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Data set on nature-based solutions

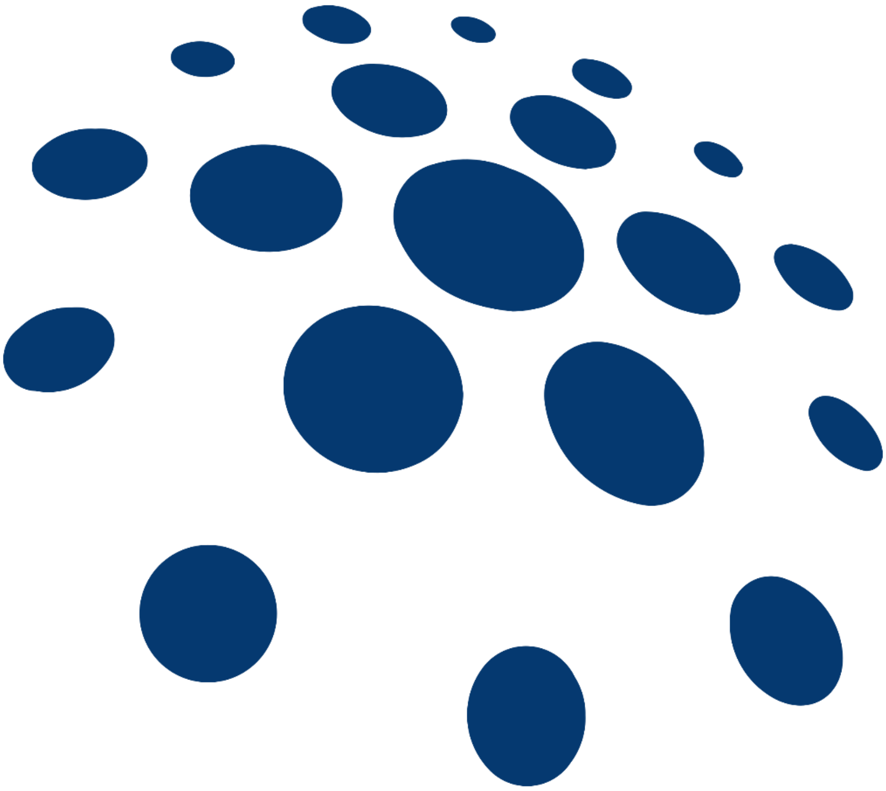

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Table of Contents

List of Tables

Executive Summary

This deliverable presents the database developed within the Net4Cities project to support the harmonised assessment of nature-based solutions (NbS) across 11 European cities. The database enables consistent, spatially explicit analysis of urban vegetation and the conditions under which NbS may contribute to improved environmental outcomes, with a particular focus on air quality and environmental noise.

Although NbS are widely recognised as effective tools to address urban challenges such as heat stress, flooding, and biodiversity loss, their role in mitigating air pollution and noise remains difficult to assess. The effects of urban vegetation in these domains are indirect, highly dependent on local conditions, and often limited or variable. This makes it challenging to develop comparable indicators or robust evaluation frameworks across different cities.

To address this challenge, the Net4Cities project adopts an alternative approach. Rather than directly measuring impacts on pollution levels or noise, the database focuses on identifying the spatial conditions under which NbS may deliver health and environmental benefits. This is achieved through the implementation of the 3-30-300 framework, which captures three key dimensions of urban green: proximity to trees, neighbourhood-level vegetation cover, and access to larger green spaces. Accordingly, the approach provides spatial proxies of these conditions, rather than directly quantifying impacts on air pollution or noise levels.

The database integrates multiple harmonised datasets, including satellite-derived vegetation indicators and land-use information from the Copernicus Land Monitoring Service. These data are processed using a reproducible geospatial workflow to generate building-level indicators for each of the three rules. The result is a consistent and scalable dataset that allows comparison across cities while remaining sensitive to local urban structures.

The main output of this work is a spatial database implemented as a GeoPackage, where each residential unit is associated with vegetation metrics and compliance indicators for the 3-30-300 framework. This enables the identification of spatial patterns, inequalities in access to green space, and indicative priority areas for intervention.

The database provides a robust and flexible tool for urban analysis, supporting policy development, planning, and monitoring of NbS. By focusing on spatial preconditions rather than direct impact quantification, it offers a pragmatic and transferable approach to evaluating the potential benefits of urban green infrastructure in complex and data-constrained contexts.

1. Introduction

This deliverable details the analytical framework, data foundation, and methodology behind the database on nature-based solutions (NbS) created for the 11 cities in the Net4Cities project. The database is designed to support a spatially explicit, harmonised, and comparable assessment of urban NbS, with a particular focus on their potential interactions with air quality and environmental noise.

