



A methodological framework for assessing pollinator suitability in urban areas

Fabio Gatti¹ · Anna Simonetto¹ · Gianni Gilioli¹

Received: 10 June 2025 / Accepted: 13 September 2025
© The Author(s) 2025

Abstract

Interest in the suitability of urban areas for pollinators is steadily increasing, as pollinator decline and biodiversity loss are closely linked to human activities, particularly urbanization and land-use change. Although recent studies have begun exploring urban pollinator habitats, these areas are often considered inhospitable when assessed with coarse-scale assessment tools, which risk overlooking mosaics of green patches that provide essential foraging and nesting resources. The configuration and density of these green spaces vary widely, strongly influencing their potential to support pollinators. However, standardized methods for evaluating pollinator-friendly urban areas remain limited. This study presents a methodological tool for urban planning, the Green Patch Suitability Assessment, which enables comparative evaluation of urban patches at fine spatial resolution. The framework combines (i) a classification system of urban green areas (patches); (ii) a multidimensional index of patch-level pollinator suitability, and (iii) a high-resolution topographic database integrating patch from multiple commonly used urban and landscape planning datasets. Applied in a municipality in Northern Italy, the tool demonstrates the capacity to identify small green patches often overlooked in coarser datasets and to evaluate the potential effects of a newly approved municipal plan aimed at enhancing green areas and biodiversity. Scenario analysis confirmed that the framework is sufficiently sensitive to detect the effects of the nature-based solutions proposed in the city plan, thus providing a practical and operational tool for urban planning capable of assessing the contribution of small green patches that would otherwise remain unrecognized using coarser-resolution databases.

Keywords Pollinator · Suitability assessment · Nature based solution · Green patches · Urban area · Cartographic database

Introduction

Pollinators and overall biodiversity decline is a worldwide problem. Many studies have so far identified land use change and land use management at different scales as the major drivers of pollinators decline (McNIEY K2002; Kennedy et al. 2013). While research has largely focused on agricultural systems and natural habitats, urban environments have received comparatively less attention (Baldock et al. 2015,

2019), despite growing interest in recent years. Understanding pollinator dynamics in cities represents a significant challenge for urban and landscape planners, as urban green spaces form complex mosaics whose configuration and quality can strongly influence pollinator population.

Urban areas are often considered homogeneously impervious to pollinators, although they could be complex mosaics of different land uses that highly differ in their suitability for pollinators (Baldock et al. 2019). One of the most common objections is that most urban green patches are structurally isolated spatial units within a hostile landscape matrix (Wenzel et al. 2020). Nevertheless, these green patches are functionally connected through the potential exchange of individuals able to overcome unsuitable habitats. Many studies have so far demonstrated how urban areas are capable of providing support to various pollinators (Potts et al. 2010). Baldock and colleagues (2019) found levels of pollinator abundance and diversity in urban contexts comparable

✉ Fabio Gatti
fabio.gatti@unibs.it

✉ Anna Simonetto
anna.simonetto@unibs.it

✉ Gianni Gilioli
gianni.gilioli@unibs.it

¹ Università di Brescia, Via Branze, 43, Brescia 25123, Italy

with those in agricultural and conservation areas. Baldock et al. (2019) explore pollinator communities in green areas such as cemeteries, urban gardens, parking lots, and green spaces in industrial areas can provide floral resources and can host abundant bee communities. The role of private gardens in supporting pollinators diversity and abundance in the urban context is acknowledged in numerous studies (Burr et al. 2018; Lowenstein et al. 2019; Cohen et al. 2022). Phillips et al. (2020) assert that roadside margins have significant potential for pollinator conservation, Prendergast et al. (2022) emphasise the importance of areas with sparse vegetation (shrublands), and Bommarco et al. (2021) advocate the effectiveness of floral strips in supporting pollination. The potential urban context in supporting pollinator communities is also stated in the European Union Pollinators Initiative, defining specific guidelines to enhance the suitability of urban areas for pollinators (European Commission: Directorate-General for Environment et al. 2020). Consequently, urban areas could no longer be considered as a generally hostile environment but rather as an interconnected network of elements, varying in suitability, which collectively could perform the connecting function with surrounding areas (Hall et al. 2019).

