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The role of nature-based solutions in improving temperature and noise-related comfort in compact urban areas

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ABSTRACT Urban areas are increasingly affected by environmental stressors such as elevated temperatures and excessive noise, which compromise the usability of public spaces. Nature-based solutions (NBS) are gaining recognition as context-sensitive interventions to mitigate such issues, yet their effective implementation, especially in compact urban areas, depends on specific spatial and morphological conditions. This study evaluates the spatial feasibility of four NBS types: green roofs, vertical greenery, and natural terrain with high or low vegetation across four pilot streets in Ljubljana, each representing a distinct urban typology. Using high-resolution environmental data and discomfort analysis (Ravnikar et al., in press), we developed spatial suitability criteria based on a targeted literature review and technical guidelines. These were operationalised in a GIS-based overlay analysis to identify feasible implementation sites. The results confirm that spatial constraints such as limited open space, unfavourable façade orientation, and underground infrastructure—often restrict the capacity of NBS to deliver meaningful improvements. While some interventions are feasible, their impact remains fragmentary, highlighting the need to consider spatial and technical requirements from the earliest planning stages. Proactive integration of NBS into spatial development is essential to move beyond isolated interventions and achieve systemic environmental benefits.

INDEX TERMS Nature-based solutions, compact urban area, noise, temperature, spatial suitability analysis, GIS-based overlay analysis.

I. INTRODUCTION

Urban areas face increasing environmental issues, including elevated temperatures, noise pollution, air quality deterioration, and humidity fluctuations—all of which significantly impact the usability of public spaces [1], [2], [3], [4]. In response to these issues, Nature-Based Solutions (NBS) as sustainable spatial solutions, based on natural processes, can enhance environmental quality and improve urban comfort [5], [6].

However, the successful implementation of NBS depends on multiple factors, including the practical feasibility of different types of NBS and the contextual suitability of the location, while the identification of critical sites constitutes a key step toward creating more comfortable urban streets. Within the broader smart cities concept, spatial planning is likewise evolving towards data-responsive approaches. This study builds upon previous work by Ravnikar et al. [7] which employed high-resolution environmental data—collected via Information and Communication Technologies (ICT)—where we identified location-specific temperature and noise issues in the urban fabric of Ljubljana, Slovenia. Building on these findings, four pilot streets, each representing a distinct urban typology, were selected for deeper analyses to find the most suitable NBS to improve environmental conditions.

The core contribution of this study is the development of a structured approach to select the right type of NBS, considering locations spatial characteristics and spatial requirements of the NBS implementation. The study analyses the spatial feasibility of different NBS, where the analysis takes into account the spatial, morphological, and regulatory constraints that often limit intervention opportunities in dense urban settings. To strengthen this spatial evaluation, the study incorporates insights from review-based and empirical literature that quantify the environmental benefits of NBS.

Studies such as [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18] provide reference values of spatial solutions and its natural for measurable impacts, particularly temperature reduction and noise mitigation. By comparing this documented comfort improvement performance with the results of the spatial suitability analysis, the study offers a more holistic, evidence-based framework for identifying viable and impactful NBS interventions. Given the morphological characteristics of compact urban environments, the successful implementation of NBS is strongly influenced by both above- and below-ground spatial constraints. For instance, planting tall vegetation requires sufficient unobstructed underground space, while vertical greenery relies on continuous and appropriately oriented façades. To operationalize these requirements, the study establishes a set of spatial assessment criteria based on the review of relevant literature and guidelines (e.g., [19], [20], [21], [22], [23], [24]. These criteria are applied in a GIS overlay analysis to evaluate the feasibility of implementing NBS in the selected pilot streets, providing a replicable method for context-sensitive urban greening. The implementation of this approach is based on GIS software, which is already a standard and widely adopted tool among spatial planners.

By comparing the spatial suitability of pilot cases with literature review evidence upon potential environmental nature-based outcomes, the study addresses the hypothesis: "The spatial feasibility of NBS in compact urban environments is highly dependent on morphological and infrastructural constraints, which limit their capacity to address temperature and noise issues at the street level."

The main contribution of this study is to provide a decision-support framework that helps urban planners identify which types of NBS can effectively address specific environmental issues, while accounting for local spatial constraints in cities. Beyond this practical contribution, the study also advances the broader field of data-driven urban planning by demonstrating how bottom-up, ICT approaches and the use of high-resolution environmental data can support more climate-responsive spatial planning.

A. BACKGROUND

Bottom-up methods—such as in situ measurements with portable and transportable devices—are beginning to capture environmental variations within cities [25], [26], [27], [28]. These methods can help urban planners uncover hidden urban dynamics and, when the data are of sufficient resolution and quality [2], they can also identify potential environmental issues, thereby enabling planning practices that respond with more context-appropriate spatial solutions. Ravnikar et al. (2025) [7] identified noise pollution and elevated temperatures as key environmental issues on four pilot streets in Ljubljana, which serve as baseline input for this analysis (see Figure 1). Street A, with its relatively compact urban pattern combining low- and high-density segments, records noise discomfort 89% of the time, of which 81% is classified as extremely uncomfortable. Street B, characterized by an open, low-density urban layout, shows noise discomfort in 81% of the time measured. Street C, a densely built-up urban tissue, reports noise discomfort in 86% of the time, all of which falls into the extreme discomfort category. Street D, a dense historic urban pattern, experiences noise discomfort 78% of the time. Temperature-related discomfort also varies across the four streets. Street A shows thermal discomfort in 68% of the time, with 24% considered extremely uncomfortable. In Street B, temperature discomfort occurs 57% of the time, with 16% classified as extreme. Street C records temperature discomfort 81% of the time, while Street D experiences it in 68% of the time [7].

To guide the selection of suitable NBS interventions, this research draws on the conceptual framework developed by Goličnik Marušić et al. [29]. Their "matching matrix" systematically connects urban morphological types with specific NBS categories and environmental objectives. This matrix serves as a foundational tool in identifying which types of NBS—such as green roofs, vertical greenery, or natural terrain with high or low vegetation—are appropriate for particular street typologies and environmental stressors.

Recent empirical and review-based research has increasingly quantified the environmental performance of various NBS types in urban settings [30], [31], [32]. Studies provide reference values for measurable outcomes such as temperature reduction and noise mitigation, serving as important benchmarks in planning interventions. For instance, green walls have been shown to reduce air temperatures by up to 0.59 °C and façade surface temperatures by over 11 °C, depending on orientation and vegetation coverage [12]. Green roofs contribute to roof-level cooling [33], delay stormwater runoff, and improve surface insulation [13], [14], with recorded pedestrian-level temperature reductions of up to 0.2 °C [9], [16]. Similarly, forests have been shown to influence rainwater dynamics by reducing surface runoff through enhanced interception, stemflow, and evapotranspiration processes [34]. Shrubs and hedges can lower surface temperatures by up to 19 °C compared to asphalt [17] and provide localized cooling through evapotranspiration[18]. Urban forests and parks are among the most effective types of green spaces for temperature reduction, consistently demonstrating cooling effects throughout the year [35]. Grass-covered areas also contribute to thermal regulation, with observed differences of up to 3.4 °C compared to paved surfaces [10], while street trees (particularly two rows of large street trees) have been shown to lower Physiological Equivalent Temperature (PET) by up to 8.7 °C in compact urban settings [15]. In addition, noise attenuation effects have been observed in relation to vegetated buffers and tree belts, which can reduce noise levels by several decibels when placed strategically between sources and receptors [8], [11]. These findings are echoed in large-scale compendia such as [22], [23], [24].

However, despite NBS proven environmental benefits, these results often stem from context-specific simulations or specific localised case studies conditions, and NBS broader applicability remains highly dependent on spatial conditions. In dense urban environments, where physical space is often limited and fragmented, successful implementation of NBS hinges on the availability of suitable above- and below-ground space. Literature and technical guidelines underline that each type of NBS requires specific spatial conditions—for instance, free façade surfaces and favourable orientation for vertical greenery, low roof slope and structural capacity for green roofs, or clearances from infrastructure for tall vegetation [22], [23], [24].

