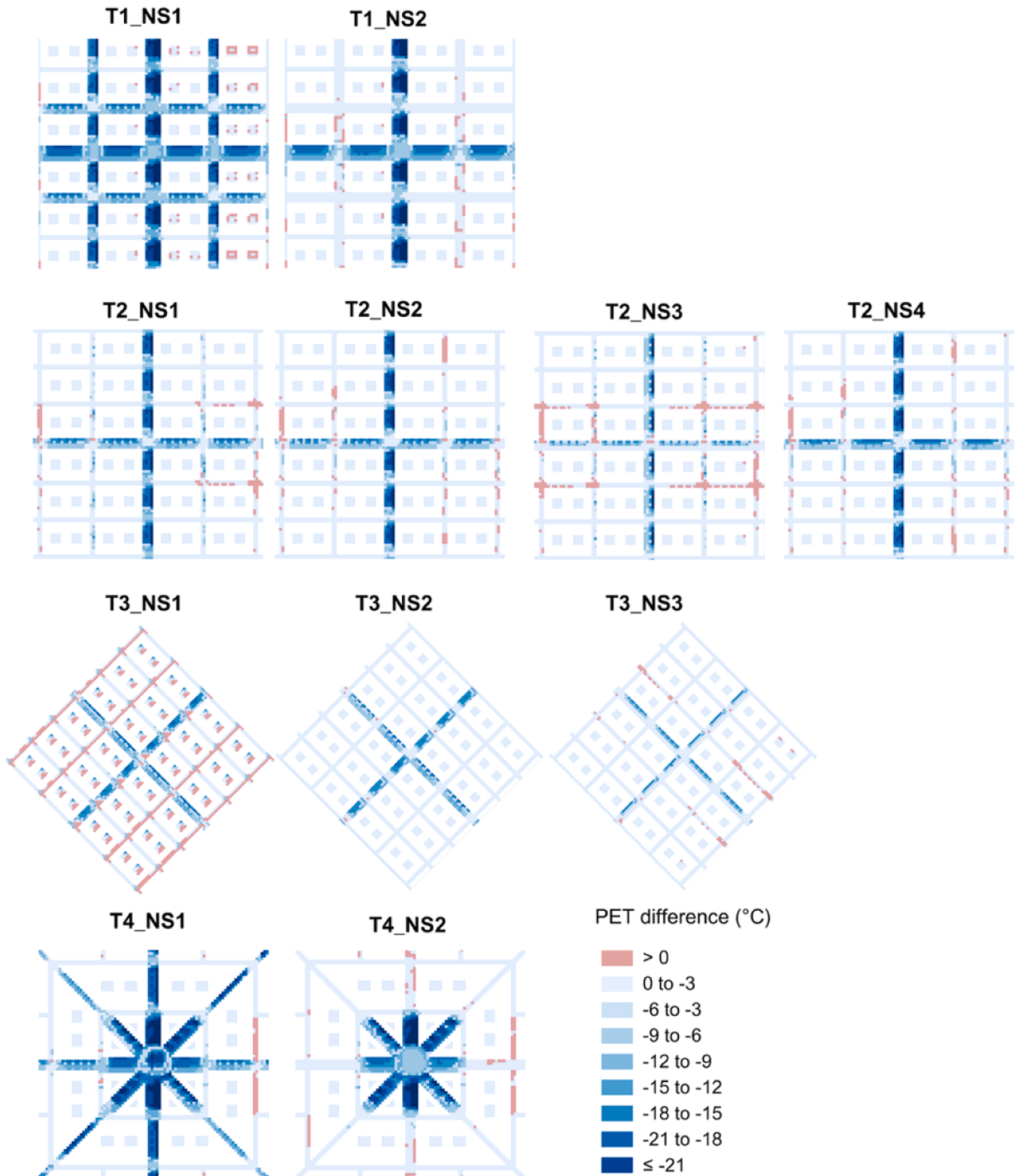


Fig. 4. PET difference map of each scenario for the period of 13:00–15:00 from ENVI-met simulations.

(Option 2), removing additional greening to prioritise implementation.

3.4. Thermal sensation performance of new designs

ENVI-met simulations were conducted to evaluate the thermal performance of the proposed neighbourhood scenarios. PET values were calculated at each grid point and compared to a no-greening reference. Cooling performance metrics were assessed to inform scenario selection, including cooling capacity (mean PET reduction, percentage change in thermal sensation class), and cooling efficiency.

3.4.1. Cooling capacity

The PET difference map presents the PET spatial performances of each scenario (Fig. 4). PET difference was observed at each map point compared to the no-greening scenario across typologies. The PET reduction results show scenarios have a varied impact on the reduction of overall mean PET for each neighbourhood (Fig. 5b). The results are presented per neighbourhood typology. Detailed simulation results, including means, standard deviations, and 95% confidence intervals, are provided in Table S3, and results of the ANOVA and Tukey's HSD post-hoc tests are presented in Table S4. The Tukey grouping letters in Fig. 5b indicate significant differences among scenarios within each typology.

For T1, NS1 achieves an overall cooling effect of 7.89 °C. NS2, which excludes grass and places trees only on the sun-exposed side of secondary streets, achieves a PET reduction of 3.85 °C.

For T2, NS1 results in a PET reduction of 2.71 °C. NS4's staggered

tree layout is 0.08 °C cooler than the parallel pattern, and post-hoc testing indicates that the difference is not statistically significant. Such marginal thermal differences fall within the uncertainty range of microclimate modelling and can be interpreted as thermally equivalent, with design feasibility becoming the distinguishing factor. NS3, with one row of trees on the high-radiation side, achieves a PET reduction of 1.55 °C.

In T3, NS2 shows the greatest mean PET reduction at 1.79 °C, driven by locations with significant cooling. NS1, with a mean reduction of 1.33 °C, yields more widespread but moderate cooling. This highlights that tree-grass interventions do not always result in the most cooling, even though many studies suggest otherwise (Bartasaghi-Koc et al., 2020; Fu, 2022; Lobaccaro & Acero, 2015). T2-NS1 includes more green coverage than other T2 scenarios and achieves the highest PET reduction in that typology. In contrast, T3-NS1, despite also having more green coverage than T3-NS2, results in lower PET reduction. As T2-NS1 and T3-NS1 apply the same strategy, the difference can be attributed to morphological context. This shows that combining trees and grass does not always yield additive cooling, underscoring the influence of layout.

For T4, NS1, which includes 24 m streets mostly covered with grass, two rows of trees on main and secondary streets, and a green roundabout, achieves a PET reduction of 7.3 °C. NS2, with two rows of trees on main streets only, results in 4.23 °C cooling.