The work is motivated by the growing recognition that although NbS are widely promoted to address urban environmental challenges, although their contributions to air pollution mitigation and noise reduction are still complex to operationalise (Vashist et al, 2024). In contrast to other domains such as urban heat mitigation or stormwater management—where cause–and–effect relationships are relatively well established—the influence of urban vegetation on air pollution and noise operates through indirect, context-dependent, and sometimes competing mechanisms. The magnitude and direction of these effects are uncertain, highly sensitive to local conditions including urban morphology, vegetation structure, micro-meteorological dynamic (e.g., wind flow, turbulence), and acoustic context, and at times counterproductive — for instance, in confined street canyons where vegetation can reduce ventilation rather than improve it. Section 2 develops this argument in full.

In response to this challenge, this deliverable introduces a structured and harmonised framework, implemented through the project database, to characterise the spatial and morphological conditions under which NbS benefits may plausibly arise. Rather than directly quantify impacts on air quality or noise, the approach provides spatial indicators of potential exposure to urban green that can be combined with monitoring and modelling outputs from other Net4Cities WPs. By systematically linking urban vegetation patterns with the built environment at the scale of residential areas, the database enables consistent cross-city comparison and supports interpretation and planning.

The deliverable details the conceptual framework, data selection principles, and integration methodology that underpin the database. It also describes how heterogeneous data sources—including Earth observation products such as those from the Copernicus Land Monitoring Service—are harmonised and combined to ensure reproducibility and scalability across different urban contexts.

The remainder of this document is structured as follows: Section 2 presents the overall framework and conceptual approach; Section 3 describes the data sources and selection criteria; Section 4 details the data processing and integration methodology; and Section 5 outlines the database structure and implementation

2. Conceptual framework

2.1. Nature-based solutions, green infrastructure, and urban green

NbS, green infrastructure (GI), and urban green are closely related concepts that together describe how natural and semi-natural systems can be planned, designed, and managed to deliver environmental, social, and economic benefits in urban areas (Štrbac et al., 2023).

NbS provide the overarching conceptual framework. They refer to actions inspired by, supported by, or copied from nature that address societal challenges while delivering multiple environmental, social, and economic co-benefits (European Commission, 2015). Within urban contexts, NbS are increasingly promoted as integrated responses to climate adaptation, public health, biodiversity loss, and environmental quality. A defining characteristic of NbS is their focus on function and performance—nature is treated not only as an amenity, but as an active system delivering services such as temperature regulation, pollutant removal, water retention, and psychological restoration (Somarakis et al., 2019).

Green infrastructure is an integral component of the NbS framework and emphasizes the spatial organisation and connectivity of natural and semi-natural areas (Fang et al., 2023). Green infrastructurel refers to strategically planned networks of green and blue spaces designed to maintain ecosystem functions and enable ecological connectivity across scales (European Commission, 2013). In cities, green infrastructure supports multifunctionality by linking parks, street trees, private gardens, riparian corridors, and peri-urban green areas into coherent systems rather than isolated elements.

Urban green refers to the actual physical elements in cities—parks, street trees, green roofs, community gardens, riparian corridors, or small pocket forests. These components form the building blocks that can be organised into green infrastructure and used to deliver NbS outcomes.

These three concepts can therefore be understood as forming a functional hierarchy (Zarei and Shahab, 2025):

- Urban green provides the physical elements available in cities.
- Green infrastructure organises these elements into connected, multifunctional systems.
- NbS determine how these systems are applied to address specific societal challenges.

In this way, the three concepts form a coherent hierarchy: urban green as the elements, green infrastructure as the system, and NbS as the purpose-driven application.

2.2. Measuring the impact of NbS on air quality and noise

Despite the growing recognition of NbS in European and national urban policies, their implementation has consistently prioritised objectives such as climate adaptation, heat mitigation, flood risk management, and biodiversity enhancement (Zarei and Shahab, 2025). The systematic application of NbS to address air pollution and environmental noise remains comparatively fragmented.

A systematic literature review conducted within Net4Cities (Liu et al., 2026), covering 26 papers and 38 projects, indicates both the potential and the limitations of NbS for improving air quality. Well-designed interventions can reduce local $PM_{2.5}$, PM_{10}, and NO_2 concentrations by approximately10–30% under specific local conditions, representing a meaningful benefit for populations in close proximity. At the city or regional scale, however, these contributions drop to less than 1% of overall pollutant reductions, reflecting the dominant role of emission sources and atmospheric dynamics at those scales.