Despite the importance of green areas in supporting pollinators, their effective distribution and quality in urban contexts remain poorly investigated (Li et al. 2019; Doroski et al. 2021; Semerdzhieva and Borisova 2021; Yang et al. 2022), and quantitative tool for their assessment are still lacking. Current evaluations of urban green areas suitability often rely on coarse land-use categories (Davis et al. 2017), rather than on individual patch assessments enabled by high-resolution identification tools, which can provide actionable information for urban and landscape planning. The suitability of a patch can be represented by its capacity to supply food resources or to provide nesting sites (Wray and Elle 2015). These patch traits can be described through expert judgment (Zulian 2013; Stange et al. 2017) or measured directly. Food supply can be estimated based on floral abundance or pollen availability (Hicks et al. 2016; Dmitruk et al. 2021), while nesting site availability is often associated with the presence of bare ground (Cohen et al. 2021). Indirect indicators, such as pollinators diversity and abundance (Davis et al. 2017; Bartholomée et al. 2020) or functional traits of pollinators (Winfree et al. 2007) are also commonly used. However, community-level indicators are influenced not only by patch-level traits, but also by surroundings landscape features (e.g. roads, adjacent green areas). Additional parameters relevant for assessing patch suitability include patch geometry (Biella et al. 2022), size (Silva et al. 2021), vegetation cover (Dylewski et al. 2019), environmental conditions (e.g., presence of pollutants, climatic variables), or landscape characteristics (Prendergast

et al. 2022). Incorporating such high-resolution and multidimensional information into planning tools allows for more precise evaluation of urban green areas, supporting informed decisions in urban and territorial management.

This study proposes a framework for the quantitative assessment of pollinator suitability of green areas in urban patchy environments. The framework, termed Green patch Suitability Assessment (GSA), is designed as a tool to support urban and territorial planning and is built upon three core components: (i) a classification system for green areas (hereafter referred to as green patches) that distinguishes among the patch types within both the urban area and the surrounding rural landscape; (ii) a suitability assessment of each patch using a newly developed multidimensional index, the Patch Suitability Index (PSI), and (iii) a high-resolution spatial identification of patches based on a geographic database of urban green areas, integrating patch traits derived from commonly used topographic sources. While the framework is broadly applicable across pollinator groups, in this study the parameterization focused primarily on Apoidea, a major component of pollinators (Ollerton, 2021), for which the literature provides the most extensive data.

We firstly compared our database with green patch distributions derived from two widely used land use database. We then applied the GSA framework to a pilot case study in the city of Brescia, Northern Italy, which recently adopted a municipal Green Areas and Biodiversity Plan (Brescia municipality 2024) aimed at enhancing biodiversity and the provision of ecosystem services within the urban area. The plan includes an index of Nature-Based Solutions — an operational tool comprising a set of actionable measures designed to achieve its ecological objectives. We conducted a scenario analysis based on the most pollinator-friendly solutions proposed in the plan and evaluated the capacity of GSA to detect corresponding changes in habitat suitability.

Materials and methods

Patch classification

The land use classification system of GSA is structured as a two-level hierarchical framework. The first classification level is inspired by the first level of Corine Land Cover (CLC) system and comprises six classes: Urban green patches, Arable patches, Permanent crop patches, Natural green patches, Impervious patches and Water body patches. The second classification level further differentiates the first-level classes based on their characteristics relevant to the suitability index (e.g., patch size, presence of floral resources, trees, or nesting areas), as detailed in the following section.

The Urban green patch class encompasses 12 s-level patch types: Car parks, Cemeteries, Industrial estates (Baldock et al. 2019), Private gardens (Egerer et al. 2020), Private parks, Public parks, Public gardens (Baldock 2020), Road verges (Henriksen and Langer 2013), School gardens, Sidewalks, Tree rows, Sport and leisure facilities. Gardens and parks were differentiated into public and private categories to provide decision-makers with relevant information for the effective management and planning of public green spaces.

The Natural green patch class represents green areas characterized by a permanent cover of spontaneous vegetation. At the second classification level, it comprises four patch types: Mixed Woodlands, Hedgerows, Shrublands and Meadows (Dylewski et al. 2019).