The percentage change in thermal sensation class corresponds closely to the PET reduction results (Fig. 5a). For all typologies, the ranking is consistent with the PET reduction findings. T1-NS1

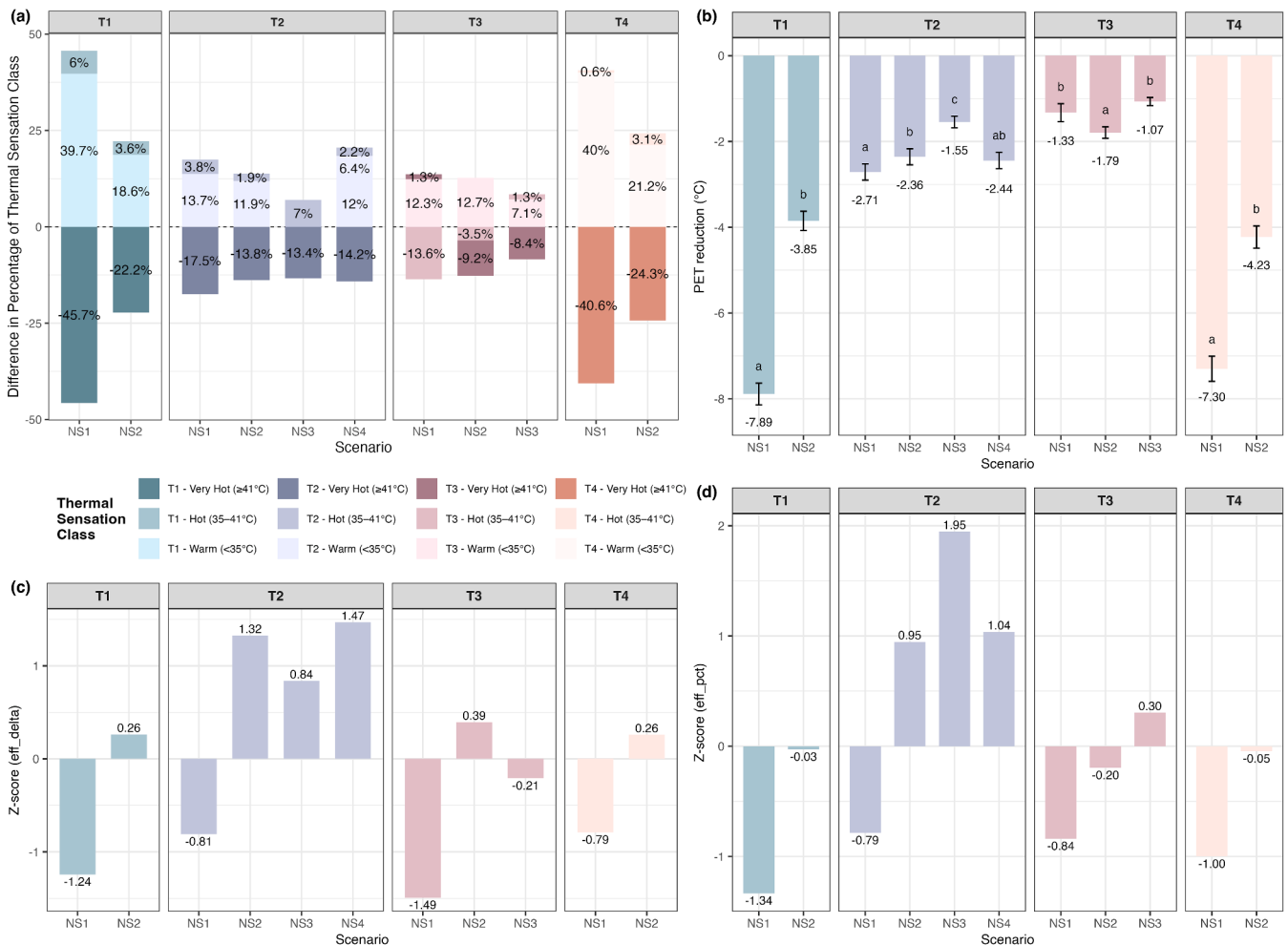


Fig. 5. Thermal performance comparing scenarios in each typology at the neighbourhood scale, including Percentage change in thermal sensation class (a); Mean PET reduction (b); cooling efficiency regarding PET reduction per green cover (c) and regarding Thermal sensation class change per green cover (d).

demonstrates the most significant reduction in the 'Very Hot' category, with 45.7% of areas shifting to the 'Hot' or 'Warm' classes, followed by T1-NS2 at 22.2%. For T2, NS1 shows a 17.5% decrease in 'Very Hot' areas, followed by NS4 at 14.2%. In T3, NS2 remains the most effective cooling scenario due to its substantial reduction in cooler areas (12.7%). Meanwhile, NS1 sees 13.6% of 'Hot' areas transition, but also experiences a slight increase (1.3%) in 'Very Hot' areas, therefore the overall cooler area is 11%. T4-NS1 also achieves a notable reduction of 40.6% in the 'Very Hot' category, whereas NS2 shows a more modest decrease at 24.3%.

3.4.2. Cooling efficiency

In terms of cooling efficiency, we applied two metrics proposed by Wu et al. (2025): the ratio between PET reduction and green coverage (Fig. 5c), and the ratio between thermal sensation class change and green coverage (Fig. 5d). In this study, both metrics were further standardised using z-scores to enable cross-scenario comparison.

Based on these metrics, scenarios with grass (Tx-NS1) generally exhibit lower efficiency compared to tree-only scenarios. For T1, NS2 is

much more efficient than NS1, indicating that planting trees on both sides of main wide streets can maximise cooling benefits per unit of green coverage. For T2, the difference between NS1 and NS2 is less pronounced. T2-NS1 achieves the highest cooling efficiency among all tree-grass scenarios, while T2-NS4 demonstrates the highest cooling efficiency across all scenarios, suggesting this typology's suitability for planting strategies focused on high cooling efficiency.

For T3, NS1 performs the worst in terms of cooling efficiency across all the scenarios in different typologies. Additionally, its PET reduction and thermal sensation class changes, as shown in Fig. 5a and b, are comparable to other scenarios, leading to the decision to exclude NS1 from the final guidelines.

For T4, the grass-inclusive scenario is less efficient than planting two rows of trees solely on main streets. However, it has a higher efficiency than in T1, reflecting improved performance when trees and grass are planted in the sun-exposed roundabout area.