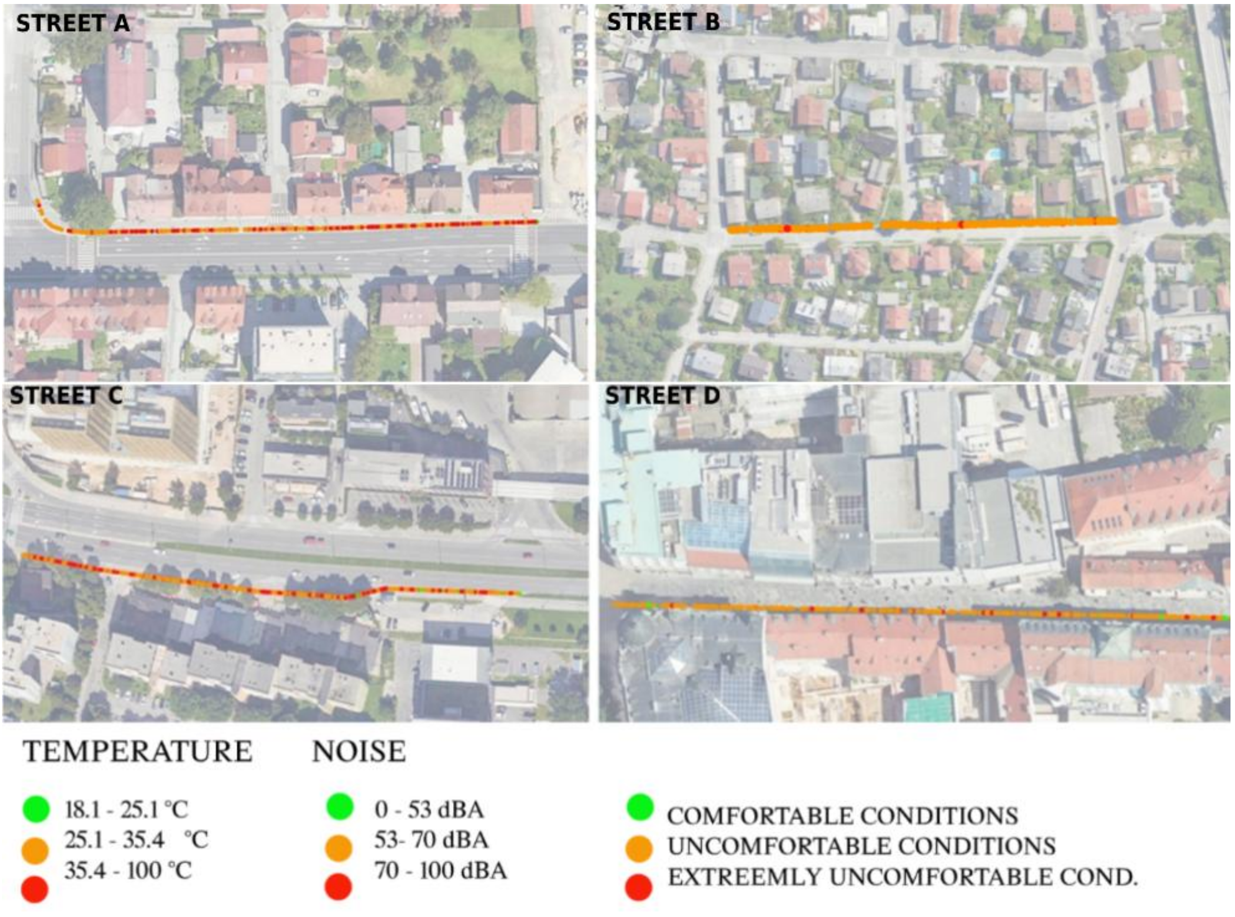
To address these spatial constraints, this study develops a set of assessment criteria informed by relevant literature and guidelines (e.g., [12], [20], [21], [36]). These criteria specify the spatial and technical preconditions for each NBS type. For example, vertical greenery requires a window-to-wall ratio of at least 65%, proper façade orientation, and high pedestrian exposure; green roofs require a slope under 11° and minimal roof-level obstructions; high vegetation needs adequate horizontal and vertical distance from infrastructure, and sufficient root volume; and low vegetation relies on available permeable or minimally paved surfaces. Minimum required surface areas for effective implementation range from 1 m² to 16 m², depending on the NBS type and environmental objective.

These criteria are systematically operationalized in a GIS-based overlay analysis across the four pilot streets to assess the realistic feasibility of implementing NBS within spatially constrained urban environments.

In recent years, different approaches for assessing the suitability of NBS have been developed. Many of them focus on larger spatial scales (regional level), such as the use of spatial multi-criteria analysis for identifying suitable NBS locations for urban flood mitigation [37]. Others focus on the strategic placement of NBS at the scale of urban districts or entire cities—for instance, for flood management [38]; for identifying optimal locations based on soil temperature, air quality, and accessibility of green spaces [39]; or for guiding placement according to ecological, social, and governance criteria [40]. While these approaches provide valuable guidance for implementing NBS in urban planning at macro (regional) and meso (city and district) scales, and represent an important foundation for strategic planning, they less frequently address the micro scale of individual streets. Yet it is precisely at this level where environmental discomforts such as heat and noise are most directly experienced by users, and where spatial design most closely interacts with the human scale. The advantage of our study lies in its focus on the micro scale as the final stage of NBS implementation, systematically assessing whether specific solutions are actually feasible within a given urban fabric.

As noted by [41], multi-criteria decision-making tools for NBS planning are rarely accessible and are often difficult to adapt to different contexts. This study's approach is transferable to other urban environments, with its primary utility situated at the street level in dense urban areas facing significant environmental pressures of elevated temperatures and noise. The framework enables a systematic assessment of the spatial feasibility of different NBS types in such locations, while acknowledging that the applied thresholds (e.g., façade-to-window ratios, roof slope) must always be adjusted to local contexts, including building standards and planning objectives of individual cities. An additional advantage of the method is that the entire procedure is carried out within a GIS environment, which is already widely established and commonly used by urban planners, thereby increasing its practical relevance and transferability to planning practice.

FIGURE 1. **Temperature and noise related discomfort levels across four pilot streets in Ljubljana** [7]



II. METHODOLOGY

This study follows a mixed-methods approach, combining results of environmental data driven case study analysis, literature review, and structured-site evaluation of NBS suitability, and QGIS software.

The key methodological steps in this paper are as follows:

- Identifying NBS types suggested by Goličnik Marušić et al. [29] based on a matrix that targets specific environmental issues while considering the characteristics of a specific urban pattern; and the case study description.

- Developing criteria for assessing the suitability of locations based on spatial requirements regarding the identified NBS types (spatial suitability analyses). The specific characteristics of streets and buildings require a detailed assessment of the suitability of the location. Since each NBS type has particular spatial and technical requirements for integration, certain on-site conditions must be met to ensure successful implementation. To ensure this, we developed suitability criteria for each NBS type based on a review of the relevant literature e.g. [20], [21], [22], [23], [36], [42] . To the selected types upon Goličnik Marušić et al. [29], natural terrain with high vegetation, natural terrain with low vegetation, green walls, and green roofs, further several spatial criteria were assigned. These criteria range from window-to-wall ratio as regards the vertical green NBS type, to underground infrastructure as regards to natural terrain with high vegetation NBS type. An overview is summarised in Table 1.

- Commenting on the feasibility of implementing the proposed NBS based on the analysis of location suitability and a literature review on the effectiveness of NBS in delivering environmental improvements within spatially constrained urban areas.

TABLE I
CRITERIA DEVELOPED ACCORDING TO THE NBS TYPE.

Vertical green	Green roof	Natural terrain with high vegetation	Natural terrain with low vegetation
Window-to-wall ratio	Roof slope	Overhead infrastructure	Minimum surface
Orientation	Structural integrity of roof	Distance from streetlights and traffic signage	Land use
Concentration of people		Road visibility	
Cultural heritage protection regimes		Vistas	
		Tree-to-building spacing	
		Underground infrastructure	
		Minimum surface	
		Land use	

A. IDENTIFYING NBS TYPES AND CASE STUDY DESCRIPTION

The process of extracting NBS types from the matching matrix was based on two key aspects: the specific characteristics of the urban pattern of pilot cases and the identification of environmental issues in individual pilot case. The matching matrix [29] facilitated a systematic connection between environmental needs (identified type of issue) and effective solutions, ensuring a transparent selection of appropriate interventions. The matrix was applied to four pilot cases with different types of urban fabric, ranging from relatively compact urban pattern with both low-density and dense areas, an open, low-density urban pattern, densely built-up urban tissue and densely built-up historic urban pattern (see figure 1). In this way, we identified the following solutions to tackle temperature in or noise related issues (see Table 2).

Street A, characterized by a relatively compact urban pattern with areas of low-dense and dense urban pattern, faces hight temperatures and noise conditions. The proposed NBS includes natural terrain with high vegetation and vertical green for noise, and additionally low vegetation and green roofs for temperature. Street B, characterized by low-density urban pattern, also faces high levels of temperature and noise conditions. The proposed solutions are the same as for Street A: natural terrain with tall vegetation and vertical greenery for noise, and additionally low vegetation and green roofs for temperature. Street C represents a densely built-up urban pattern. The proposed NBS includes natural terrain with high vegetation and vertical green for noise, and additionally low vegetation and green roofs for temperature. Street D, as a historical densely built-up pattern, has limited spatial possibilities. Therefore, for both issues – temperature and noise – only vertical green is proposed. However, despite that green roofs are not identified as suitable in the evaluation matrix, we recognised that their implementation could be feasible in this specific case due to the appropriate roof slope.

TABLE 2
THE EXTRACTION NBS TYPES FOR ADDRESSING TEMPERATURE AND NOISE ISSUES, BASED ON THE URBAN TISSUE TYPE OF EACH STREET.