The picture is further complicated by adverse configurations: dense canopies in street canyons, or species with high biogenic volatile organic compound (BVOC) emissions, can increase NO_2 or O_3 concentrations by 5–25%. These findings indicate that the effectiveness of NbS for air quality is not inherent to the presence of vegetation, but depends on spatial configuration, species selection, and the surrounding urban morphology. Overall, NbS effectiveness is highly context-dependent and cannot be generalized across different urban environments without detailed local analysis.

The situation is structurally similar for noise, though the underlying mechanisms differ. Vegetation can attenuate sound propagation and improve acoustic perception, but its physical effectiveness is generally limited compared to engineered barriers and remains highly context-dependent (Rey-Gozalo et al., 2023; Bakker et al., 2023). In practice, the most consistent effects of urban green on noise are perceptual rather than physical: visible vegetation reduces annoyance and improves soundscape quality even without measurable reductions in sound pressure levels (Van Renterghem, 2019, EEA, 2025).

The diverse ways in which NbS affect air quality and environmental noise, with impacts varying by scale, pose significant methodological challenges. The lack of standardised metrics, shared indicators, and uniform evaluation frameworks makes it difficult to consistently evaluate and compare NbS impacts across various contexts. This issue is particularly evident in multi-city initiatives, such as the 11 cities in Net4Cities, where differences in urban form, climate, data access, and governance complicate establishing a unified assessment approach.

Given the difficulty of directly quantifying NbS impacts on air quality and noise, the Net4Cities project adopts a complementary perspective grounded in a robust and expanding body of epidemiological and environmental health evidence: that urban green space generates measurable health benefits independently, and that these benefits partly buffer the harmful effects of the very stressors — air pollution and noise — that NbS struggle to mitigate physically.

The pathways through which urban green space affects health are now well established. Greenspace is generally understood to benefit human health through the following domains: restoring capacities through attention restoration and stress recovery; and building capacities by supporting physical activity and social cohesion (Browning et al., 2022). Critically, these pathways do not operate independently. Cardiovascular benefits, for instance, can arise simultaneously through enhanced physical activity, improved mental restoration leading to reduced chronic stress, and reduced exposure to air pollution and noise (Liu et al., 2021). The health benefits of green space are therefore not reducible to any single mechanism, which is precisely what makes them robust across different urban contexts.

The restorative pathway is particularly relevant for residents exposed to air pollution and environmental noise because it operates even when physical mitigation is absent or only modest. The restorative properties of visible vegetation appear to be the dominant mechanism by which green space is associated with improved noise perception: high-quality visible natural features lead to sustained attention restoration and stress relief, counteracting the negative outcomes of prolonged exposure to environmental noise. There is also evidence that noise annoyance at home decreases substantially when outdoor nature is visible through the window (Dzhambov and Dimitrova, 2015). This is not a trivial perceptual artefact — based on rough quantitative estimates, the equivalent perceived reduction attributable to high-quality visible green from home could reach 10 dBA ADS, a figure comparable to the effect of a substantial engineering intervention. In urban areas with ongoing noise or pollution, this is particularly relevant: residents experiencing the highest exposure levels are also the ones who could benefit most from access to urban green spaces, even before any actual decrease in pollutants or noise levels.

This is the foundation of the Net4Cities approach. Rather than attempting to quantify NbS impacts on specific pollutants or sound pressure levels — an exercise that would require measurement infrastructure and intervention data that are unavailable at the scale and consistency needed for cross-city comparison — the project focuses on characterising the conditions under which these health co-benefits are most likely to be realised. Green spaces between dwellings and heavily trafficked roads can reduce noise annoyance for residents; vegetation can conceal unappealing structures; and landscaping around housing can maintain privacy and avoid a sense of crowding — effects that operate through exposure reduction, restoration, and stress buffering simultaneously (Kruize et al., 2019). Whether a resident has a tree within sight of their window, whether their neighbourhood has sufficient canopy cover, and whether they live within walking distance of a larger green area are therefore not merely planning metrics: they are proxies for the degree to which urban green can plausibly moderate the health burden of living in a noisy, polluted city.

The database developed in this deliverable operationalises these conditions through the 3-30-300 framework, described in the following section. The indicators it produces do not predict decibel reductions or pollutant concentrations. They characterise the spatial preconditions — proximity, coverage, and accessibility of urban vegetation — that the evidence consistently associates with reduced noise annoyance, lower stress, and improved health outcomes for urban residents.