GUIDELINES FOR T1

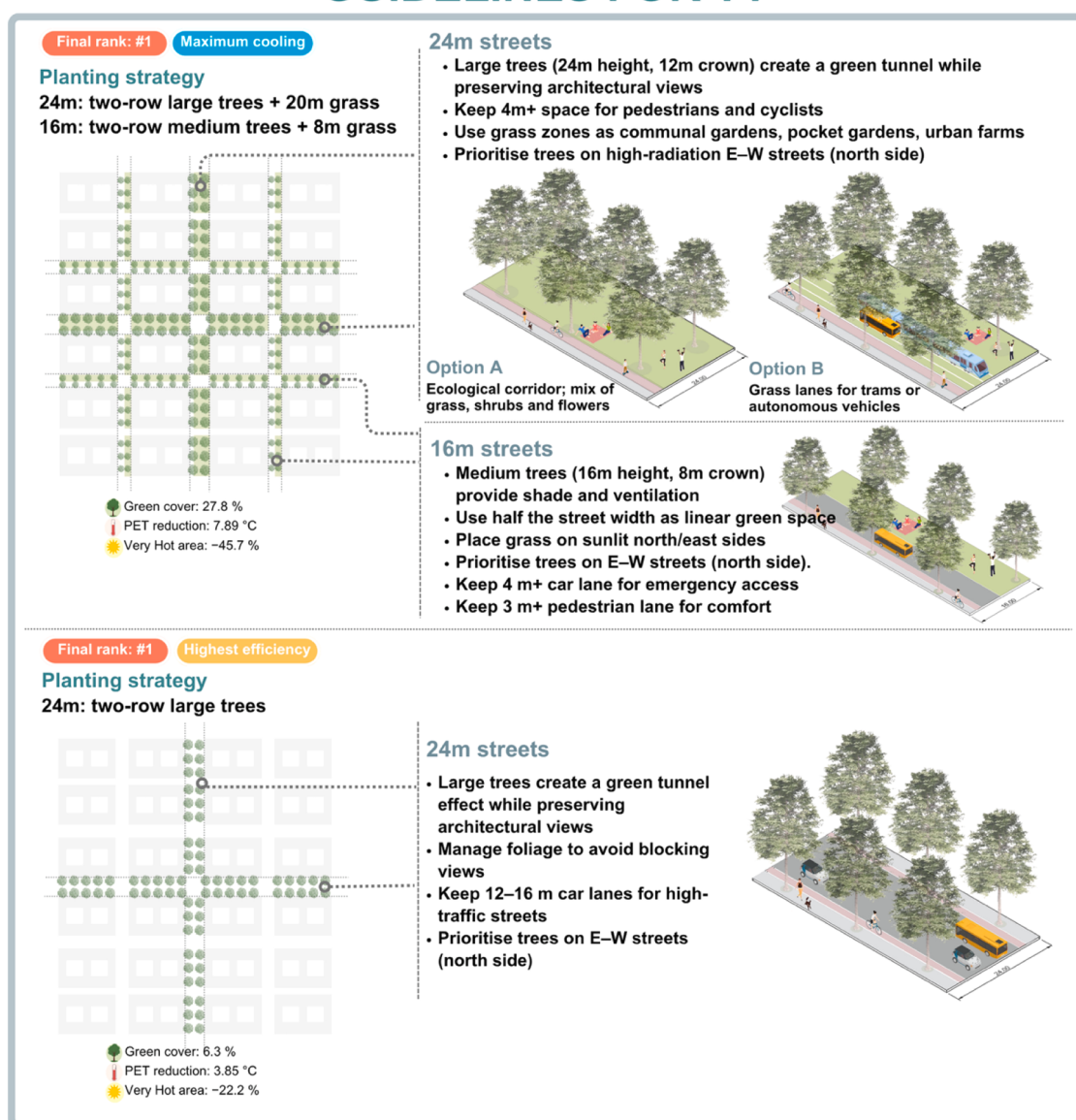


Fig. 6. Final design guidelines for T1-Mainly wide streets with N-S and E-W orientations.

3.5. Design guidelines

Based on the simulation results, we developed guidelines to assist practitioners in the spatial design of street trees and grass within neighbourhoods (Figs. 6–9). The guidelines include the green coverage (canopy and grass cover within the neighbourhood), detailed design descriptions for each scenario and specific recommendations synthesised from practitioners' feedback.

Table 4 presents the process of selecting final design scenarios based on cooling capacity (PET reduction and thermal sensation change) and cooling efficiency. The detailed scoring system can be found in Table S5. The decision-making process led to the scenarios being categorised into three groups: "Maximum cooling", "Highest efficiency", or "Discarded", ensuring that only the best-performing designs were included in the final guidelines. The "Maximum cooling" scenarios were those that demonstrated the highest PET reduction potential, while the "Highest efficiency" ones provided an optimal balance between cooling and other considerations such as cost and maintenance. Scenarios marked without selection under "Maximum cooling" or "Highest efficiency" were not

included in the final guidelines.

The final design guidelines are presented below for each typology, based on the scenarios selected through the evaluation process described in Table 4. For each typology, two recommended strategies are shown: one prioritising maximum cooling, and one prioritising cooling efficiency under resource constraints. The guidelines are illustrated to highlight the key planting strategies in different street configurations and expected cooling outcomes. All recommendations are informed by the simulation results and practitioner feedback discussed in Sections 3.1 to 3.4 to support practical decision-making in neighbourhood greening. These guidelines provide morphology-based reference strategies for heat-prone compact mid-rise neighbourhoods in temperate western European contexts. They are most applicable where street-width structures, street orientations, and height-to-width ratios are comparable to the typologies used in this study.

GUIDELINES FOR T2

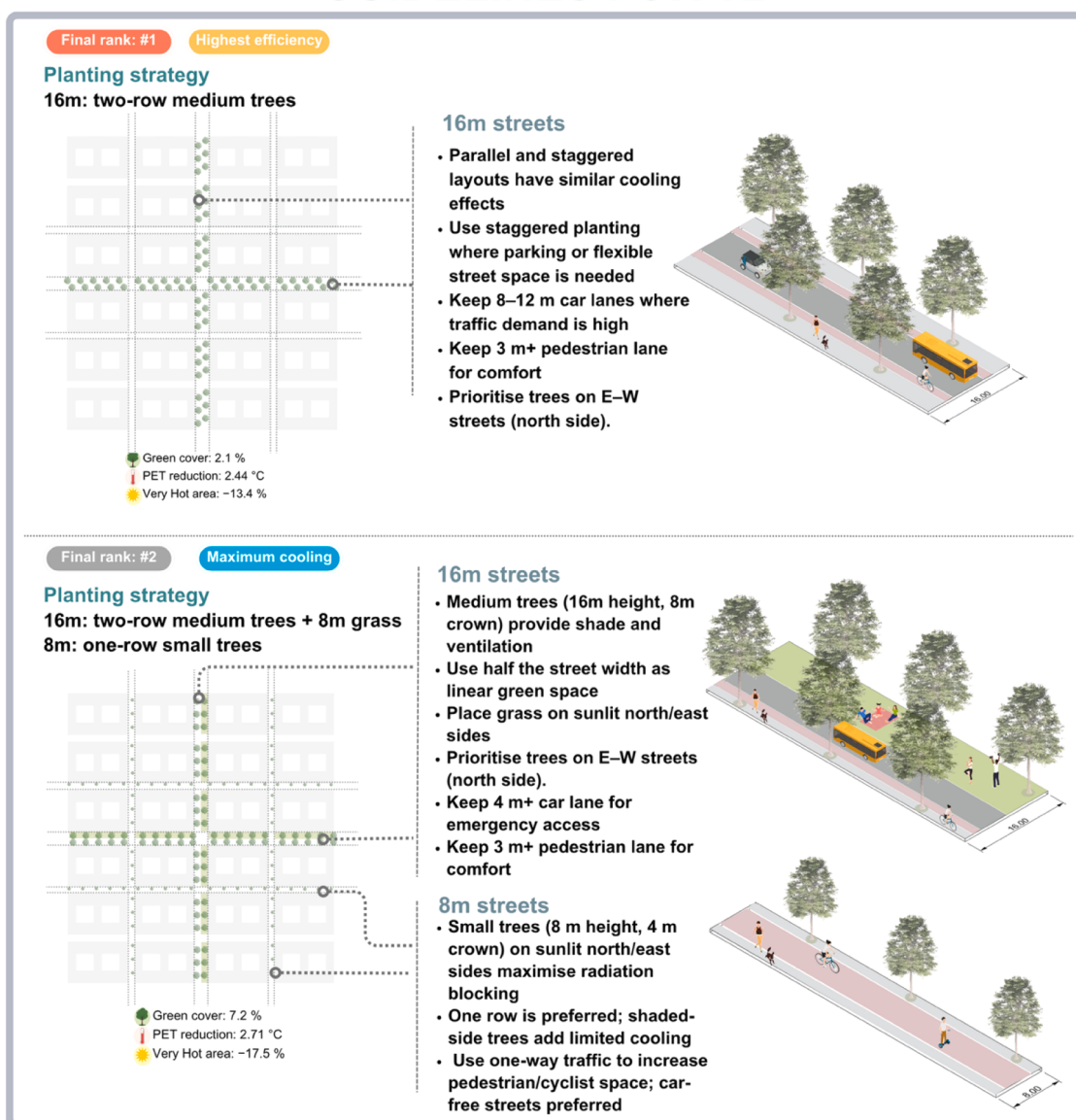


Fig. 7. Final design guidelines for T2-Mainly narrow streets with N-S and E-W orientations.