	Street A	Street B	Street C	Street D
				
URBAN PATTERN	Relatively compact urban pattern with areas of low-dense and dense urban pattern	Low-density urban pattern	Densely built-up urban pattern	Densely built-up historic urban pattern
IDENTIFIED URBAN ISSUE	Temperature, noise	Temperature, noise	Temperature, noise	Temperature, noise
POSSIBLE NBS TYPE BASED ON THE URBAN TISSUE TYPE AND ENVIRONMENTAL ISSUE (Goličnik et al. 2023)	For noise: Natural terrain with high vegetation, Vertical green For temperature: Natural terrain with high vegetation, Natural terrain with low vegetation, Vertical green, Green roof	For noise: Natural terrain with high vegetation, Vertical green For temperature: Natural terrain with high vegetation, Natural terrain with low vegetation, Vertical green, Green roof	For noise: Natural terrain with high vegetation, Vertical green For temperature: Natural terrain with high vegetation, Natural terrain with low vegetation, Vertical green, Green roof	For noise: Vertical green For temperature: Vertical green.

B. DEVELOPING CRITERIA FOR SUITABILITY OF LOCATIONS BASED ON SPATIAL REQUIREMENTS REGARDING THE IDENTIFIED NBS TYPES

The approach must enable a comprehensive assessment of the capacity of NBS to improve environmental comfort in different urban contexts and provide insight into how their implementation varies depending on spatial constraints. In that sense, the selection of specific street segments is guided by the need to include different urban patterns to ensure versatility in environmental and spatial conditions within dense urban areas. In the assessment of the potential of streets for NBS implementation, surfaces that are directly part of the street are considered in the analyses. In addition to the areas directly comprising the streets, publicly accessible spaces adjacent to these streets, including buildings that directly border them, were also considered as potential sites for interventions. This narrow scope of the study area reflects the study's emphasis on addressing environmental issues at the micro-locational level, enabling a detailed examination of the potentials and constraints presented by the street as a fundamental unit of urban space. One of the key reasons for such a limitation is to assess the feasibility of interventions at the street level. Cities often adopt a fragmented approach to solutions, implementing them locally rather than comprehensively. The approach taken allows for testing impacts on the smallest possible scale, providing opportunities for further adjustments and potential expansion to other streets or larger urban areas. By focusing on streets, the study addresses whether it is possible to effectively improve conditions within such a constrained area using NBS, and by this reflects the realities of urban planning, where interventions often need to work within limited resources and existing spatial constraints. It also allows for the exploration of how targeted improvements can inform broader urban strategies.

The following section focuses on the key aspects relevant to consider before implementing of NBS on site. For each type of NBS (natural terrain with high vegetation, natural terrain with low vegetation, green walls, and green roofs), the criteria are presented. Furthermore, the section provides a detailed explanation of how these criteria were applied in our case study, and finally, how the intervention was defined as feasible/unfeasible for improving site comfort conditions.

1. VERTICAL GREEN

As shown in Table 1, vertical greening—as an NBS aimed at addressing temperature reduction and noise mitigation—is evaluated against four key criteria.

Window-to-wall ratio (WWR) criterion is about the optimal ratio between the free façade surface and openings (windows, glazing, doors) for targeting temperature issue. Literature identifies that 65% coverage of greenery on facade achieves a cooling effect ranging from 0.26 °C to 0.46 °C, depending on the specific urban patterns. In comparison, for 100% coverage, the cooling effect ranges from 0.36 °C to 0.59 °C, while for 35% coverage, it is limited to a range of 0.19 °C to 0.32 °C [16]. Based on these findings, a minimum threshold of 65% greenery coverage was established, indicating that a building façade with at least 65% greening is effective in delivering a meaningful cooling effect.

The second criterion considers the façade orientation. When implementing vertical greening, the location must be carefully assessed in terms of climatic conditions. As a general rule to consider, only north-facing façades are deemed suitable for greening [21] or façades of buildings that remain shaded for most of the day due to surrounding structures.

The next criterion relates to the visual exposure of facades. Green walls are incorporated into areas where there is a high flow of people or where there is a lack of greenery in densely built-up areas [21]. Protection of buildings under cultural heritage protection regimes addresses the constraints imposed by cultural heritage protection, which frequently limit the feasibility of façade greening.

2. GREEN ROOFS

Green roofs, as an NBS targeting temperature reduction and noise mitigation, are proposed to be evaluated based on two key criteria. The primary criterion for assessing surfaces suitable for green roof implementation is the roof slope of buildings directly adjacent to streets. Urban planning regulations in larger cities increasingly mandate the greening of flat roofs and those with a low slope (up to 11°) [21]. Therefore, in this study, all buildings with roofs sloped less than 11° and directly adjoining streets were evaluated as potential candidates for green roofs.

Structural integrity of roof was addressed. Successful green roof implementation requires that the roof's structure can support the additional weight of the substrate, vegetation, and retained water (especially during heavy rainfall). Since load-bearing capacity varies between buildings and no city-wide structural data were available, all buildings were evaluated as potentially suitable for extensive green roofs, which impose an additional load of approximately 70 kg/m², including retained water *[42]*, or 60–80 kg/m² [19]. In Slovenia, such loading is generally within the structural capacity of standard flat roofs of residential and other conventional buildings, particularly those constructed with massive concrete slabs. The evaluation of structural integrity as well considered whether the roof surfaces included elements such as solar panels, air conditioning units, ventilation systems, or glass roofing. However, the structural capacity or load-bearing potential of the roofs was not included in the analysis.

3. NATURAL TERRAIN WITH HIGH VEGETATION

Natural terrain with high vegetation, as an NBS targeting both temperature reduction and noise mitigation, is suggested to be evaluated against a broad range of criteria, which are summarised below.

Overhead infrastructure is a criterion that refers to insurance of safety and uninterrupted operation of infrastructure, adequate clearances from overhead electrical lines and other utilities must be maintained when planting high vegetation.

Distance from streetlights and traffic signage determines that when planting trees near streetlights and traffic signage, tree canopies must not obstruct lighting or traffic signals. Advertising billboards were not considered significant for preserving views.

Further, in planning vegetation placement, the potential impact on road visibility must be also considered. This criterion determines that trees must not be planted in areas where they could obstruct driver visibility, especially at key traffic points such as intersections and pedestrian crossings. Additionally, trees must be planted at a minimum distance of 1 meter from the road edge.

Special attention is also given to preserving unobstructed views of significant architectural, historical, or cultural structures, as well as vistas recognized as integral to the identity of the space.

Distance from existing buildings is a criterion that determines the required planting distance for trees being away from buildings. It depends on their height and species. According to Šiftar et al., [20] the distances vary from 3 m for small trees (up to 15m in high), to at least 7,5m for tall trees (up to 40 m in hight).

When planning tree planting in urban areas, the relationship between root growth and existing subsurface/underground infrastructure must be addressed. The potential issues posed by the proximity of vegetation to underground utilities depend on the depth of the utilities and the technical design of individual locations. Root growth of trees is mostly to a depth of up to 1.5 m [20], yet the following recommended distances by infrastructure type shall be considered regarding the variety of infrastructures: Sewage Infrastructure is typically located at depths greater than 1.5 meters; main pipelines pose no critical risk from tree roots. However, to prevent potential interference, a minimum planting distance of 2 meters for trees and 1 meter for shrubs must be maintained. Water Supply Systems are typically located at depths 0.7–1.0 m below ground level. Therefore, a recommended distance would be 2 m from trees to prevent root damage to water pipes. Gas pipelines ate typically located at depths 0.7–1.0 m below ground level. Therefore, planting vegetation with roots between 0.7 m and 1 m deep is allowed, whereas planting vegetation with roots deeper than 1 m is prohibited within 2.5 m of the pipeline. Electric networks, Communication systems, and public lighting are typically located at depths 0.5 m below ground level, meaning high vegetation could not be planned on such surfaces. Recommended distance from trees is 2 m, and 1m from shrubs. Heating network is typically located at depth 0.7 m, so planting vegetation with roots deeper than 0.7 m is prohibited. Recommended distance for vegetation planting is 2.5 m from the pipeline.

When determining potential areas for natural terrain with high vegetation, it is as well crucial to consider the surface dimensions required for optimal plant growth, yet as well the capacity of vegetation to produce a cooling/attenuation benefit. Although a single tree does not produce a cooling effect a pedestrian could feel, still can offer shading, so for improving temperature conditions minimum dimension is related to the minimum dimension for growth of at least one tree. The Slovenian tree planting manual *[20]* emphasizes that for trees with a crown width of up to 10 m, the recommended minimum planting pit size is 16 m², with a depth of at least 0.8 m, in accordance with DIN 19816 (2002), as cited in *[20]*.

These requirements apply to individual (isolated) plantings. When multiple trees are planted together, they may share part of the underground growing space, provided that the recommended planting distances between tree trunks are respected. This distance should reflect the expected size of the mature crown of the given tree species—typically at least 50% of the projected crown diameter.