The Permanent Crop Patch and Arable Patch classes refer to agroecosystem land parcels whose suitability is influenced by agricultural management practices. These classes distinguish between land cultivated with annual crops (arable land) and land managed with permanent crops, such as vineyards. Both classes are further subdivided at the second level into low, medium, and high suitability categories, based on their capacity to provide floral resources for pollinators or to offer shading. For example, vineyards are considered highly suitable, while orchards fall into the medium suitability category.

The Impervious patches class includes areas with sealed or paved surfaces, such as buildings and roads. As these structures are almost entirely unsuitable for pollinators, no further subclassification is applied at the second level.

The Water bodies patch class includes areas covered by water, such as lakes, ponds, and rivers. Although these areas do not offer direct food or nesting resources for pollinators, these may enhance the suitability of adjacent green patches by providing water. Similar to Impervious patches, no further classification is applied at the second level.

The GSA classification system is structured so that each third-level CLC category corresponds to at least one second-level GSA class, enabling the broadest possible application of the protocol. The correspondence table between CLC classes and the GSA classes is provided in the Supplementary Material 1 (Table S1).

Patch suitability assessment

The Patch Suitability Index (PSI) is a multidimensional index designed to quantify the suitability of patches for supporting pollinators. It has been specifically developed to rely on data that are readily available to urban and territorial planners. The PSI integrates five key components, each representing a primary factor influencing habitat suitability:

structural characteristics of the patch (STR); availability of food resources (FRA); availability of nesting resources (NSA); mitigation of thermal stress (TMC); and absence of disturbance caused by human activities (DIS). Each component is measured by an indicator ranging from 0 to 1. The overall PSI value, also ranging from 0 (indicating an area completely unsuitable for pollinators) to 1 (indicating the highest suitability), is determined by the weighted sum of the five component indicators:

$$PSI = 0.2 * STR + 0.3 * FRA + 0.3 * NSA + 0.1 * TMC + 0.1 * DIS$$

Impervious surfaces and water bodies are assigned a PSI value of 0, as they do not directly provide foraging or nesting resources. However, water bodies—defined here as open water surfaces excluding their shores—may indirectly enhance the suitability of nearby patches by supplying materials for nest construction. This contribution is explicitly captured in the P_WB indicator, which accounts for water availability when accessible from suitable nesting areas.

The structural component (STR) is based on a single factor: patch area (P_{area} —in m^2), which serves as a proxy for the capacity of a green area to provide suitable habitat for pollinators (Meyer et al. 2017). STR is computed as:

$$STR = \begin{cases} \frac{\ln P_{area}}{10} & \text{if } \ln P_{area} \leq 10 \\ 1 & \text{otherwise} \end{cases}$$

The food resources availability component (FRA) uses floral density (FD) as a proxy for foraging rewards, which generally increases with floral density but plateaus at higher values due to intra-specific floral competition (Essenberg 2012). This index, derived strictly from literature, does not capture flower quality or phenology, yet it provides a general characterization of patch types. FD values were assigned to each patch type (Level I and Level II; see Table S2) based on reported flower density data, allowing for consistent comparison across patches (Montero-Castaño et al. 2016; Lynch et al. 2021). FRA is calculated as follows:

$$FRA = 0.1433 * \ln FD + 0.001$$

The nesting site availability (NSA) component is calculated from two variables: the estimated proportion of the patch suitable for nesting (P_{NS}), derived from literature values (Zulian et al. 2013), and the proportion of the patch within a 10 m buffer of water bodies (P_{WB}), as identified in the GSA dataset. Water bodies themselves do not provide food or nesting sites but contribute essential materials for nest construction and increase the availability of suitable surfaces in neighbouring patches (Twerd et al. 2022; Dylewski

et al. 2024). Due to the absence of fine-scale field validation, P_{NS} values rely on published studies (Table S2). While a single P_{NS} value cannot capture the full diversity of nesting preferences among pollinator species, it offers a practical proxy for evaluating potential nesting site availability at the patch level. The NSA index is calculated as follows:

$$NSA = \begin{cases} P_{NS} + P_{WB} & \text{if } P_{NS} + P_{WB} \leq 1 \\ 1 & \text{otherwise} \end{cases}$$

The thermal stress mitigation capacity (TMC) component is based on the cooling capacity factor, calculated according to Zawadzka et al. (2021). This index integrates three parameters: shading provided by shrub or tree canopy cover index (S), evapotranspiration (ETI), and albedo (A):

$$TMC = 0.6 * S + 0.2 * ETI + 0.2 * A$$

Values for ETI and A are provided in Table S2 for each patch class. The value of S, as described in Table 1, depends on the patch class and the canopy area within the patch (P_{Canopy}), which is estimated as a 1 m radius circle around each tree within the patch perimeter.