2.3. Assessment framework: 3-30-300 rule

The 3-30-300 rule has recently emerged as a concise and intuitive framework for assessing and guiding urban tree cover and green space provision. It is grounded in a growing body of research linking urban vegetation to physical health, mental well-being, thermal comfort, and environmental quality.

The rule integrates three complementary dimensions of human interaction with urban green:

- Immediate proximity to trees
- Neighbourhood-scale vegetation abundance
- Access to larger green spaces

By combining these dimensions, the 3-30-300 rule moves beyond aggregate measures of green coverage to capture how greenery is available, accessible, and perceptible in everyday environments. Its strength lies in its simplicity and communicability, making it particularly suitable for policy engagement while remaining compatible with quantitative spatial analysis.

Each element of the 3-30-300 rule reflects a distinct spatial scale and type of interaction between people and urban green:

- Rule 3 refers to the visibility of trees from the home or immediate surroundings. This micro-scale dimension is associated with daily exposure, visual contact, and local environmental regulation, including shading and microclimatic effects.
- Rule 30 addresses the presence of vegetation at the neighbourhood scale. It reflects the proportion of tree canopy cover within a walkable distance and is linked to broader ecosystem services such as air quality regulation, temperature moderation, and opportunities for informal recreation.
- Rule 300 captures access to larger, multifunctional green spaces within reasonable walking distance. These spaces—such as parks or urban forests—support physical activity, social interaction, restoration, and biodiversity, and are particularly important for longer visits and more diverse uses.

The three components are intended to be complementary rather than interchangeable: each captures a distinct dimension of green space provision, and meeting one target does not compensate for failing to meet the others. Together, these rules describe a layered relationship between urban residents and green infrastructure, acknowledging that different benefits occur at different spatial scales.

From an NbS perspective, the 3-30-300 rule is particularly valuable because it aligns ecological functions with social outcomes. It provides a structured way to assess not only the presence of vegetation, but also its potential to deliver benefits where people live.

The framework also facilitates the identification of spatial inequalities in access to urban green. By applying the same rules consistently across all buildings within a city, disparities between neighbourhoods become visible, supporting targeted interventions and prioritisation of NbS investments.

Moreover, the rule-based nature of the framework allows results to be aggregated, compared, and monitored over time, making it suitable for performance tracking and policy reporting at multiple governance levels.

Within the Net4Cities project, the 3-30-300 rule is adopted as a conceptual assessment framework and translated into a series of spatial indicators using harmonised geospatial datasets and reproducible analytical workflows.

The rule is operationalised through:

- Satellite-derived vegetation metrics to identify tree and green cover
- Harmonised land-use datasets to characterise green urban areas
- Building-level spatial analysis to link vegetation indicators to residential exposure

Each rule is implemented at a specific spatial scale using buffer-based analyses and zonal statistics, ensuring consistency across cities while maintaining sensitivity to local urban structures. The resulting indicators form the basis for the database described in subsequent chapters and provide a transparent link between NbS concepts, geospatial data, and policy-relevant metrics.

While the 3-30-300 rule provides a useful and communicable framework, it is a simplification of complex human–environment interactions and should be interpreted as indicative rather than exhaustive. Moreover, there is no standard set of indicators for measuring the three components of the rule, and it does not account for the quality or typology of the green. For example, under the rule, some species may be allergenic and have a negative impact, counteracting the potential benefit of green.

3. Data sets

3.1. Overview

To guarantee comparability across cities, reproducibility, and data continuity—including future updates—the project prioritises open, publicly accessible data that are quality-checked, version-controlled, and maintained by institutions over the long term. This approach ensures methodological robustness, traceability, and the ability to systematically update data over time.

The implementation of the 30-30-300 approach has specific requirements:

- Boundaries of the cities. The spatial extent of the analysis must be clearly defined. Relying strictly on administrative boundaries may introduce significant edge effects, as green spaces located just outside the city limits can contribute to accessibility and exposure. Where possible, buffer zones or functional urban areas should be considered to reduce, but not fully eliminate, such biases.
- Residential buildings. Buildings constitute the minimum unit of analysis within the cities. The three parameters are calculated based on the buildings.
- Vegetation index. The measure of the urban green applied to each scale (3-30-300)

3.2. City boundaries

This project uses Local Administrative Units (LAU) as the standard spatial boundary for cities. This selection is motivated by the need for data harmonisation, policy significance, and methodological reliability, which are crucial for effective cross-city analysis.

The LAU (municipal) level is the lowest administrative level at which demographic, environmental, and health-related indicators are systematically available and comparable across European cities, in accordance with Eurostat's statistical framework (Eurostat, 2024).