For planting of tall shrubs (higher than 1.5 m) Dremel et al. *[36]* suggests that even 1 m² of vegetation can contribute to temperature regulation in urban areas. Additionally, vegetated surfaces of at least 5 m² can contribute to noise reduction. Therefore, the criterion sets the minimum area of shrubs taller than 1.5 m to improve temperature conditions at least 1 m² and the minimum size to improve noise conditions at 5 m².

The criterion land use considers the following categories as the basis for new or complementary NBS: all existing natural terrain surfaces are understood as potential for implementing natural terrain with high vegetation. Existing trees are considered as the most effective source of shading and are therefore prioritized for preservation. This means that new NBS solutions can only complement trees as understory vegetation. Existing paved surfaces that are not occupied by pedestrian, cycling or traffic infrastructure are also considered potential areas for NBS. These include extensions of sidewalks and parking areas as well.

4. NATURAL TERRAIN WITH LOW VEGETATION

As shown in Table 1, natural terrain with low vegetation—an NBS aimed at addressing temperature reduction and noise mitigation—is suggested to be evaluated against two criteria. The primary criterion for assessing surfaces suitable for natural terrain with low vegetation is the land use. Surfaces with natural terrain on site represent the potential for implementing natural terrain with low vegetation. Existing trees and shrubs higher than 1.5m are to be preserved. Existing paved surfaces that are not occupied by pedestrian, cycling or traffic infrastructure are also considered potential areas for planning natural terrain with low vegetation, including extensions of sidewalks and parking areas as well.

The final criterion is requiring the minimum dimensions to address environmental issues effectively was introduced, based on the research findings of Dremel et al. *[36]*. This criterion identifies the smallest spatial units necessary for effective implementation of natural terrain with low vegetation, ensuring meaningful contributions to environmental improvements in urban areas. These findings suggest that even 1 m² of vegetation can contribute to temperature regulation in urban areas. This threshold allows for the identification of even the smallest spatial units that can be incorporated into NBS planning, which is particularly important in areas with limited available space. Furthermore, it was found that surfaces with at least 5 m² of vegetation can contribute to noise reduction in urban environments.

5. KEY INSIGHTS

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In the analytical procedure, a spatial analysis was performed in the QGIS environment for each street considered based on the above criteria. For each individual type of NBS, the method of spatial overlap of layers (intersect) is used, whereby the data layers are based on criteria relevant to a particular type of NBS. By overlapping these layers, the identification of areas that are suitable for the implementation of an individual type of NBS according to the criteria is achieved. Suitability maps are created, which at the level of individual streets show potential locations for the implementation of vertical green, green roofs and natural with high and low vegetation.

Suitable areas for vertical greening were identified using four main criteria. These are: façade orientation (only north-facing or mostly shaded façades are considered climatically appropriate), window-to-wall ratio (a minimum of 65% uninterrupted surface is required to achieve a meaningful cooling effect), visual exposure (priority is given to highly frequented or densely built-up areas lacking greenery), and cultural heritage protection (façades under heritage restrictions are excluded).

Roofs suitable for greening were identified based on two main criteria: roof slope and structural integrity. Only roofs with a slope of 11 degrees or less were considered appropriate, as steeper roofs were evaluated as unsuitable. Additionally, roofs with existing infrastructure—such as solar panels, ventilation systems, air conditioning units, or extensive glass surfaces—were excluded.

Surfaces suitable for the implementation of natural terrain with tall and low vegetation are identified through spatial integration that considered both overhead and underground infrastructure, as well spatial constraints such as required clearance from street lighting and traffic signage, preservation of road visibility, key visual corridors, and appropriate tree-to-building distance. In terms of land use, areas with existing natural terrain are identified as areas for preservation or supplementation with NBS. All street areas not occupied by cycling, pedestrian or transport infrastructure are also considered as potential areas for the development of new NBS. Areas with appropriate existing use and a minimum required area (16 m² for tree; and 1 or 5 m² for shrubs and lower vegetation) were defined as suitable.

III. SPATIAL SUITABILITY ANALYSIS

This section presents the results of the spatial suitability assessment for implementing various NBS across four urban streets. Each NBS type—green roofs, vertical green walls, natural terrain with high vegetation, and natural terrain with low vegetation—was evaluated through spatial analysis in QGIS. The analysis aimed to identify locations where specific types of NBS are feasible, based on the simultaneous fulfilment of all relevant criteria. The following sub-sections provide detailed findings for each street, structured by NBS type, and include specific surface measurements, limitations, and information weather the solution is technically possible on each street.

A. *APPLICATION OF SUITABILITY EVALUATION CRITERIA IN RELATIVELY COMPACT URBAN PATTERN WITH AREAS OF LOW-DENSE AND DENSE URBAN PATTERN (CASE OF STREET A)*

Through the application of the defined suitability evaluation criteria, we identified specific locations along Street A that meet the spatial requirements for the implementation of various types of NBS. Three types of NBS — green roofs, and natural terrain with both high and low vegetation — were considered as potentially applicable along Street A.

1. VERTICAL GREEN

First, suitable facades in relation to Window-to-Wall Ratio (WWR) are mapped. Facades with at least 65% wall surface are mapped and integrated into QGIS, forming a database of facades where the Window-to-Wall Ratio (WWR) does not exceed 35%—meaning that windows, doors, or other openings occupy no more than 35% of the total façade surface. The analysis showed that in our case of relatively compact urban areas most of the buildings on the street do not exceeds 35%, which means that regarding the window-to-wall ratio the facades are suitable for greening. Next, north-facing façades or façades of buildings that remain shaded for most of the day due to surrounding structures were mapped, where the analyses showed that all façades on the street are south-facing and thus unsuitable for vertical green. In relation to visual exposure of facades, we identified that this street experiences predominantly high traffic, with both pedestrians and cyclists passing through, meaning the street is suitable for greening the facades. The criterion of cultural heritage protection was considered in the analysis to exclude buildings under architectural and settlement heritage protection as unsuitable for greening the facades. It was found that there is only one building under architectural heritage protection on this street, which makes the rest of the buildings suitable for greening. However, because the street does not simultaneously meet all key criteria—particularly in terms of façade orientation—vertical greening is deemed unfeasible in this street.

2. GREEN ROOF

The analysis of roof slopes showed that only one building on the street A consists slope under 11°, making the rest buildings roofs unsuitable for greening. In terms of the structural Integrity of buildings roofs, the analysis showed that most roofs of buildings does not consist of

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infrastructure related to solar panels, air conditioning units, ventilation systems, or glass roofing, making them suitable for greening according to this criterion.

3. NATURAL TERRAIN WITH HIGH VEGETATION

The analysis showed the presence of overhead infrastructure, street lighting and traffic signage on Street A. In addition, one building protected as cultural heritage was identified and the visibility of the road space was taken into account. There is underground infrastructure on most area of the street, including sewage systems, water supply networks, gas pipelines, electric grids, communication systems, meaning most surfaces along the road are unsuitable for the implementation of natural terrain with high vegetation.

Continuing with a land use criterion, the analysis showed that Street A has some areas not occupied by pedestrian or cycling infrastructure, making them suitable for planting vegetation. In addition, a compact green area with natural terrain, shrubs and trees was identified, which can be further supplemented with natural solutions (NBS).

Addressing the criterion of minimum surface, we found that Street A comprises suitable surfaces for addressing temperature and noise. These surfaces occur along the street in a longitudinal-linear strip between the street and the roadway, in a form of the paved, extensions of sidewalk. Their size exceeds 1 m², which corresponds to the minimum required surface area to contribute to the mitigation of temperature impacts. They also exceed 5 m², which is consistent with the minimum threshold for targeting noise reduction in the urban environment. The analysis also identifies one compact-sized area, with a surface larger than 16 m², suitable for addressing noise and temperature issues, and large enough to plant at least one tree. The size of this surface was also influenced by the tree-to-building spacing criterion.

After the spatial intersection process, the study identified that only one area meets all the criteria for implementing natural terrain with high vegetation (see results section A.)

4. NATURAL TERRAIN WITH LOW VEGETATION

The surfaces identified as potential for the implementation of natural terrain with low vegetation are currently paved sidewalk extensions running parallel to the road, offering suitable space for introducing low vegetation NBS. The analysis revealed the presence of vacant areas exceeding 1 m², which meets the minimum threshold for addressing temperature issues, and areas over 5 m², suitable for mitigating noise impacts. These surfaces are appropriate for implementing natural terrain with low vegetation, as they fulfill the dimensional requirements for effective performance in both aspects. By intersecting spatial layers of land use and surface dimensions, we identified continuous and dispersed areas along Street A that satisfy both criteria (see results section A) Additionally, a compact area with existing natural grass cover was identified. This area also presents potential for the implementation of low vegetation NBS, including low shrubs and perennials, provided that plant height does not exceed 1.5 m. Despite its potential for higher vegetation, the limitations regarding visibility and spatial constraints suggest it should be classified within the category of low vegetation NBS.