The disturbance (DIS) component is inversely to the intensity of anthropogenic disturbance, measured as the proportion of the patch affected by a 20 m road buffer (P_{RO}). This buffer serves as a proxy for traffic-related disturbance. DIS is computed as:

$$DIS = 1 - P_{RO}$$

To ensure clarity in the application of our methodology, it is important to specify the pollinator groups considered in this study. While the framework is designed to be applicable across various pollinator groups, the current implementation focuses mainly on Apoidea. This reflects the relative abundance of ecological data available for this group, which are essential for calculating the PSI, compared to the limited information for other pollinator superfamilies. Within Apoidea, we concentrated on wild bees, as managed honeybees (*Apis mellifera*) are typically present in the study area due to beekeeping.

Table 1 Coefficient value for the tree canopy cover (S) parameter

Patch class	S value
Mixed woodland	$S = 1$
Hedgerow, Shrubland, Permanent crop	$S = 0.5$
Impervious patch	$S = 0$
Other classes	$S = \begin{cases} \frac{P_{Canopy}}{P_{Area}} & \text{if } P_{Canopy} < P_{Area} \\ 1 & \text{otherwise} \end{cases}$

Patch identification

To apply the suitability analysis to an area of interest, it is necessary to classify the patches according to the GSA system defined in Table S1. The procedure of patch identification involves two main steps: (i) selection of the basic topographic database and support databases and (ii) databases integration. The following section offers a detailed walkthrough of the procedure, using the case study introduced in this work to clearly demonstrate each step of the process.

It is important to note that the two levels of the classification system were designed to offer flexibility: if, in some areas, it is not possible to assign a patch to a second-level class due to data limitations, the analysis can still be carried out using only the first-level classification. Although this results in a lower degree of precision in the suitability estimates, the method remains applicable. Alternatively, a mixed approach combining first- and second-level classes can be adopted, retaining the most detailed information where available.

Step 1 - Selection of the basic topographic database and support databases

In this step, all relevant land use databases for the study area were identified, despite variations in spatial resolution and intended purpose.

Since the area of interest is the city of Brescia (Northern Italy, Lombardy Region), the primary reference map used was the Regional Topographic Geodatabase (DBTR) (Lombardia Region 2020). This geodatabase, provided by the regional administration to assist municipalities with urban planning, features a high-resolution mapping scale of 1:1000 and a minimum mapping unit of 2 m². The DBTR offers a patch classification system that organizes spatial elements into five layers: roads, buildings, water bodies, and green areas. Each layer is further divided into two sub-levels, describing individual patches by their use and function. The DBTR classification was directly integrated into the GSA classification framework. A database of green areas, which includes all publicly managed gardens and parks, was kindly provided by the Municipality of Brescia to help distinguish between public and private green spaces.

For the characterization of woodland patches, the regional forest database (Lombardy Region 2025) was used as a reference. This database, developed at a survey scale of 1:10,000, represents each polygon as a woodland patch with a minimum width of 20 m and a minimum area of 2,000 m². It includes attributes such as wood type and dominant canopy species, which were utilized to further detail the woodland patches identified as forest in the DBTR.

The regional tree database (Lombardy Region 2018) and the municipal database of public trees (each identified at species level) were used to identify green infrastructure like urban tree rows. These databases were first integrated into a single database, representing 112,023 trees within the study area.

The DUSAF (Agricultural and Forestry Land Use Destination) database of Lombardy Region (2020) is a polygon shapefile mapped at a scale of 1:10,000, with a minimum mapping unit of 1,600 m². While its classification system is based on the CLC framework, DUSAF offers greater detail for certain categories—for instance, distinguishing between railway and road networks, as well as separating parks from uncultivated green areas. Within the Brescia municipal area, 2,079 patches have been identified. Additionally, the database includes a line shapefile representing thickets and hedgerows, which was used to identify hedgerows within agricultural plots. These features are key components of green infrastructure and play a significant role in supporting pollinators in agricultural landscape (Altieri 1999; Langellotto et al. 2018; Jeanneret et al. 2021).