GUIDELINES FOR T3

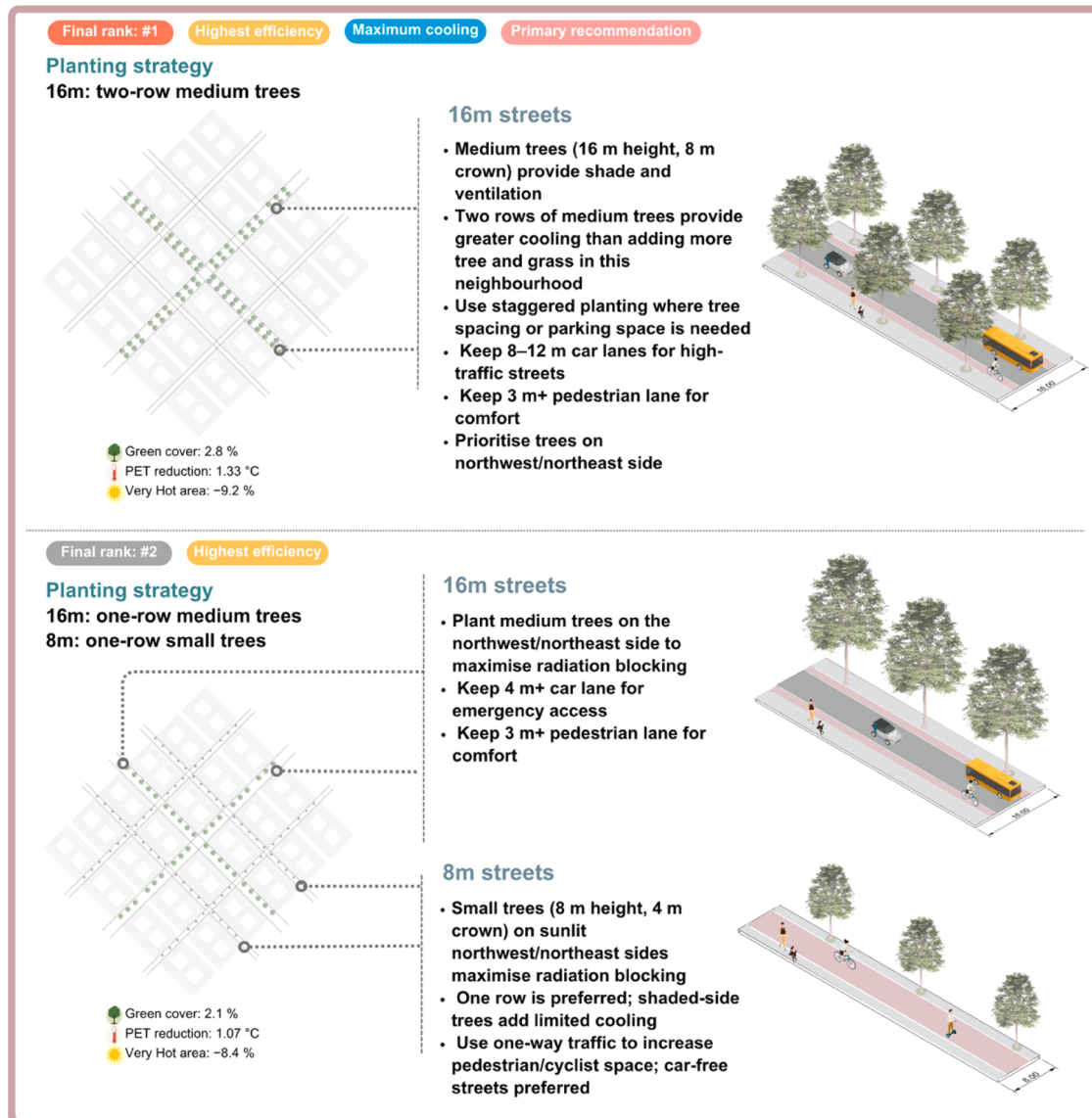


Fig. 8. Final design guidelines for T3-Mainly narrow streets with NE-SW and NW-SE orientations.

3.6. Contributions and implications

3.6.1. Contribution to urban greening and cooling knowledge

This research addresses a critical gap in urban greening and climate adaptation literature: the lack of neighbourhood-scale greening guidelines that specify street-level planting strategies while integrating climatic performance and practical considerations. While previous ENVI-met and greening studies have provided evidence on how vegetation amount, canopy coverage, grass coverage, urban density, and cooling efficiency influence thermal performance (Ouyang et al., 2020; Ziter et al., 2019; Yang et al., 2020; Ouyang et al., 2023), this study moves beyond coverage-ratio optimisation by identifying how greening resources can be prioritised across neighbourhoods with different street widths, orientations, and practical applicability constraints. The practitioner-refined scenarios specify tree size, planting rows, grass placement, hardscape mobility space, and prioritised street types within each neighbourhood typology.

This research further challenges the assumption that increasing greening amount always results in greater cooling. While some studies recommend tree-grass combinations as effective strategies (Xi et al.,

2023; Lobaccaro & Acero, 2015), this study revealed a “1 + 1 < 2” effect in T3. The practitioner-refined scenario increased both tree canopy and grass cover, but produced lower PET reduction than the tree-only layout: 1.33 °C for T3-NS1 compared with 1.79 °C for T3-NS2. This suggests that additional greening, even when combining more canopy and grass surfaces, does not automatically generate additive cooling benefits. Instead, the cooling effect depends on how greening is spatially configured within a given neighbourhood morphology.

3.6.2. Methodological advancement through RTD

The methodological contribution lies in adapting an RTD-informed approach to neighbourhood-scale street-tree and grass prioritisation. This study starts from previously thermally ranked greening scenarios, translates the best-performing scenarios into street-scale design profiles, refines them with practitioners, and then re-simulates the revised neighbourhood scenarios. Modelling is therefore treated as decision support within a design-led, practitioner-engaged process, rather than as an end in itself. Instead of relying only on researcher-defined simulation scenarios, this study engages urban designers and landscape architects through focus group workshops (Ramakreshnan et al., 2019), using their