B. APPLICATION OF SUITABILITY EVALUATION CRITERIA IN LOW-DENSITY URBAN PATTERN (CASE OF STREET B)

For Street B, two types of NBS — natural terrain with high and low vegetation — were considered potentially applicable.

1. NATURAL TERRAIN WITH HIGH VEGETATION

The analysis identified the presence of overhead infrastructure in the form of street lighting and traffic signalisation along Street B. Taking this into account, we mapped specific areas where the implementation of natural terrain with high vegetation would not obstruct or interfere with existing above-ground elements. With regard to underground infrastructure, the analysis revealed the presence of various underground installations beneath most of the street, making large portions of the surface unsuitable for planting tall vegetation. However, exceptions were identified—most notably a compact green area with a central part free of underground infrastructure, as well as several linear zones parallel to building facades (see Figure 3).

In relation to land use, potential areas were identified along the street, characterised by existing roadside vegetation. As well compact green area (mentioned above) represent a potential site, containing a combination of low vegetation (grass), high vegetation (shrubs), and a single larger tree, which was identified for preservation and further enhancement through additional planting.

Regarding the minimum surface criterion, the analysis confirmed the presence of areas exceeding 16 m²—sufficient to accommodate at least one additional tree. This surface is located within the aforementioned compact green area. Furthermore, we identified additional areas suitable for greening, running parallel to the street and adjacent to residential buildings. These areas and characterised by existing natural terrain, offer potential for planting trees and shrubs.

After considering all criteria and intersecting the relevant spatial layers, the analysis showed that the implementation of natural terrain with high vegetation is possible in two locations along Street B (see Results section B).

2. NATURAL TERRAIN WITH LOW VEGETATION

The analysis identified areas along Street B that are not occupied by existing tall shrub vegetation and are therefore suitable for the implementation of low-vegetation NBS. These areas include surfaces with existing grass-covered terrain (e.g. roadside vegetation) and other free spaces where land use does not conflict with additional planting. This satisfies the existing land use criterion for implementing natural terrain with low vegetation.

Regarding the minimum surface criterion, the analysis revealed the presence of multiple free areas exceeding 1 m^2, which meets the threshold for addressing temperature issues, and areas over 5 m^2, which are suitable for mitigating noise impacts. These surfaces are thus considered spatially appropriate for achieving meaningful environmental effects.

By intersecting spatial data layers for land use and surface dimensions, we identified several intermittent grass-covered areas along Street B that meet both criteria (see Results section B).

C. APPLICATION OF SUITABILITY EVALUATION CRITERIA IN DENSELY BUILT-UP URBAN PATTERN (CASE OF STREET C)

For Street C, two types of NBS — Vertical green, green roof, natural terrain with high and low vegetation — were considered potentially applicable.

1. VERTICAL GREEN

First, façades were evaluated based on the Window-to-Wall Ratio (WWR). The analysis showed that most buildings on Street C have predominantly glazed façades, meaning they do not meet the WWR criterion and are thus unsuitable for greening.

Next, façade orientation was assessed. The analysis found that all façades on Street C are north-east facing, which meets the criterion and makes them suitable in terms of orientation.

The visual exposure criterion was considered through the concentration of people along the street. The street is characterized by high pedestrian and cycling traffic, particularly during commuting hours, which means that from a visibility and exposure perspective, the street is well-suited for green wall implementation.

Lastly, the cultural heritage protection criterion was evaluated to identify potential legal restrictions. The analysis showed that none of the buildings on Street C are under architectural or settlement heritage protection, making them suitable with respect to this criterion.

Although Street C fulfils several individual criteria—orientation, visual exposure, and cultural heritage—the high proportion of glazed surfaces means that the WWR criterion is not met. Consequently, the implementation of vertical green walls is not feasible on this street, as all conditions are not met simultaneously.

2. GREEN ROOFS

The analysis revealed that most buildings on Street C have low-slope roofs 11° or less, making them suitable for greening according to this criterion.

The second criterion assessed was the structural integrity of the roof, with particular attention to the presence of infrastructure such as solar panels, HVAC systems, and glass roofing. The results show that most rooftops are free from such obstructions, meaning that they can structurally support green roof installation.

Based on both criteria, all buildings along Street C were found to be suitable for green roof implementation. Since the majority of buildings are single-story, this further enhances the potential for cooling benefits to reach street level and improve pedestrian comfort.

3. NATURAL TERRAIN WITH HIGH VEGETATION

The analysis identified the presence of overhead infrastructure along Street C, including street lighting and traffic signalisation. These above-ground elements were taken into account when mapping areas suitable for NBS implementation, ensuring that tall vegetation would not interfere with existing infrastructure.
With regard to underground utilities, the analysis revealed a high density of underground installations beneath large portions of the street. This significantly reduced the area suitable for planting high vegetation. Nevertheless, specific segments remain viable, particularly where underground infrastructure is absent or less dense.

In terms of existing land use, potential locations were identified on two currently paved parking areas, which were considered for conversion into green spaces. Additionally, there is a segment along the street characterised by a tree-lined area and natural terrain, suitable for the planting of taller shrubs and supplementary vegetation.

Regarding the minimum surface criterion, the analysis confirmed the existence of multiple areas exceeding 16 m² and not occupied by pedestrian or cycling infrastructure. These areas include continuous green strips running almost the entire length of the street, as well as a larger parking area, both offering potential for NBS implementation.

After intersecting all criteria and analysing the suitability of available surfaces, the implementation of natural terrain with high vegetation was found feasible in three locations (see Results section C).

4. NATURAL TERRAIN WITH LOW VEGETATION

The analysis confirmed that the existing land use on Street C is compatible with the implementation of low-vegetation NBS. Several unoccupied surfaces, including paved parking areas and green strips, were identified as potentially suitable for introducing low-growing vegetation. Regarding the minimum surface criterion, the analysis revealed the presence of multiple unoccupied areas larger than 5 m², which meets the spatial threshold required to address both temperature regulation and noise mitigation. These areas were therefore classified as suitable for the implementation of low-vegetation NBS. By intersecting spatial data layers related to land use and surface dimensions, we determined that most locations suitable for high vegetation are also appropriate for low vegetation. However, as low vegetation is not subject to the same spatial restrictions imposed by underground infrastructure, additional areas were identified—particularly on paved surfaces—where low-vegetation NBS could be more extensively applied. Low vegetation is already present in certain sections of Street C, primarily in the form of existing roadside greenery. However, the analysis indicates substantial potential to expand this vegetation into new areas, such as the aforementioned parking surfaces (see Results section C).

D. APPLICATION OF SUITABILITY EVALUATION CRITERIA IN DENSELY BUILT-UP HISTORIC URBAN PATTERN (CASE OF STREET D)

1. GREEN ROOF

The analysis revealed that nearly 50% of the total roof area along Street C consists of low-slope roofs (up to 11°), making them suitable for greening according to this criterion. The analysis also showed that 24% of the total roof area is occupied by infrastructure such as solar panels, air conditioning units, ventilation systems, or glass roofing, which makes these sections unsuitable for green roof installation. While several buildings on the street meet the criterion for roof slope, the presence of rooftop infrastructure on certain buildings limits the overall potential for green roof implementation. Based on the spatial overlay analysis conducted in QGIS, we identified buildings along the street that meet both key criteria for green roof implementation—having an appropriate roof slope and being free of obstructive infrastructure. The detailed results are presented in Results, section D.

2. VERTICAL GREEN

The analyses showed that only one façade on the street was identified as meeting this criterion, with a sufficient wall surface area and a WWR below 35%, meaning that windows and openings occupy less than 35% of the façade. In terms of orientation, the analysis showed that most façades on the street are north-facing or remain in shadow for the majority of the day due to adjacent buildings. This orientation is favourable for vertical greening, as it reduces exposure to excessive solar radiation and prevents overheating of the vegetation. Regarding the concentration of people, this street experiences consistently high levels of activity throughout the day. The presence of retail establishments and its location in the historic centre of Ljubljana result in both frequent foot traffic and longer dwell times, making the street highly visible and suitable for vertical greening from a social and functional perspective. However, in relation to cultural heritage protection, the analysis determined that vertical greening is not feasible. The entire street lies within a settlement heritage protection zone, and most buildings are additionally protected under architectural heritage regulations, which significantly limit possible interventions on façades. Although the street meets certain criteria—such as favourable orientation and high visual exposure—the presence of strict heritage protection and the very limited number of façades with an appropriate WWR make the implementation of vertical green walls unfeasible in this location.