Table 2 Description of selected nature-based solutions from the green areas and biodiversity plan and estimated impact on patch classification or patch suitability index (PSI) index components

Nature based solution	Description	Patch features improvements
1. Urban lawns management	Reduction in mowing frequency and establishment of unmown areas to allow nectar-producing species to complete their flowering cycle.	Increase in <i>FD</i> , resulting in improved <i>FRA</i> (particularly in gardens and parks).
2. Canopy improvement of public parks and gardens	Plantings of trees and bushes to increase canopy coverage.	Increase in <i>S</i> and <i>P_{NS}</i> , resulting in improved <i>TMC</i> and <i>NSA</i> components, respectively
3. Canopy improvement of urban streets	Plantings of new tree rows along streets	Conversion of impervious patches classified as parking areas in DBTR into tree row patches.
4. Canopy improvement of parking areas	Tree planting in existing parking lots	Conversion of impervious patches classified as parking areas in DBTR into car park patches.
5. Green areas creation	Replacement of paved sidewalks with sealed surfaces with grassy areas	Conversion of impervious patches classified as sidewalk in the DBTR into sidewalk patches.

Note: *FD*: Floral density, *S*: shrub or tree canopy cover index, *P_{NS}*: proportion of the patch considered suitable for providing nesting sites, *TMC*: thermal stress mitigation capacity; *FRA*: floral resources availability; *NSA*: nesting availability; DBTR: Topographic Geodatabase of Lombardy region

Step 2 - Database integration

After identifying all relevant spatial datasets, the next step involved integrating them into a single, comprehensive geodatabase to support patch identification and classification based on the GSA system. This integrated database consolidated all necessary attributes derived from the source layers, enabling consistent classification and suitability assessment of each spatial unit.

For the case study, data integration was conducted using spatial analysis and geoprocessing tools available in the QGIS software (ver 3.28 - Florence). This workflow enabled the extraction and assignment of relevant attributes to each DBTR polygon (patch), including vegetation cover type, land use, and the presence of trees, bushes or thickets. Priority was assigned to the base topographic database classification due to its higher spatial resolution, which enabled more accurate differentiation among the six Level I patch classes of the GSA system. The DUSAF classification system was used as a secondary source to classify DBTR patches lacking specific labels. The final classification of each patch was based on the combination of attributes extracted from all supporting datasets, following the hierarchical rules detailed in Table S3.

Although the integration procedure was developed and applied to the Brescia municipal area, it was designed with scalability in mind, making it transferable to other regions and compatible with alternative topographic datasets.

Assessing nature-based solutions through scenario analysis

The PSI index was firstly applied to the municipality of Brescia to evaluate the potential effects of nature-based solutions proposed in the Green Areas and Biodiversity Plan (Brescia municipality 2024). A scenario analysis focused on interventions most likely to improve patch suitability for pollinators (Table 2) and was limited to publicly owned areas. We hypothesized that the implementation of specific measures would lead to measurable changes in selected reference parameters for particular patch types. Changes in the PSI index at city level were then examined to assess the tool's sensitivity in capturing such variations. Measures such as the green roofs or the establishment of hedgerows and buffer strips along the borders of arable land patches were excluded, as they occur on private properties and fall outside the directly jurisdiction of the municipality.

To assess the effect of each selected measure, four levels of implementation were considered: 25%, 50%, 75%, and 100% of the currently available patches eligible for the proposed interventions (Baldock et al. 2019).

A one-way ANOVA was performed to test whether differences in PSI values among the land-use categories were statistically significant.

Results

The Municipality of Brescia (Northern Italy) spans 9,033 hectares. Based on the 2018 CLC cartography, the area is divided into 57 polygons (Fig. 1), featuring a densely urbanized core (CLC=1) surrounded by rural and natural zones (CLC=2 or 3), which exhibit lower degrees of urbanization.

Patch identification

Within the municipality of Brescia, a total of 106,870 patches were identified using GSA classification. Of these, 31,294 are green patches, representing 43.9% of the study

area and 29.3% of all patches. By comparison, the DUSAF dataset identifies 591 green areas—classified under codes 141, 142, 311, 313, 322, 324, and 333—covering 26% of the study area, while the CLC dataset identifies only 7 green areas, covering 17% of the study area (Fig. 2).