LAU boundaries are selected based on the official city name and, where necessary, extended to include neighbouring municipalities when monitoring stations are located outside the core LAU boundary. The inclusion of additional LAUs may affect aggregated figures at city level. However, this does not apply when the spatial dimension (map) is represented, nor when focusing on the area around the monitoring stations.

In the case of Tbilisi, which is outside the EU statistical system, the analysis applies to a functionally equivalent municipal delineation within the Tbilisi Municipality.

Administrative city boundaries (LAU) may not reflect the functional extent of urban green exposure. In cities such as Oslo, where urban areas and recreational green spaces extend beyond LAU limits, restricting the analysis to LAU boundaries is likely to underestimate accessibility indicators and introduce systematic bias in cross-city comparisons (e.g. 300 m). To mitigate this issue, green spaces outside the administrative boundaries have been included within a 500 m buffer zone to avoid the border effect.

3.3. Residential buildings

To identify and spatially delineate residential buildings, this project uses data from the Copernicus Urban Atlas[1]. Urban Atlas provides a harmonised, high-resolution land-use and land-cover dataset for European urban areas with more than 50 000 inhabitants, ensuring consistency and comparability across cities.

Urban Atlas is a component of the Copernicus Land Monitoring Service, offering land use/land cover maps divided into 17 urban classes with a minimum mapping unit of 0.25 hectares at a spatial resolution of up to 10 meters. It covers the reference years 2006, 2012, 2018, 2021, and 2024, with updates every three years. The latest 2024 data have been selected for Net4Cities.

In this project, residential areas are derived from the following Urban Atlas classes, which collectively represent the built residential fabric of cities:

- Continuous urban fabric (11100): densely built-up residential areas with a high proportion of sealed surfaces.
- Discontinuous dense urban fabric (11210): predominantly residential areas with a dense but non-continuous built structure.
- Discontinuous medium-density urban fabric (11220): residential areas with intermediate building density.
- Discontinuous low-density urban fabric (11230): mainly residential areas with detached or semi-detached buildings and significant green space.
- Discontinuous very low-density urban fabric (11240): predominantly residential areas with sparse buildings, often at the urban fringe.

These classes do not delineate individual buildings but define aggregated residential zones where housing is the dominant land use. This aggregation may limit the spatial precision of the analysis and constitutes a methodological limitation of the approach, particularly with respect to Rule 3, as the delineation of polygons (i.e., groups of buildings) has a greater influence at finer spatial scales. Nevertheless, Urban Atlas provides population data for each individual element (aggregated building), enabling the rules to be expressed in terms of the number of people benefiting from access to green spaces.

Since Urban Atlas is unavailable for Tbilisi, we used data from OpenStreetMap[2] (OSM). OSM could also serve as a substitute for Urban Atlas in the other cities considered, since it provides delineations of individual buildings. However, in this study, we prioritised Urban Atlas because it provides population data for individual spatial elements. Therefore, the use of OSM would require integrating population data at a scale suitable for the buildings of OSM, which is not currently available for the whole of Europe.

Features were selected based on specific tags that represent residential built forms:

- standalone houses (building=house),
- apartment blocks (building=apartments),

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[1] https://land.copernicus.eu/en/products/urban-atlas?tab=overview

[2] https://www.openstreetmap.org

- detached and semi-detached homes (building=detached, building=semidetached_house),
- terraced houses (building=terrace),
- and generic residential structures (building=residential).

OpenStreetMap provides highly detailed, high-resolution spatial data at the building level. However, the quality, completeness, and attribution of the data can vary across different areas because it is crowdsourced. Although OSM could theoretically be used for all cities to achieve finer spatial detail, Urban Atlas was chosen for EU cities due to its harmonised quality-checked classification and population data for each polygon.

3.4. Vegetation

To operationalise the 3-30-300 rule—which links urban greenery to health through (i) visibility of trees, (ii) neighbourhood-level canopy cover, and (iii) access to green space, two data sets have been combined:

- Normalised Difference Vegetation Index[3] (NDVI), derived from Copernicus satellite data, provides a continuous and spatially explicit measure of vegetation presence and vitality. NDVI is computationally efficient and widely available, making it particularly suitable for consistent application across multiple cities. However, NDVI does not differentiate between vegetation types (e.g. trees, shrubs, or grass) and may therefore overestimate tree presence in certain urban contexts. In addition, the spatial resolution of NDVI data may limit the representation of fine-scale urban vegetation patterns, particularly in dense urban environments. Single trees from existing public census data would be the appropriate data to be used. However, this information was not available for all the cities.
- Urban Atlas is used to complement NDVI by providing land-use information of public green spaces relevant for assessing accessibility (Rule 300), which NDVI alone can not distinguish.