IV. ROBUSTNESS, ACCURACY AND VALIDATION OF SPATIAL DATA

1. THRESHOLD SENSITIVITY ANALYSIS

To assess the robustness of the spatial suitability analysis, a ±10% sensitivity test was performed within a subsection of Street B. The test examined the suitability of locations for high vegetation (trees) by varying two key parameters: (1) the minimum offset from underground infrastructure and (2) the minimum offset from buildings. Both criteria strongly influence the feasibility of tree placement. For the first criterion, the minimum required distance from underground utilities—including sewage systems, water and gas pipelines, electricity and communication networks, and district heating systems—was varied by ±10%. In the original model, the offset was set in the range of 2.0–2.5 m (depending on the specific type of infrastructure) to ensure the safe placement of high vegetation (trees), primarily because of the potential risk that root systems pose to underground utilities. Adjusting this range by ±10% resulted in changes in the calculated suitable area. When the threshold was reduced to 1.8–2.25 m, the suitable area increased from 17.3 m² to 22.1 m² (+27.8%). Conversely, increasing the threshold to 2.2–2.75 m reduced the suitable area to 12.9 m² (−25.4%). These results demonstrate that small changes in spatial thresholds can significantly influence suitability outcomes, underlining the importance of careful, context-sensitive threshold definition in spatial planning involving nature-based solutions. Although the additional 5 m² gained by lowering the threshold does not suffice for an additional tree — as approximately 16 m² is required per tree, even minor increases in vegetated surface can positively affect microclimatic conditions**.** A detailed overview of threshold sensitivity analysis (the location of anaysed area, threshold values and their impact on suitable area) is presented in Appendix, threshold sensitivity analyses.

2. DATA ACCURACY

The spatial analysis in this study is based on multiple GIS datasets with varying resolution and precision. Minor geometric deviations (typically within ±0.5 m) were observed, particularly in building outlines and street elements. These deviations could influence the delineation of suitability zones for certain NBS types, such as tree planting, which requires specific horizontal offsets. Roof slope was assessed visually with an estimated accuracy of ±1–2°, which was adequate for evaluating extensive green roof feasibility. To address these uncertainties and ensure spatial reliability, all critical layers were visually validated using high-resolution Google Satellite imagery, DOF orthophotos, and field verification. This multi-source validation significantly reduced positional uncertainty and ensured that the spatial assessment reflects realistic on-site conditions. A detailed overview of threshold values and their impact on suitable area is presented in Appendix, data accuracy section.

3. VALIDATION OF SPATIAL DATA

We conducted a ground-truth check to evaluate the accuracy of the GIS dataset used in our model. For this purpose, the land cover layer was selected, as land cover represents a key precondition for the spatial implementation of NBS and was therefore considered one of the most important variables. Two complementary validation methods were applied on four selected streets: (1) visual interpretation of very high-resolution satellite imagery (Google Satellite) and (2) on-site field verification of all selected locations. For each street, 15 control points were examined, resulting in a total of 60 validation points. Both methods were cross-checked against data from the proposed GIS dataset. Across all four streets, 60 such points were examined, consistently confirming a 100% match between the GIS dataset and the combined evidence from high-resolution satellite imagery and field verification, demonstrating the reliability of the spatial data used in this study. To illustrate the procedure, a sample evaluation of five control points on Street B is provided in the Appendix (section Validation of spatial data).

V. RESULTS

This chapter first presents a general overview of the spatial feasibility analysis, summarised in a comparative table (Table 3), that reflects the suitability of different NBS types across the pilot sites. Subsequently, the results are discussed in greater detail for each individual street, allowing for a context-sensitive interpretation based on their distinct urban characteristics.

TABLE 3
SUMMARY OF THE RESULTS RELATED TO APPLICATION OF THE CRITERIA OF SUITABILITY ANALYSES.

VERTICAL GREEN				
Criteria:	Street A:	Street B:	Street C:	Street D
A suitable window-to-wall ratio (WWR).	Yes, most buildings have a suitable ratio.	Irrelevant (The buildings do not directly border the street.)	No	Yes, one building has a suitable ratio.
Suitability of facade orientation	No	Irrelevant (The buildings do not directly border the street.)	Yes	Yes, almost all buildings.
Concentration of people	Yes	No	Yes	Yes
The areas are protected by cultural heritage protection regimes	Yes, one building is under architectural heritage regime.	No	No	Yes
Suitability of street surfaces for vertical green implementation	No	No	No	Yes
GREEN ROOF				
Criteria:	Street A:	Street B:	Street C:	Street D:
Suitable roof slope	No, most of the buildings don't have suitable roof slope.	Irrelevant (The buildings do not directly border the street.)	Yes, most of the buildings have suitable roof slope.	Yes, 4 out of 10 buildings have a suitable roof slope.
Structural integrity of roof that would prevent greening	No	Irrelevant (The buildings do not directly border the street.)	No	Yes, some of the buildings.
Suitability of street surfaces for green roof implementation	Yes, one building is suitable.	Irrelevant	Yes, all buildings are suitable for greening.	Yes, 50% of the total roof area on the street is suitable for greening.
NATURAL TERRAIN WITH HIGH VEGETATION				
Criteria:	Street A:	Street B:	Street C:	Street D:
Presence of overhead infrastructure	Yes	Yes	Yes	Yes
Presence of streetlights and traffic signage	Yes	Yes	Yes	Yes
Road visibility	Yes	Yes	Yes	No. Street is a traffic-free pedestrian zone.
Presence of vistas	No	No	No	Yes
Tree-to-building spacing that needs to be considered	Yes	Yes	Yes	Yes
Presence of underground infrastructure	Yes, on most surfaces.	On some surfaces.	On some surfaces.	Yes, on most surfaces.
Suitability of surfaces considering criterium of minimum surface	Yes	Yes	Yes	Yes
Potential for NBS considering existing land use potential	Yes	Yes	Yes	No
Suitability of street surfaces for natural terrain with high vegetation implementation	Yes	Yes	Yes	No

NATURAL TERRAIN WITH LOW VEGETATION				
Criterion:	Street A:	Street B:	Street C:	Street D:
Potential for NBS considering existing land use potential	Yes	Yes	Yes	No
Suitability of surfaces considering criterium of minimum surface	Yes	Yes	Yes	No
Suitability of street surfaces for natural terrain with low vegetation implementation	Yes	Yes	Yes	No

A. POTENTIAL FOR IMPROVED HIGH TEMPERATURE AND NOISE RELATED CONDITIONS IN STREET A

Based on the spatial suitability analysis following the criterions outlined above (Table 3), we identified three potential NBS could be implemented on street A. These solutions include Green roofs to mitigate temperature extremes, Natural terrain with high vegetation to address both temperature and noise issues, and Natural terrain with low vegetation to improve temperature conditions.

Along Street A, we identified areas suitable for low-vegetation NBS extending over a total length of 99 m and a width of 1 m, primarily in the form of a roadside strip that currently serves as an extended sidewalk. These surfaces are distributed along nearly the entire street, allowing for widespread implementation and, consequently, contributing to temperature regulation. However, low vegetation primarily addresses thermal issues and has little effect on noise reduction. According to the literature, grass surfaces can lower air temperature significantly compared to asphalt, with differences of up to 3.4 °C at 1.2 m height **[14]**. Hedges have shown cooling effects of approximately 1.13–1.29 °C per m² through evapotranspiration and can reduce surface temperatures by up to 19 °C compared to asphalt [17]. Similarly, shrubs have been shown to maintain surface temperatures 7.2–11.4 °C lower than concrete pavement [18]. The implementation of low-vegetation NBS appears to be a viable strategy for mitigating air temperature. While the precise cooling effect would require simulation to quantify, the continuous presence of green elements along most of the street suggests a contribution to temperature reduction. However, since the primary pedestrian surface remains asphalt, the cooling effect would largely be confined to the narrow vegetated strip along the sidewalk. Furthermore, as this solution does not address noise, that environmental issue remains unresolved.

Natural terrain with high vegetation can only be introduced in one specific location—a compact green area covering 44 m². Within this space, it would be feasible to plant either two/three trees with a crown diameter of 10 m. These could be complemented with shrub undergrowth to enhance microclimatic effects. Although we also identified potential for natural terrain with low vegetation in this area, we prioritize the implementation of high vegetation due to its greater impact on cooling and noise attenuation. As this area represents only 7 meters of the total 154-meter street length, the effect of high vegetation is expected to remain confined to this compact zone (see Figure 2). According to the literature, both temperature and noise-related issues can be addressed through the use of natural terrain with high vegetation. Trees – especially two rows of large street trees – can lower the Physiological Equivalent Temperature by up to 8.7 °C, significantly improving human thermal comfort in urban neighbourhoods [15]. By providing effective shade, they also enhance perceived thermal comfort, often referred to as "feels-like" conditions. Since the areas suitable for greening is possible only in a limited section of the street, we conclude that this NBS lacks the capacity to enhance thermal comfort along the entire corridor. Nevertheless, its implementation remains justified for improving local microclimatic conditions within the designated area. This is particularly relevant near the intersection, where the presence of shade could at least partially enhance the thermal comfort of pedestrians waiting to cross the street.