GUIDELINES FOR T4

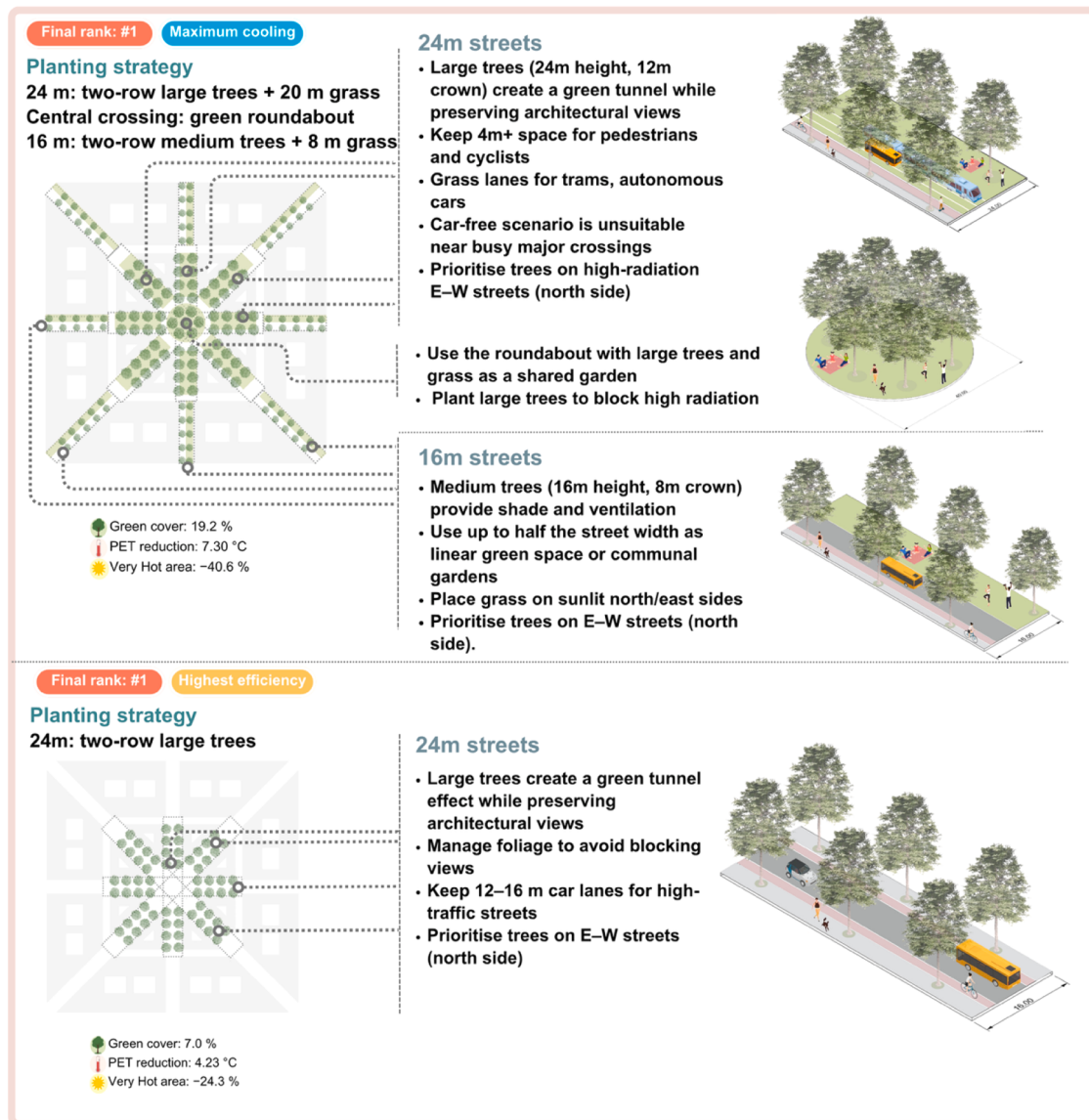


Fig. 9. Final design guidelines for T4-Mainly wide streets with four orientations divided by 45°.

feedback to reshape the initial scenarios.

This process is essential because variables such as vegetation type, tree size, spatial configuration, and neighbourhood morphology can generate hundreds of possible design combinations. Testing all combinations parametrically would be computationally demanding and would include options that may be unrealistic in practice. Practitioner input helped narrow the design space toward plausible and implementable configurations for re-simulation, demonstrating how RTD can support structured collaboration between urban climate researchers and design practitioners in neighbourhood cooling research.

The study also advances methodological understanding by comparing two performance perspectives: maximum cooling and cooling efficiency relative to green coverage. Previous studies addressed these separately, either optimising thermal performance (Liu et al., 2021; Krayenhoff et al., 2020) or improving efficiency (Yang et al., 2020; Ouyang et al., 2023). Combining both in one framework highlights that scenarios with the highest absolute cooling are not always the most efficient, which is particularly important in compact neighbourhoods where street space is limited and greening interventions must be balanced with existing functions.

Furthermore, this research forms a staged evidence-to-practice workflow for climate-responsive greening guidelines, together with the preceding typology-development and preliminary simulation studies. The process starts with identifying heat-prone neighbourhood typologies (Wu et al., 2022), then develops and thermally ranks preliminary greening scenarios (Wu et al., 2025), incorporates practitioner assessment, re-simulates refined designs, and finally translates the results into visual and morphology-specific guidelines.

3.6.3. Implications for planning, policy, and practice

For municipalities, planning agencies, and design firms, this workflow provides a reference for developing evidence-based, understandable, transferable, and operational greening guidelines. Practitioners often lack practical guidance on how to integrate climate-responsive strategies into everyday design work (Brown, 2010; Lenzholzer et al., 2020). This study responds to this gap by translating microclimate simulation results into spatially explicit recommendations that also account for visual experience, functionality, cost, and maintenance. The guidelines are particularly useful in early-stage design, where practitioners need to compare greening alternatives before detailed designs.

Table 4
Summary of scenario performance, synergies, trade-offs, and guideline selection.

Scenario	Maximum cooling	Highest efficiency	Final rank	Synergies	Trade-offs
T1-NS1	✓		#1	Extensive tree and grass coverage delivers maximum cooling.	High cost; increased pruning required for visibility; higher irrigation and maintenance needs.
T1-NS2		✓	#1	Balances absolute cooling and resource efficiency on wide streets.	No greening on secondary streets.
T2-NS1	✓		#2	Full green coverage provides strong absolute cooling.	High cost; increased pruning and maintenance requirements.
T2-NS2			#3	Performed better cooling than single-row plantings on main and secondary streets.	Low efficiency relative to space used.
T2-NS3			#4	–	Lowest absolute cooling; smaller tree sizes improved visibility, but cooling was insufficient.
T2-NS4		✓	#1	Staggered planting pattern improved both absolute and efficient cooling while preserving parking space.	No greening on secondary streets.
T3-NS1			#3	–	Highest greening cost and maintenance with lower cooling performance than NS2.
T3-NS2	✓	✓	#1	Moderate green coverage yields the highest absolute and efficient cooling.	No greening on secondary streets.
T3-NS3		✓	#2	Scattered planting achieves high cooling efficiency.	Low absolute cooling due to small trees on secondary streets, which improves visibility.
T4-NS1	✓		#1	Extensive tree and grass coverage provides	High costs; more space required; pruning

Table 4 (continued)

Scenario	Maximum cooling	Highest efficiency	Final rank	Synergies	Trade-offs
T4-NS2		✓	#1	strong absolute cooling. Balances cooling benefits with cost and low-maintenance needs.	needed to maintain visibility. No greening on secondary streets.

The visual format of the guidelines further supports communication between researchers, designers, engineers, policy-makers, and non-expert stakeholders. Visual and morphology-specific recommendations can make microclimate evidence easier to interpret and apply in design and planning processes (Cortês et al., 2020; Munnik & Lenzholzer, 2020). They can also support communication with local decision-makers and communities by showing tangible examples of how street greening can improve outdoor thermal conditions. In this way, the guidelines contribute not only to professional design decision-making, but also to more transparent and communicative climate adaptation planning.

Finally, this study highlights the need for continued collaboration between urban climate researchers and design practitioners. The full evidence-to-practice workflow offers a transferable methodological reference for these collaborations. Future mobility trends, including reduced car use, superblocks, and autonomous mobility, may create further opportunities to reallocate street space for green infrastructure (NACTO, 2019; Fisher, 2021; Luo et al., 2019; Nieuwenhuijsen, 2024). Continued interdisciplinary collaboration will be essential to refine these guidelines, test them in real projects, and improve their transferability across different urban and climatic contexts.

3.7. Limitations and further research

This study presents several limitations that suggest directions for further research. The participatory process involved a small group of professionals with backgrounds in urban design and landscape architecture. While this ensured a consistent design perspective, it may have limited the range of concerns. Including experts from fields such as urban forestry and engineering could have brought other practical considerations related to functionality, cost, and maintenance. The number of practitioners involved in the workshops was limited. In this study, the workshops were used to refine design scenarios within a Research-Through-Design framework, relying on professional judgement rather than broad representation. Future research could involve a larger and more diverse practitioner group to test the robustness of these findings across contexts.