In summary, these data is combined as follows:

- “3” (visibility of trees): NDVI values are analysed in the immediate residential environment to characterise the presence and intensity of surrounding vegetation. While NDVI does not capture actual visibility, it provides a proxy for local green exposure to green, which has been shown to be associated with psychological restoration and reduced stress.
- “30” (neighbourhood tree canopy): Aggregated NDVI values are used to quantify the relative level of vegetation cover within a defined neighbourhood buffer, supporting an objective assessment of whether sufficient green presence exists at the local scale.
- “300” (access to green space): This rule focuses on access to public spaces. Therefore, NDVI is combined with Urban Atlas, which provides attributes for public, private, or unknown spaces. Selected areas are combined with spatial distance analyses to identify green areas and assess residential proximity to vegetated spaces, ensuring that access criteria are evaluated consistently across cities.

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[3] https://land.copernicus.eu/en/products/vegetation?tab=vegetation_indices

It should be noted that Copernicus already provides the Street Tree Layer[4] dataset as a supplementary resource to Urban Atlas. However, it has been shown that this dataset has limitations when compared with existing local tree inventories and that NDVI is a more reliable proxy. (Aleixo et al., 2024)(Ubach, 2026).

NDVI is computationally efficient, globally available via Sentinel-2, and can be processed consistently across all participating cities using cloud-based platforms such as Google Earth Engine. Given the need for a lightweight, scalable solution, NDVI provides an acceptable balance between simplicity and ecological relevance, even if more advanced indices or multi-sensor data could theoretically improve discrimination accuracy

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[4] https://land.copernicus.eu/en/products/urban-atlas?tab=street_tree_layer

4. Methodology

4.1. Deriving vegetation from NDVI

The Normalised Difference Vegetation Index (NDVI) was used as an approximation to identify trees. Based on a multi-city analysis was conducted across Antwerp (Belgium), Barcelona (Spain), and Berlin (Germany). The methodology leveraged Google Earth Engine (GEE) to process Sentinel-2 Surface Reflectance (SR) data, focusing on the growing season (May–September) between 2020 and 2025. Cloud masking was applied using the Scene Classification Layer (SCL) to exclude pixels affected by clouds, shadows, or snow, ensuring data quality.

NDVI, calculated as (B8 – B4)/(B8 + B4), was derived for each image in the collection, where B8 and B4 represent the near-infrared and red spectral bands, respectively. The 75th percentile NDVI value was computed across the time series to capture peak vegetation vigour, mitigating seasonal variability. This percentile-based approach was chosen to robustly represent the upper range of vegetation health, minimising the influence of outliers or temporary fluctuations.

The analysis was validated using a dataset of 1.22 million publicly inventoried urban trees, enabling the calibration of city-specific NDVI thresholds. Inventories where extracted from the European Data[5] and filtering by the tags “tree cadaster”, “urban trees” and “trees” in different langauges. Later on data sets with less than 1000 points of out of the scope are excluded. The resulting NDVI layers were clipped to administrative boundaries and visualised to assess spatial patterns. This methodology ensured methodological consistency across diverse urban environments, facilitating the application of a harmonized approach across cities.

The selected NDVI threshold represents a compromise between detection accuracy and false positives, and results should therefore be interpreted as approximate indicators rather than precise representations of tree cover.

The tree inventory data utilised in this study is compiled and maintained by local public entities, thereby resulting in a presence-only dataset. This type of data captures confirmed tree locations but lacks information on true absences, which can introduce potential biases in the analysis. To address this limitation, tree detection rates were computed across a range of NDVI thresholds. For example, applying a threshold of NDVI > 0.4 yielded a tree detection rate of 85.29%, while a more conservative threshold of NDVI > 0.5 resulted in a detection rate of 77.69%. Given the absence of true negative data, a threshold of 0.5 was selected to balance detection accuracy and minimise the inclusion of false positives, such as non-tree vegetation or urban artefacts. While this approach enables consistent application across cities, it should be noted that NDVI thresholds provide an approximation of tree presence and may not fully distinguish between tree cover and other types of vegetation.

4.2. Rule 3: Proximity to Trees

Objective: Provide an approximation to the presence of trees in the immediate surroundings of residential buildings. .

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[5]

Threshold: The theoretical threshold of the rule is at least one occurrence of 3 trees within the immediate vicinity of the building (proxy for potential visual exposure).