The next type of NBS considered in this study is the green roof. The literature review suggests that green roofs are an effective nature-based solution (NBS) for mitigating the urban heat island effect in cities but have limited impact on noise reduction. However, their impact on temperature reduction at pedestrian level remains minimal, with a recorded decrease of up to 0.2°C on the downwind side **[**13**]**. The result of the analysis identified that only one building is suitable for roof greening, with a roof surface of just 60 m², accounting for only 3% of the total street length (5 m out of 154 m). Due to the small surface area and thus limited impact of green roofs on cooling, we conclude that this solution addresses temperature issues only in a fragmentary manner and has not the capacity for improve user comfort.

Given the high levels of uncomfortable environmental conditions, achieving a "comfortable" classification solely through these proposed solutions would not be feasible for improving noise or temperature conditions. However, in the broader context of mitigating urban heat, these solutions still play a significant role in cooling the city, especially if the feasibility and implementation of NBS are expanded to additional streets.

FIGURE 2. **The results of the suitability assessment for implementing different types of NBS on Street A indicate that only natural terrain with High Vegetation and Low Vegetation can be successfully implemented.**

B. POTENTIAL FOR IMPROVED HIGH TEMPERATURE AND NOISE RELATED CONDITIONS IN STREET B

On Street B, which faces high temperatures and noise, we identified two possible NBS types as suitable for implementation based on the spatial suitability analysis: natural terrain with high vegetation to address both temperature and noise issues, and natural terrain with low vegetation to address the temperature issue.

Areas suitable for high-vegetation NBS were identified in two locations in street B. The first is a compact green area measuring 17 m², where one larger tree (with a crown diameter of 10 m) can be planted—along with accompanying tall shrub undergrowth. However, this location is representing only 1.4% of the total street length (211 m). The second location includes linear zones parallel to buildings, covering approximately 60 m². Within this area, it is feasible to plant up to three larger trees (with a crown diameter of 10 m) or up to six smaller trees (with a crown diameter of approximately 6 m), along with accompanying understory shrubs (see Figure 3). These areas represent 10% of the total street length. Given the limited surface area suitable for greening, we assess that the proposed solution would only fragmentarily improve pedestrian thermal comfort. Moreover, it would not contribute to noise reduction, as it is not positioned between the noise source and the pedestrian sidewalk.

Implementing natural terrain with low vegetation is possible on areas forming a discontinuous linear strip measuring 126 m in length (approximately 60% of the total street length) and approximately 1 m in width, running parallel to the road on the widened sidewalk zone. In addition, a compact green area of 85 m² was identified,

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featuring existing grass cover and offering additional potential for planting low shrubs and perennial species. All identified areas fulfil the criteria for land use and minimum spatial requirements, making them suitable for implementing low-vegetation NBS. As discussed previously (see results, section A), low vegetation is effective primarily in temperature regulation, while it has limited impact on noise reduction. Given the spatial distribution of suitable areas along a significant portion of the street, we estimate that such interventions could contribute to improved temperature conditions, particularly for pedestrians. However, as the primary pedestrian surface remains paved, the cooling effect would be localized, and noise issues would remain largely unaddressed.

FIGURE 3. **The results of the suitability assessment for implementing different NBS types on Street B indicate that only natural terrain high and Low Vegetation can be successfully implemented.**

C. POTENTIAL FOR IMPROVED HIGH TEMPERATURE AND NOISE RELATED CONDITIONS IN STREET C

On Street C, which faces high temperatures and noise, we identified three possible NBS types as suitable for implementation based on the spatial suitability analysis: natural terrain with high vegetation to address both temperature and noise issues, natural terrain with low vegetation to address the temperature issue and green roof.

Along Street C, all buildings were identified as suitable for green roof implementation, fulfilling both key criteria—low roof slope (≤ 11°) and absence of obstructive rooftop infrastructure. The total area of rooftops meeting these conditions amounts to 2,623 m², which represents 72% of all roof surfaces on the street. Given that the majority of buildings are single-story, the potential for the cooling effect to reach street level is enhanced. However, according to existing research, green roofs have a limited impact on pedestrian-level temperature—with reductions of up to only 0.2 °C in the downwind zone [13]. Despite this limitation, green roofs can still contribute to broader urban cooling strategies, and their implementation would prevent further heating of paved or unshaded surfaces at the city scale.

Continue with the natural terrain with high vegetation. Along this street, it is feasible to plant approximately 14 larger trees (with a crown width of 10 m) across two sites currently occupied by paved parking areas, covering a total of 236 m². These trees could be complemented by the planting of tall shrubs, contributing to increased vegetative cover and improved microclimatic regulation. In addition, a third location—consisting of a continuous green strip running along nearly the entire length of the street—was identified as suitable for the planting of tall shrubs. Although the vegetation at these three locations would not provide direct shade over the main pedestrian or cycling corridors, it would still contribute to ambient cooling through evapotranspiration and surface shading in adjacent areas, so we see it as feasible. In terms of noise reduction, the solution appears unfeasible, as effective sound buffering requires vegetation to be positioned between the road—the primary noise source—and the pedestrian zones, which is not possible in this case.

And finally, natural terrain with low vegetation. Based on the literature review on the effects of natural terrain with low vegetation for temperature and noise reduction, it is well established that shrubs and grass can effectively reduce ambient temperatures through evapotranspiration and surface shading. However, their impact on noise reduction is limited, as low vegetation does not create sufficient physical barriers between noise sources and pedestrian areas. In the case of Street C, the analysis identified a total of approximately 2,500 m² of surface suitable for the implementation of low vegetation. This represents an increase of 279% compared to the current extent of low-vegetation cover. Therefore, this solution appears highly effective, particularly because low shrubs and perennial species would replace paved parking surfaces, which currently occupy a large portion of the space along the street. Although the proposed vegetation would not provide direct shade over the street or pedestrian areas, we still consider this intervention meaningful due to the substantial surface area involved. The conversion of impervious, heat-retaining surfaces into vegetated areas would significantly reduce surface temperatures and mitigate urban heat island effects.

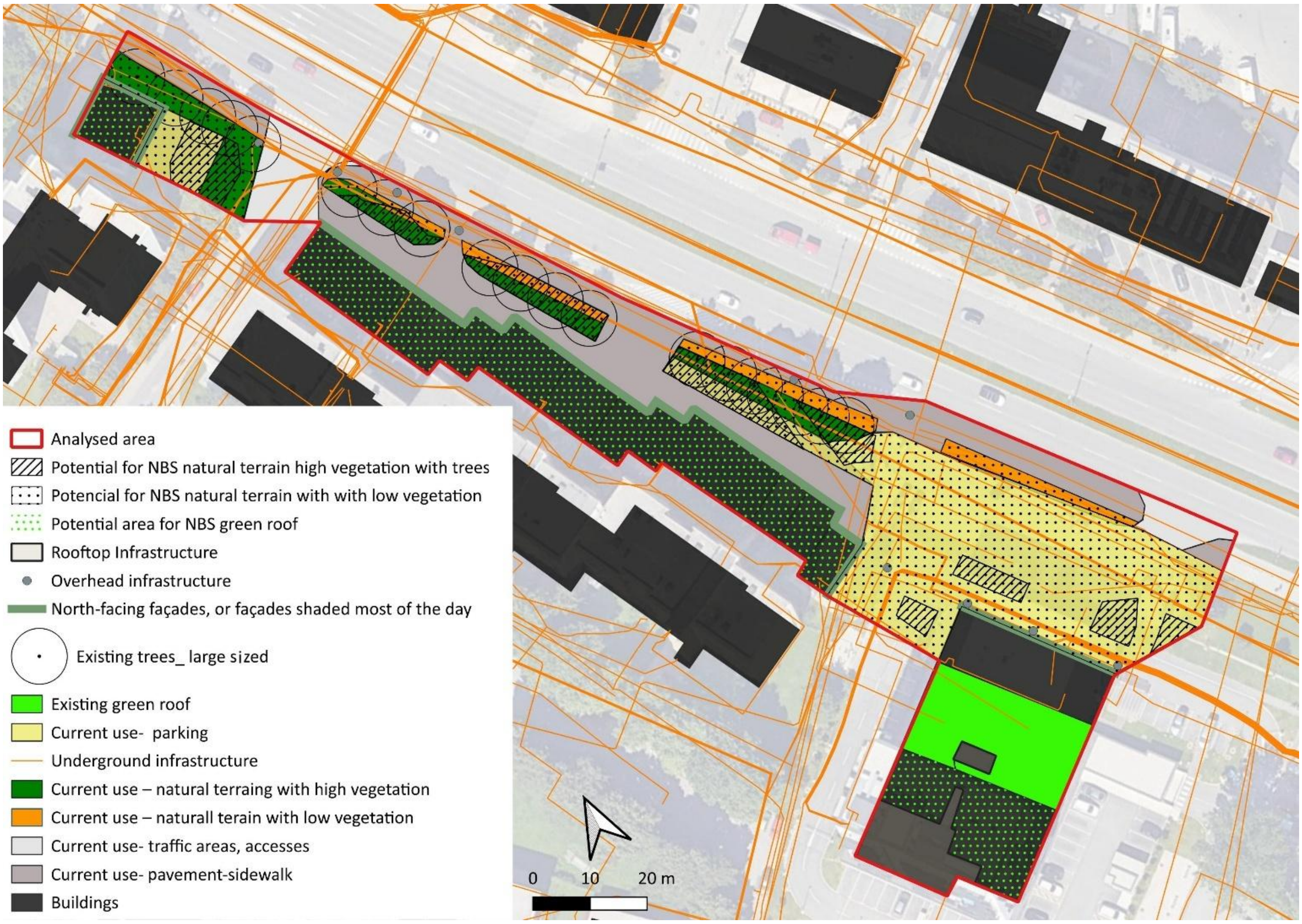

FIGURE 4. **The results of the suitability assessment for implementing different NBS types on Street C indicate that only NBS Natural terrain with high Vegetation, and low vegetation and green roof can be successfully implemented.**

D. POTENTIAL FOR IMPROVED HIGH TEMPERATURE AND NOISE RELATED CONDITIONS IN STREET D

Based on the spatial suitability analysis, only one type of NBS was identified as potentially feasible on Street D: the implementation of green roofs, primarily aimed at improving temperature conditions.