The ENVI-met simulations were designed as controlled comparisons among greening scenarios under identical boundary conditions. The results depend partly on assumptions related to boundary conditions, vegetation representation, material properties, and thermal comfort parameters. These assumptions may influence absolute PET values, while the main interpretation focuses on relative differences among scenarios. Future research should test the guidelines in real neighbourhoods and compare simulated cooling effects with field measurements, and add sensitivity tests for ENVI-met inputs, such as wind conditions, vegetation parameters, surface albedo.

While this study focused on daytime thermal conditions, investigating nocturnal and seasonal performance would help ensure year-round effectiveness of urban greening strategies (Fu, 2022; Zhang et al., 2017). Besides, cooling simulations were based on meteorological data from temperate European cities, limiting the generalisability of findings. Future studies could adapt and test the strategies in different

climatic zones to assess broader applicability (Wong et al., 2021; Yu et al., 2017). The proposed design scenarios focus primarily on spatial aspects, with limited differentiation by vegetation species. Since plant characteristics such as canopy form, seasonal behaviour, and maintenance demands vary, including species-specific choices could improve both performance and feasibility (Fu, 2022).

4. Conclusion

This research used a research-through-design process to identify effective spatial designs of street trees and grass for neighbourhood cooling. Design practitioners evaluated the scenarios based on visual experience, functionality, cost, and maintenance. These scenarios were then refined with respect to key design factors, including tree size, placement, tree–grass combinations, and the proportion and distribution of green surfaces. Following ENVI-met simulations, we assessed their cooling performance in terms of both maximum cooling and cooling efficiency. The resulting neighbourhood-specific design guidelines provide practical and applicable strategies for urban planners, designers, and landscape architects.

For neighbourhoods with N–S and E–W wide streets, plant two rows of large trees with grass covering 20 m of the 24 m street surface between buildings, and medium trees on secondary streets with 8 m grass coverage on 16 m surfaces. If resources are limited, prioritise large trees on main streets. For neighbourhoods with N–S and E–W narrow streets, use medium trees on main streets and one row of small trees on the high-radiated side (north and east) of secondary streets. For neighbourhoods with NE–SW and NW–SE narrow streets, two rows of medium trees on main streets are most effective, followed by one row of medium trees on main streets and small trees on the high-radiated side (northwest and northeast) of secondary streets. For neighbourhoods with wide radial streets, plant two rows of large trees with 20 m grass strips on 24 m streets and medium trees with 8 m grass on 16 m streets. Use large trees and grass in central roundabouts. If resources are limited, focus on two rows of large trees on 24 m streets.

Our findings demonstrate that greater green coverage is not always the most effective strategy, highlighting the importance of specific design guidelines for different neighbourhood typologies. Accordingly, the final guidelines reflect not only thermal simulation results but also practitioner insights, ensuring that recommended strategies are both climatically effective and implementable. By applying these solutions, urban planners and designers can create sustainable, comfortable, and visually appealing streetscapes, contributing to broader goals of climate resilience and liveability in urban environments.

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, Conceptualization. **Bardia Mashhoobi:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Sanda Lenzholzer:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Laura Narvaez Zertuche:** Supervision, Methodology. **Andy Acred:** Supervision, Project administration, Methodology.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.scs.2026.107583](https://doi.org/10.1016/j.scs.2026.107583).

Data availability

Data will be made available on request.

References

- Abolata, A. (2020). Vegetation in different street orientations of aspect ratio (H/W 1:1) to mitigate UHI and reduce buildings' energy in arid climate. *Building and Environment*, 172, Article 106712. <https://doi.org/10.1016/j.buildenv.2020.106712>
- Abolata, A., & Sodoudi, S. (2019). Evaluating urban vegetation scenarios to mitigate urban heat island and reduce buildings' energy in dense built-up areas in Cairo. *Building and Environment*, 166, Article 106407. <https://doi.org/10.1016/j.buildenv.2019.106407>
- Armson, D., Stringer, P., & Ennos, A. R. (2012). The effect of tree shade and grass on surface and globe temperatures in an urban area. *Urban Forestry & Urban Greening*, 11(3), 245–255. <https://doi.org/10.1016/j.ufug.2012.05.002>
- Arnold, H. (1993). *Trees in urban design*. New York: Van Nostrand Reinhold.
- Asgarzadeh, M., Lusk, A., Koga, T., & Hirate, K. (2012). Measuring oppressiveness of streetscapes. *Landscape and Urban Planning*, 107(1), 1–11. <https://doi.org/10.1016/j.landurbplan.2012.04.001>
- Banerjee, S., Pek, R. X. Y., Yik, S. K., Ching, G. N., Ho, X. T., Dzyuban, Y., Crank, P. J., Acero, J. A., & Chow, W. T. L. (2024). Assessing impact of urban densification on outdoor microclimate and thermal comfort using ENVI-met simulations for Combined Spatial-Climatic Design (CSCD) approach. *Sustainable Cities and Society*, 105, Article 105302. <https://doi.org/10.1016/j.scs.2024.105302>
- Bartasaghi-Koc, C., Haddad, S., Pignatta, G., Paolini, R., Prasad, D., & Santamouris, M. (2021). Can urban heat be mitigated in a single urban street? Monitoring, strategies, and performance results from a real scale redevelopment project. *Solar Energy*, 216, 564–588. <https://doi.org/10.1016/j.solener.2020.12.043>
- Bartasaghi-Koc, C., Osmond, P., & Peters, A. (2020). Quantifying the seasonal cooling capacity of 'green infrastructure types' (GITs): An approach to assess and mitigate surface urban heat island in Sydney, Australia. *Landscape and Urban Planning*, 203, Article 103893. <https://doi.org/10.1016/j.landurbplan.2020.103893>
- Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, 5(1), Article 1. <https://doi.org/10.1038/sdata.2018.214>
- Brown, R. D. (2010). *Design with microclimate: The secret to comfortable outdoor space*. Island Press.
- Carmona, M. (2021). *Public places urban spaces: The dimensions of urban design* (3rd ed.). Routledge. <https://doi.org/10.4324/9781315158457>
- Cortésão, J., & Lenzholzer, S. (2022). Research through design in urban and landscape design practice. *Journal of Urban Design*, 27(6), 617–633. <https://doi.org/10.1080/13574809.2022.2062313>
- Cortésão, J., Lenzholzer, S., Klok, L., Jacobs, C., & Kluck, J. (2020). Generating applicable urban design knowledge. *Journal of Urban Design*, 25(3), 293–307. <https://doi.org/10.1080/13574809.2019.1650638>
- Cui, P., Jiang, J., Zhang, J., & Wang, L. (2023). Effect of street design on UHI and energy consumption based on vegetation and street aspect ratio: Taking Harbin as an example. *Sustainable Cities and Society*, 92, Article 104484. <https://doi.org/10.1016/j.scs.2023.104484>
- Darbani, E. S., Rafieian, M., Parapari, D. M., & Guldmann, J.-M. (2023). Urban design strategies for summer and winter outdoor thermal comfort in arid regions: The case of historical, contemporary and modern urban areas in Mashhad, Iran. *Sustainable Cities and Society*, 89, Article 104339. <https://doi.org/10.1016/j.scs.2022.104339>
- De Munnik, N., & Lenzholzer, S. (2020). Revealing urban climate through animated visualizations. *Journal of Landscape Architecture*, 15(2), 74–85. <https://doi.org/10.1080/18626033.2020.1852712>
- Egerer, M., Schmack, J. M., Vega, K., Barona, C. O., & Raum, S. (2024). The challenges of urban street trees and how to overcome them. *Frontiers in Sustainable Cities*, 6. <https://doi.org/10.3389/frsc.2024.1394056>
- Ewing, R., & Handy, S. (2009). Measuring the unmeasurable: Urban design qualities related to walkability. *Journal of Urban Design*, 14(1), 65–84. <https://doi.org/10.1080/13574800802451155>
- Fang, Y.-N., Tian, J., Namaiti, A., Zhang, S., Zeng, J., & Zhu, X. (2024). Visual aesthetic quality assessment of the streetscape from the perspective of landscape-perception coupling. *Environmental Impact Assessment Review*, 106, Article 107535. <https://doi.org/10.1016/j.eiar.2024.107535>