Method:

- A 25-meter buffer is created around each building polygon to represent the immediate residential environment. This distance is used as a simplified proxy for potential visual exposure to nearby vegetation. However, this approach does not account for building height, orientation, or visual obstructions, and therefore may not accurately reflect actual visibility. The 25 m buffer has been decided accordign to existing literature review ().
- NDVI values are sampled within each buffer; if any pixel has an NDVI ≥ 0.5, the building is marked as compliant with Rule3 (Rule3 = 1).
- Results are stored as a geospatial layer, indicating whether each building meets the proximity criterion.

4.3. Rule30: Vegetation in the neighbourhood

Objective: Assess the availability of green space in the neighbourhood.

Threshold: Theoretical threshold I a minimum of 30% of tree cover in the neighbourhood. Here we approximate to dense vegetation.

The neighbourhood can be defined using various approaches, such as administrative boundaries or morphological units. In this project, a fixed-distance buffer around residential areas is used to ensure consistency and comparability across cities.

Method:

- A 500-meter buffer is generated around each building polygon. It should be noted that the selected Urban Atlas classes may already include green areas around buildings.
- The NDVI raster is sampled within each buffer to calculate:
  - Total number of pixels and total area.
  - Number and area of pixels with NDVI ≥ 0.5 (interpreted as general vegetation, not limited to trees).
  - Percentage of green area (PercGreen) relative to the buffer area.
- Buildings with ≥30% vegetation coverage within the buffer are flagged as compliant with Rule30 (Rule30 = 1).

The use of a fixed-distance buffer does not account for variations in urban morphology or perceived neighbourhood boundaries.

Note: NDVI-based estimates represent general vegetation cover and do not distinguish between trees and other types of vegetation. In addition, the spatial resolution of the data may limit the representation of fine-scale urban green patterns.

4.4. Rule 300: Access to Large Green Urban Areas

Objective: Evaluate access proximity to large green urban areas (e.g., parks) within 300 meters.

Method:

- A 300-meter buffer is created around each building.

- The GUA dataset is sampled within each buffer to calculate:
    - Total number of pixels and total area.
    - Number and area of pixels classified as GUA (value = 1).
- Buildings with access to ≥5,000 m² of GUA within the buffer are flagged as compliant with Rule300 (Rule300 = 1).

Note: This approach evaluates spatial proximity rather than actual accessibility, as it does not account for the street network, physical barriers, or actual accessibility conditions. This may lead to an overestimation of accessibility to green space in certain urban contexts.

4.5. Integration and Output

The results from Rule3, Rule30, and Rule300 are combined into a single geospatial dataset. Each residential unit is assigned to a total score (NRules), indicating how many rules it satisfies based on the applied spatial proxies (ranging from 0 to 3).

City-wide statistics are computed, including:

- Total vegetation coverage (km² and %) based on NDVI ≥ 0.5.
- Total green urban area (km² and %) based on the GUA mask.

Results are stored as GeoPackage layers and CSV files for further analysis and visualisation.

The resulting indicators should be interpreted as spatial proxies of potential exposure to urban green, rather than direct measures of environmental or health outcomes.

4.6. Tools and Libraries

Geospatial processing is implemented using a Python-based stack composed primarily of GeoPandas, Rasterio, and Fiona. GeoPandas is used to manage and manipulate vector datasets, including administrative boundaries, residential areas, buffers, and analysis zones. It enables spatial operations such as reprojection, spatial joins, and geometric transformations within a consistent coordinate reference system.

Raster data, including satellite-derived vegetation indices, are handled using Rasterio. This library supports efficient reading, masking, resampling, and alignment of raster datasets with vector geometries. Raster–vector interactions—such as extracting raster values within defined neighbourhood buffers—are performed to ensure that vegetation metrics are spatially aligned with residential areas. Fiona serves as the underlying I/O interface to ensure robust, interoperable reading and writing of geospatial file formats.

To maintain consistency across cities, all datasets are reprojected to a common projected coordinate system prior to analysis. This ensures accurate distance-based calculations (e.g. neighbourhood buffers) and area-based metrics (e.g. percentage of vegetated surface). The processing workflow is designed to be modular, allowing each dataset to be validated, transformed, and analysed in a structured and reproducible manner.

The full analytical workflow is implemented as an automated Python script, enabling scalable application across multiple cities with minimal manual intervention. Automation covers the entire pipeline, from data ingestion and preprocessing to spatial analysis and output generation. City-specific inputs (e.g. boundaries or identifiers) are parameterised, allowing the same workflow to be systematically applied to different study areas.