The analysis showed that 35% of the total roof area—equivalent to 2,802 m² out of 8,047 m²—meets both key criteria for green roof implementation: low roof slope (≤ 11°) and absence of obstructive rooftop infrastructure (see Figure 5). Although this represents a considerable portion of the total rooftop area, current research indicates that green roofs have only a negligible impact on pedestrian-level temperatures—typically reducing air temperature by up to 0.2 °C in the downwind zone [13]. Moreover, the cooling effect of green roofs diminishes with building height. Given that most buildings along Street D are three to four stories high, the potential for noticeable temperature reduction at street level is limited. As such, the implementation of green roofs on this street is not considered a priority NBS in terms of improving thermal comfort for pedestrians. Nevertheless, green roofs may still contribute to long-term urban cooling and stormwater retention on a broader scale.

FIGURE 5. **The results of the suitability assessment for implementing different NBS types on Street D indicate that only NBS green roof can be successfully implemented.**

VI. CONCLUSION

Based on the results of the spatial suitability analysis, it is evident that while NBSs offer potential for addressing temperature and noise issues in dense urban areas, their effectiveness is highly dependent on spatial constraints and urban morphology. Across all four analysed streets, the feasibility of implementing NBS is significantly limited by the available space and the need for optimal placement to achieve meaningful environmental benefits. High vegetation, which is often the most effective solution for both temperature reduction and noise mitigation, cannot be optimally positioned on any of the studied streets in a way that would fully address both issues. In multiple cases, such as Street A, Street B, and Street C, high vegetation could not be placed between the noise source and pedestrians, thereby limiting its impact on noise reduction. Meanwhile, on Street D, no NBS interventions are feasible except for roof greening, which does not provide significant temperature reduction at the pedestrian level nor contribute to noise mitigation.

These findings highlight that the role of NBS in enhancing urban comfort is not only dependent on their theoretical potential but also on the spatial and morphological constraints of each site. While low vegetation can be more widely implemented, its environmental impact is limited, particularly in addressing noise-related issues. Moreover, the results indicate that achieving a "comfortable" classification solely through NBS is not feasible for these streets, as their effectiveness is restricted by urban density, existing infrastructure, and street layout. However, despite these limitations, NBS can still contribute to broader urban cooling effects, particularly if implemented at a larger scale across multiple locations. This suggests that while NBS are essential for enhancing urban comfort, their successful implementation depends on strategic, city-wide planning that proactively considers spatial constraints. It is crucial to design urban spaces in alignment with desired climatic outcomes—ensuring sufficient above- and below-ground space for NBS integration from the outset, as retrofitting such solutions in already dense environments often proves difficult or unfeasible. In addition to spatial limitations, economic feasibility and ownership structure also play a significant role in the actual implementation of NBS. From the perspective of climate resilience, land-use decisions should be more closely aligned with the natural characteristics and capacities of the urban environment to deliver nature-based outcomes. However, this principle often conflicts with existing ownership structures. This creates a significant barrier to NBS implementation, as property owners are frequently unwilling to invest in greening measures unless there are clear incentives or policy mandates. Furthermore, economic feasibility remains a key concern: although green roofs and façade greening provide environmental benefits, their relatively high installation typically ranging from €55–70/m² for extensive roofs and €500/m² onwards for vertical greening systems—can limit adoption, especially for individual private buildings. These factors underline the importance of integrated urban planning approaches that consider not only spatial suitability, but also socio-economic conditions and governance mechanisms.

APENDIX

1. THRESHOLD SENSITIVITY ANALYSIS

TABLE 4
THRESHOLD SENSITIVITY ANALYSIS

Threshold sensitivity analysis for locating suitable area for high vegetation (tree) placement in relation to the required distance from underground infrastructure			
Threshold	**Distance (minimum required offsets from underground infrastructure for tree planting) (m)**	**Suitable area (m²)**	**Change (%)**
0% (base case)	2.0m (sewage, electric network, electric comm, water supply) and 2.5m (gas pipes, heating)	17.3	—
-10%	1.8m (sewage, electric network, electric comm., water supply.) and 2.25m (gas pipes, heating)	22.1	+27.8%
+10%	2.2m (sewage, electric network, electric comm, water supply) and 2.75m (gas pipes, heating)	12.9	−25.4%

Threshold sensitivity analysis for locating suitable area for high vegetation (tree) placement in relation to the minimum required distance from buildings			
Threshold change	**Distance**	**Suitable area (m²)**	**Change (%)**
0% (base case)	3	44	—
-10%	2.7	45.1	+2.5%
+10%	3.3	43.6	–0.9%

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FIGURE 6. **Display of an area with threshold sensitivity analysis performed.**

2. DATA ACCURACY

TABLE 5
DATA ACCURACY OF DATA SET USED IN GIS MODEL

GIS Layer (Data)	Source of base data	Resolution	Deviation	Impact on suitability maps
Buildings, roads	Topographic data collection (DTM), Slovenian ministry of natural resources and spatial planning [43]	Vector data, 1:5,000	0–50 cm	Minor impact: inaccuracies may influence the definition of suitable areas for tree planting, possibly changing vegetation suitability areas. Yet, the positioning of objects was visually validated (DOF, Google Satellite, field check), and no major deviations detected.
Roof slope	Mapped on the basis of field observation and DTM	Individual building, resolution 1:5,000 (inherited from DTM)	Estimated error ±1–2°	Minor impact
Overhead infrastructure, Roof integrity, Distance from signage/streetlights	Mapped on basis of Google Satellite imagery (visual digitization)	Individual building, resolution 1:5,000 (inherited from DTM) [44]	Accuracy ≤0.5 m	Minor impact; visual validation (DOF, Google Satellite, field check) confirmed sufficient accuracy.
Orientation of facades	Mapped facades on basis of DTM [44]	Individual facade; resolution 1:5,000 (inherited from DTM) [44]	Estimated error: ±0.5 m (incl. digitization error ±0.2 m)	Minor impact
Land use (vegetation type, paved areas)	Mapped areas on basis of digital orthophoto (DOF) [45]	0.25 m	±0.5 m	To validate data accuracy, a ground-truth check was conducted, and no anomalies were detected (see Section IV.3: Validation of spatial data).
Cultural heritage protection	Geolocated points, Register of immovable cultural heritage [46]	Not known	Not known	In this analysis, protected areas were represented solely by

				individual heritage objects. Their positional accuracy was validated by the DTM dataset.
Underground infrastructure	Utility Cadaster, Ministry of natural resources and spatial planning [43].	Vector data; usual line accuracy ≤1 m depending on source	±0.5–1 m	Minor impact: positioning errors may influence tree planting areas due to root clearance requirements. May change suitability areas slightly.

3. VALIDATION OF SPATIAL DATA

TABLE 6:
GROUND-TRUTH CHECK OF THE LAND COVER LAYER.

Po-int No.	Coord.	GIS dataset related to the land use	Satellite imagery	Field verific-ation	Match (Yes/No)
1	46.0459743, 14.4796254	Natural terrain with high veg.	High veg.	High shrub	Yes
2	46.0459957, 14.4795402	Natural terrain with low veg.	Low vegetation	Grass	Yes
3	46.0460857, 14.4795446	Building	Building	Roof of the building	Yes
4	46.0459826, 14.4796563	Natural terrain with high veg.	High vegetation	High shrub	Yes
5	46.0460571, 14.4793691	Sidewalk	Sidewalk	Paved sidewalk	Yes

FIGURE 7: **Location of points where we performed ground-truth check.**

TABLE 7:
THE RESULTS OF THE GROUND CHECK ACROSS 4 STREETS.

Street	Total points checked	Matches of points in the GIS dataset with satellite imagery and field verification	Accuracy (%)
Street A	15	15	100%
Street B	15	15	100%
Street C	15	15	100%
Street C	15	15	100%

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