- Fisher, T. (2021). Future streets: Leveraging autonomous shared vehicles for greater community health, equity. *Livability and Prosperity*. <https://conservancy.umn.edu/handle/11299/227891>.
- Frantzeskaki, N. (2019). *Seven lessons for planning nature-based solutions in cities*, 93 pp. 101–111. Environmental Science & Policy. <https://doi.org/10.1016/j.envsci.2018.12.033>
- Fu, J. (2022). Optimized greenery configuration to mitigate urban heat: A decade systematic review. *Frontiers of Architectural Research*, 26.
- Gehl, J. (2006). *Life between buildings: Using public space*. Danish Architectural Press.
- Graça, M., Cruz, S., Monteiro, A., & Neset, T.-S. (2022). Designing urban green spaces for climate adaptation: A critical review of research outputs. *Urban Climate*, 42, Article 101126. <https://doi.org/10.1016/j.uclim.2022.101126>
- Guo, C., Buccolieri, R., & Gao, Z. (2019). Characterizing the morphology of real street models and modeling its effect on thermal environment. *Energy and Buildings*, 203, Article 109433.
- Hu, T., Wei, D., Su, Y., Wang, X., Zhang, J., Sun, X., Liu, Y., & Guo, Q. (2022). Quantifying the shape of urban street trees and evaluating its influence on their aesthetic functions based on mobile lidar data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 184, 203–214. <https://doi.org/10.1016/j.isprsjprs.2022.01.002>
- Kearl, Z., & Vogel, J. (2023). Urban extreme heat, climate change, and saving lives: Lessons from Washington state. *Urban Climate*, 47, Article 101392. <https://doi.org/10.1016/j.uclim.2022.101392>
- Kim, H., Kim, H., Lee, D., Seomun, G., & Woosnam, K. M. (2025). Climate gentrification and green infrastructure in the U.S. Great Lakes region: Engaging with heat exposure and adaptation policy. *Habitat International*, 163, Article 103453. <https://doi.org/10.1016/j.habitatint.2025.103453>
- Kleerekoper, L., Dobbelssteen, A. A. J. F. van den, Hordijk, G. J., Dorst, M. J. van, & Martin, C. L. (2015). Climate adaptation strategies: Achieving insight in microclimate effects of redevelopment options. *Smart and Sustainable Built Environment*, 4(1), 110–136. <https://doi.org/10.1108/SASBE-08-2014-0045>
- Klemm, W., Lenzholzer, S., & van den Brink, A. (2017). Developing green infrastructure design guidelines for urban climate adaptation. *Journal of Landscape Architecture*, 12 (3), 60–71. <https://doi.org/10.1080/18626033.2017.1425320>. Routledge Journals, Taylor & Francis Ltd.
- Konijnendijk, C. C. (2023). Evidence-based guidelines for greener, healthier, more resilient neighbourhoods: Introducing the 3–30–300 rule. *Journal of Forestry Research*, 34(3), 821–830. <https://doi.org/10.1007/s11676-022-01523-z>
- Krayenhoff, E. S., Jiang, T., Christen, A., Martilli, A., Oke, T. R., Bailey, B. N., Nazarian, N., Voogt, J. A., Giometto, M. G., & Stastny, A. (2020). A multi-layer urban canopy meteorological model with trees (BEP-Tree): Street tree impacts on pedestrian-level climate. *Urban Climate*, 32, Article 100590.
- Lenzholzer, S. (2012). Research and design for thermal comfort in Dutch urban squares. *Resources, Conservation and Recycling*, 64, 39–48. <https://doi.org/10.1016/j.resconrec.2011.06.015>
- Lenzholzer, S., Carsjens, G.-J., Brown, R. D., Tavares, S., Vanos, J., Kim, Y., & Lee, K. (2020). Awareness of urban climate adaptation strategies – an international overview. *Urban Climate*, 34, Article 100705. <https://doi.org/10.1016/j.uclim.2020.100705>
- Lenzholzer, S., Duchhart, I., & Koh, J. (2013). Research through designing in landscape architecture. *Landscape and Urban Planning*, 113, 120–127.
- Li, H., Zhao, Y., Wang, C., Ürgü-Vorsatz, D., Carmeliet, J., & Bardhan, R. (2024). Cooling efficacy of trees across cities is determined by background climate, urban morphology, and tree trait. *Communications Earth & Environment*, 5(1), 1–14. <https://doi.org/10.1038/s43247-024-01908-4>
- Ligtermoet, E., Ramalho, C. E., Foellmer, J., & Pauli, N. (2022). Greening urban road verges highlights diverse views of multiple stakeholders on ecosystem service provision, challenges and preferred form. *Urban Forestry & Urban Greening*, 74, Article 127625. <https://doi.org/10.1016/j.ufug.2022.127625>
- Liu, L., Wang, H., & Duan, J. (2023). How streetscape affects car use: Examining unexamined features of urban environment with fine-grained data. *Cities (London, England)*, 132, Article 104096. <https://doi.org/10.1016/j.cities.2022.104096>
- Liu, Z., Cheng, W., Jim, C. Y., Morakinyo, T. E., Shi, Y., & Ng, E. (2021). Heat mitigation benefits of urban green and blue infrastructures: A systematic review of modeling techniques, validation and scenario simulation in ENVI-met V4. *Building and Environment*, 200, Article 107939. <https://doi.org/10.1016/j.buildenv.2021.107939>
- Lobaccaro, G., & Acero, J. A. (2015). Comparative analysis of green actions to improve outdoor thermal comfort inside typical urban street canyons. *Urban Climate*, 14, 251–267. <https://doi.org/10.1016/j.uclim.2015.10.002>
- Lotfata, A., Cortesão, J., Zinsmeister, H., Steeneveld, G.-J., van Zeben, J., Taylor, Z., Tan, W., & Elkhateeb, S. (2024). Climate adaptation in informal areas in hot arid climates. *Sustainable Development*, 32(1), 777–794. <https://doi.org/10.1002/sd.2708>
- Luo, Y., Wang, Y., & Tian, T. (2019). From transportation infrastructure to green infrastructure-adaptable future roads in autonomous urbanism. *Landscape Architecture Frontiers*, 7(2), 92–99.
- Mullaney, J., Lucke, T., & Trueman, S. (2014). A review of benefits and challenges in growing street trees in paved urban environments. *Landscape and Urban Planning*, 134. <https://doi.org/10.1016/j.landurbplan.2014.10.013>
- NACTO. (2019). Blueprint for Autonomous Urbanism: Second Edition. National Association of City Transportation Officials. <https://nacto.org/publication/bau2>
- Ng, W.-Y., Chau, C.-K., Powell, G., & Leung, T.-M. (2015). Preferences for street configuration and street tree planting in urban Hong Kong. *Urban Forestry & Urban Greening*, 14(1), 30–38. <https://doi.org/10.1016/j.ufug.2014.11.002>
- Nieuwenhuijsen, M., de Nazelle, A., Pradas, M. C., Daher, C., Dzhambov, A. M., Echave, C., Gössling, S., Iungman, T., Khreis, H., Kirby, N., Khomenko, S., Leth, U., Lorenz, F., Matkovic, V., Müller, J., Palència, L., Pereira Barboza, E., Pérez, K., Tatab, L., ... Mueller, N. (2024). The Superblock model: A review of an innovative urban model for sustainability, liveability, health and well-being. *Environmental Research*, 251, Article 118550. <https://doi.org/10.1016/j.envres.2024.118550>