Urban green patches account for approximately one-quarter of all patches (26.9%, Table 3), and are predominantly located in densely urbanized areas (CLC coded 111 and 112, Fig. 1). Among these, public and private gardens and parks constitute a substantial share (16.5% of the whole number), followed by sidewalk patches (5,7%) and tree rows (1,6%). These patch types are rarely captured in the DUSAF and CLC databases, which generally include only larger green spaces such as larger gardens and sport facilities. Specifically, DUSAF identifies 283 gardens and parks (code 141) and 90 sports facilities (code 142), whereas CLC records just 2 parks (code 141) and no sport facilities.

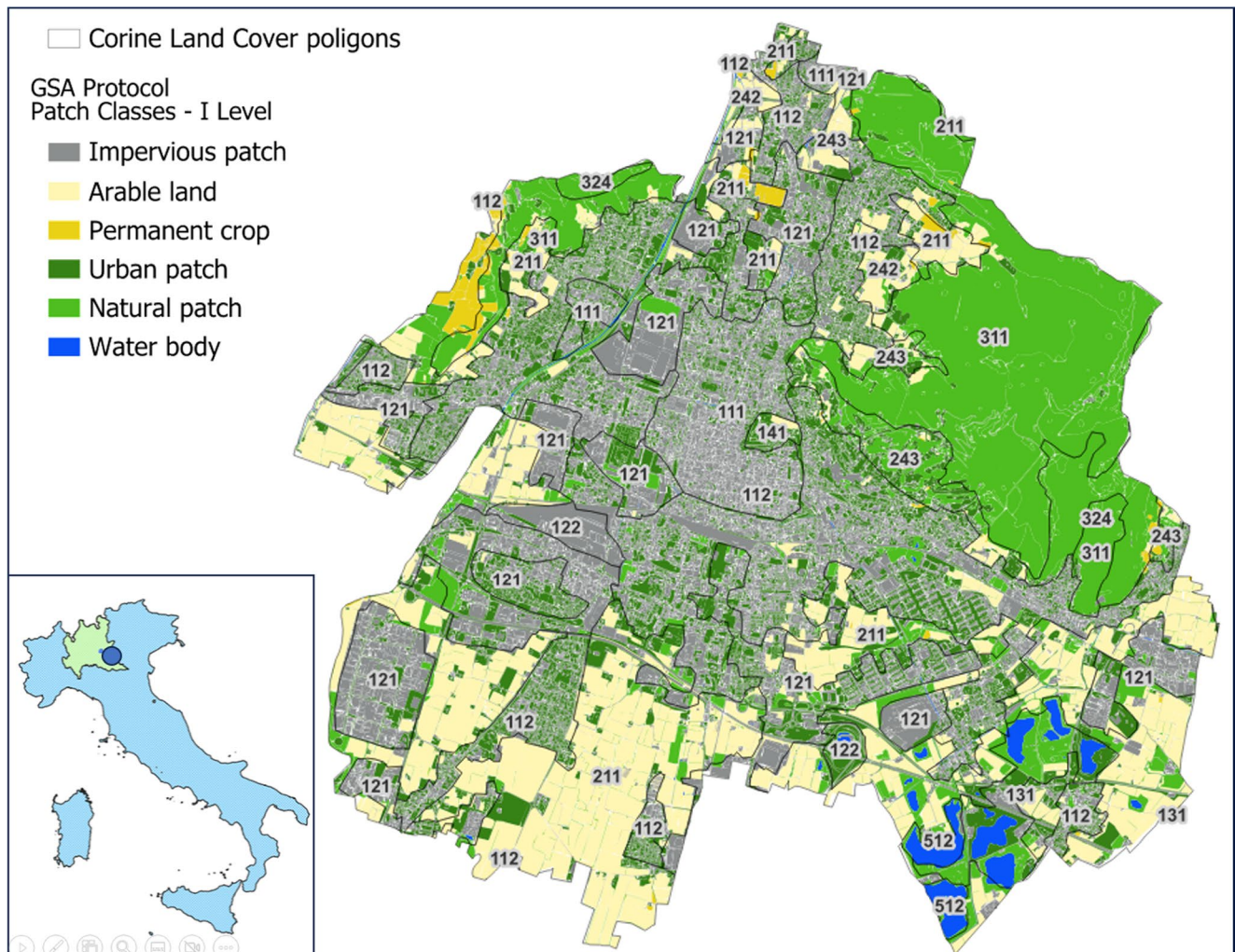


Fig. 1 Overview of the study area. On the left, the Lombardy region (in green) and the municipality of Brescia (blue point). On the right, the land use classification of the Brescia municipality according to the