This automated approach ensures consistency, reproducibility, and efficiency, particularly in multi-city analyses. It reduces the risk of manual errors, facilitates updates when new data become available, and supports iterative refinements to the methodology. Outputs are generated in standardised formats and structures, enabling straightforward comparison between cities and seamless integration into subsequent analytical or reporting stages.

By combining automation with open-source geospatial libraries, the workflow supports transparent, repeatable, and scalable spatial analysis.

5. Data base

The database is implemented as a GeoPackage (GPKG), a unified spatial data container that integrates residential spatial units, vegetation metrics, and compliance indicators related to the 3-30-300 rule. The use of the GeoPackage format ensures portability, interoperability, and efficient storage of both vector geometries and attribute data within a single file, while maintaining compatibility with common GIS software and open-source geospatial libraries.

Each record in the database corresponds to a residential spatial unit, represented either by an aggregated residential polygon or a building proxy, depending on data availability. These spatial units form the core analytical entity to which all vegetation-related indicators and rule-specific metrics are attached. The database structure is designed to support both building-level and aggregated analyses, allowing flexibility in spatial resolution while preserving methodological consistency across cities.

For each residential unit, the following categories of information are stored:

- **Spatial identifiers and geometry**, including unique IDs, administrative references, and polygon geometries in a common projected coordinate system.
- **Vegetation metrics derived from NDVI**, such as the presence of NDVI ≥ 0.5 within defined buffers, total vegetated area, and percentage of vegetated cover at different spatial scales.
- **Rule-specific compliance indicators**, including binary variables for Rule3, Rule30, and Rule300, as well as the aggregated score (NRules) indicating the number of rules satisfied by each residential unit.
- **Population attributes**, where available (e.g., from Urban Atlas), enabling results to be expressed not only spatially but also in terms of the number of inhabitants potentially benefiting from access to green spaces.

The database follows a consistent naming convention for fields and layers to ensure clarity and reproducibility. Rule-related variables are explicitly labeled (e.g., Rule3, Rule30, Rule300, NRules), facilitating straightforward filtering, aggregation, and statistical analysis. Intermediate layers generated during processing (such as buffers or clipped rasters) are stored separately during computation but only the final analytical outputs are retained in the deliverable GeoPackage to maintain a clean and interpretable structure.

All datasets included in the GeoPackage are harmonised to a common coordinate reference system to ensure that distance-based buffers and area-based calculations are spatially consistent. Attribute data types are standardised to avoid ambiguities when importing the database into different software environments.

The resulting GeoPackage serves both as a final analytical output and as a reusable data asset. It supports downstream analyses such as city-level statistics, population-weighted indicators, cross-city comparisons, and cartographic visualisation. By consolidating geometries, indicators, and metadata into a single structured file, the database enhances transparency, reproducibility, and long-term usability of the results while enabling efficient updates when new data or revised thresholds become available.

6. Recommendations on the use of the database

The database should be used as a decision-support tool to identify spatial patterns and inequalities in access to urban green. However, it should be combined with additional datasets, such as air quality measurements, noise data, and socio-economic indicators, to support comprehensive urban planning and policy decisions.

Users should be aware of the methodological limitations, particularly regarding the use of NDVI as a proxy for tree cover and the use of Euclidean buffers for accessibility assessment. Results should therefore be interpreted with caution, especially in heterogeneous urban environments.

Future applications may include integration with dynamic monitoring data and the Net4Cities Studio platform to support more advanced analyses and policy-relevant insights.

7. Conclusions

This deliverable presents a harmonised and scalable spatial database to assess the distribution and accessibility of NbS across Net4Cities partner cities. By operationalising the 3-30-300 framework, the database provides a consistent set of indicators capturing proximity, availability, and accessibility of urban green.

Rather than quantifying direct impacts on air quality and noise, the approach focuses on spatial preconditions associated with potential environmental and health benefits. This represents a pragmatic solution given current data limitations and the complexity of NbS effects.

However, the methodology relies on several simplifying assumptions, including the use of NDVI as a proxy for vegetation and buffer-based approaches for spatial analysis. These introduce uncertainties that should be considered when interpreting the results.

Future work should focus on integrating these spatial indicators with monitoring and modelling data developed in other Net4Cities WPs, particularly within the Net4Cities Studio, to enable a more comprehensive assessment of urban environmental conditions and support evidence-based policy interventions.

Acronyms

Table 1. Table of acronyms used in this template.

Acronym	Meaning
N4C	Net4Cities
QM	Quality Management
GHG	Greenhouse Gases
NbS	Nature-based Solutions

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