- Ojha, S. K., & Mukherjee, M. (2024). Investigating the potential of integrated urban greening strategies for reducing outdoor thermal stresses: A case of asymmetrical configuration in the tropical city of Bhopal. *International Journal of Biometeorology*, 68(7), 1451–1474. <https://doi.org/10.1007/s00484-024-02680-y>
- Ouyang, W., Morakinyo, T. E., Ren, C., & Ng, E. (2020). The cooling efficiency of variable greenery coverage ratios in different urban densities: A study in a subtropical climate. *Building and Environment*, 174, Article 106772. <https://doi.org/10.1016/j.buildenv.2020.106772>
- Ouyang, W., Morakinyo, T. E., Lee, Y., Tan, Z., Ren, C., & Ng, E. (2023). How to quantify the cooling effects of green infrastructure strategies from a spatio-temporal perspective: Experience from a parametric study. *Landscape and Urban Planning*, 237, Article 104808. <https://doi.org/10.1016/j.landurbplan.2023.104808>
- Ramakreshnan, L., Aghamohammadi, N., Fong, C. S., Ghaffarianhoseini, A., Wong, L. P., Noor, R. M., Hanif, N. R., Azriyati, Wan Abd, Aziz, W. N., Sulaiman, N. M., & Hassan, N. (2019). A qualitative exploration on the awareness and knowledge of stakeholders towards Urban Heat Island phenomenon in Greater Kuala Lumpur: Critical insights for urban policy implications. *Habitat International*, 86, 28–37. <https://doi.org/10.1016/j.habitatint.2019.02.007>
- Rehan, R. M. (2013). Sustainable streetscape as an effective tool in sustainable urban design. *HBRC Journal*, 9(2), 173–186. <https://doi.org/10.1016/j.hbrj.2013.03.001>
- Roe, J., & McCay, L. (2021). *Restorative cities: Urban design for mental health and wellbeing*. Bloomsbury Publishing.
- Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F., & Coumou, D. (2022). Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia. *Nature Communications*, 13(1), 1–11.
- Shen, J., & Lin, S. (2019). Progress of research through design (RtD) in landscape architecture. *Landscape Architecture*, 26(7), 51–56.
- Shi, F., Meng, Q., Pan, L., & Wang, J. (2023). Root damage of street trees in urban environments: An overview of its hazards, causes, and prevention and control measures. *Science of The Total Environment*, 904, Article 166728. <https://doi.org/10.1016/j.scitotenv.2023.166728>
- Tabassum, S., Manea, A., Ossola, A., Thomy, B., Blackham, D., & Leishman, M. R. (2021). The angriest summer on record: Assessing canopy damage and economic costs of an extreme climatic event. *Urban Forestry & Urban Greening*, 63, Article 127221. <https://doi.org/10.1016/j.ufug.2021.127221>
- Taleghani, M. (2018). Outdoor thermal comfort by different heat mitigation strategies- A review. *Renewable and Sustainable Energy Reviews*, 81, 2011–2018. <https://doi.org/10.1016/j.rser.2017.06.010>
- Tollefson, J. (2023). Earth's hottest month: These charts show what happened in July and what comes next. *Nature*, 620(7975), 703–704. <https://doi.org/10.1038/d41586-023-02552-2>
- Torres, M. N., Rodríguez, J. P., & Leitão, J. P. (2017). Geostatistical analysis to identify characteristics involved in sewer pipes and urban tree interactions. *Urban Forestry & Urban Greening*, 25, 36–42. <https://doi.org/10.1016/j.ufug.2017.04.013>
- Witze, A. (2022). Extreme heatwaves: Surprising lessons from the record warmth. *Nature*, 608(7923), 464–465. <https://doi.org/10.1038/d41586-022-02114-y>
- Wong, N. H., Tan, Kokotsa, D. D., & Takebayashi, H. (2021). Greenery as a mitigation and adaptation strategy to urban heat. *Nature Reviews Earth & Environment*, 1–16. <https://doi.org/10.1038/s43017-020-00129-5>
- Wu, Y., Mashhoodi, B., & Patuano, A. (2025a). Effective street tree and grass designs to cool European neighbourhoods. *Urban Climate*, 61, Article 102376. <https://doi.org/10.1016/j.uclim.2025.102376>
- Wu, Y., Mashhoodi, B., Patuano, A., Lenzholzer, S., Narvaez Zertuche, L., & Acred, A. (2022). Heat-prone neighbourhood typologies of European cities with temperate climate. *Sustainable Cities and Society*, 87, Article 104174. <https://doi.org/10.1016/j.scs.2022.104174>
- Wu, Y., Patuano, A., Mashhoodi, B., Lenzholzer, S., Acred, A., & Narvaez Zertuche, L. (2025b). How small green spaces cool urban neighbourhoods: Optimising distribution, size and shape. *Landscape and Urban Planning*, 253, Article 105224. <https://doi.org/10.1016/j.landurbplan.2024.105224>
- Xi, C., Wang, D., & Cao, S.-J. (2023). Impacts of trees-grass area ratio on thermal environment, energy saving, and carbon benefits. *Urban Climate*, 47, Article 101393. <https://doi.org/10.1016/j.uclim.2022.101393>
- Yang, G., Yu, Z., Jørgensen, G., & Vejre, H. (2020). How can urban blue-green space be planned for climate adaption in high-latitude cities? A seasonal perspective. *Sustainable Cities and Society*, 53, Article 101932. <https://doi.org/10.1016/j.scs.2019.101932>
- Yin, S., Lang, W., & Xiao, Y. (2019). The synergistic effect of street canyons and neighbourhood layout design on pedestrian-level thermal comfort in hot-humid area of China. *Sustainable Cities and Society*, 49, Article 101571. <https://doi.org/10.1016/j.scs.2019.101571>
- Yu, Z., Guo, X., Jørgensen, G., & Vejre, H. (2017). How can urban green spaces be planned for climate adaptation in subtropical cities? *Ecological Indicators*, 82, 152–162. <https://doi.org/10.1016/j.ecolind.2017.07.002>
- Zhang, X., Huang, B., Rinke Dias de Souza, N., Hu, X., & Cherubini, F. (2024). Regional cooling potential from expansion of perennial grasses in Europe. *Communications Earth & Environment*, 5(1), 772. <https://doi.org/10.1038/s43247-024-01923-5>

- Zhang, Y., Murray, A. T., & Turner II, B. L. (2017). Optimizing green space locations to reduce daytime and nighttime urban heat island effects in Phoenix, Arizona. *Landscape and Urban Planning*, 165, 162–171.
- Zhu, H., Nan, X., Kang, N., & Li, S. (2024). How much visual greenery can street trees generate from a humanistic perspective? An attempt to quantify the canopy green view index based on tree morphology. *Forests*, 15(1), Article 1. <https://doi.org/10.3390/f15010088>. Article.
- Ziter, C. D., Pedersen, E. J., Kucharik, C. J., & Turner, M. G. (2019). Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proceedings of the National Academy of Sciences*, 116(15), 7575–7580. <https://doi.org/10.1073/pnas.1817561116>