Corine Land Cover map (2018). The three-number codes indicate the 3rd-level classification of the CLC system. Colours refer to the 1st level classification proposed with the GSA methodology

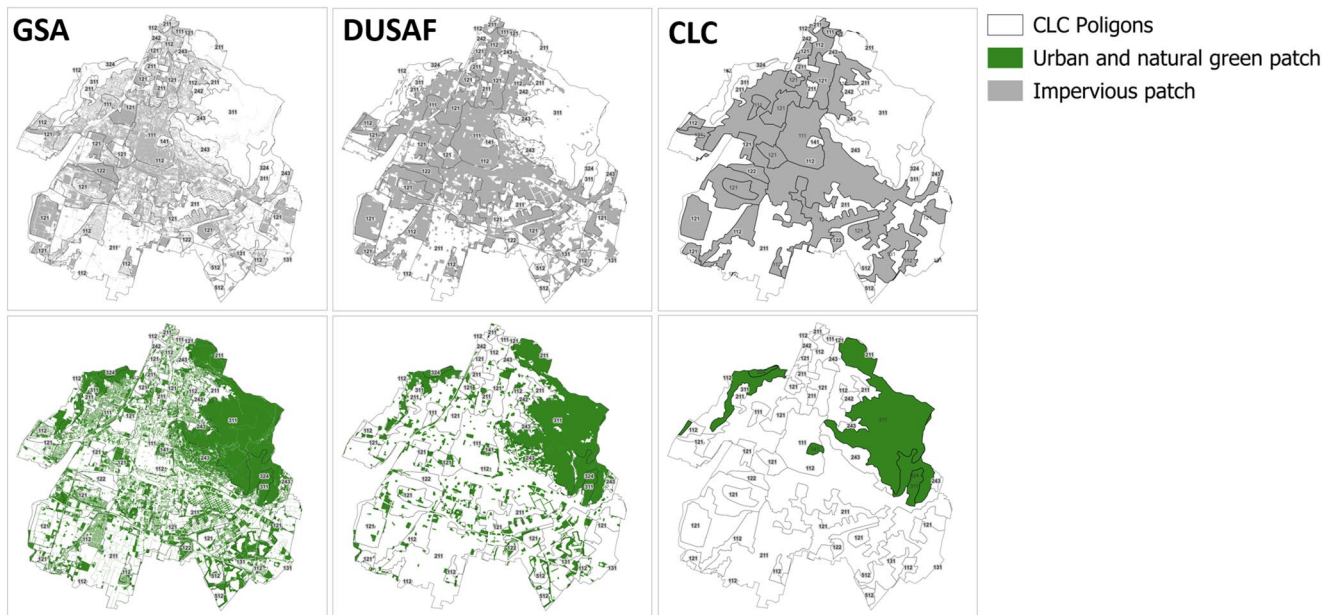


Fig. 2 Coverage and distribution of urban and natural green patches and impervious patches according to GSA (left column), DUSAF (central column), and CLC (right column). Impervious patches are dis-

played in the top row (in grey), while Urban and natural green patches are shown in the bottom row (in green)

Hedgerows occupy 43 hectares (1.2% of the total number of patches and 0.5% of the study area), representing 2% of the cropland (CLC code 211). These are absent from other databases. Although mixed woodlands, shrublands, and meadows represent just 0.9% of the total number of patches, they cover a significant share of the study area (21.4%). Cropland patches, while comprising only 1.5% of the total patch count, extend across 19.8% of the area.

Water bodies represent 0.2% of the whole patch number and 1.6% of the study area. The remaining 73,672 patches (68.9% of the total number of patches and 33.7% of the study area) are impervious for pollinators (Fig. 2). These include land types corresponding CLC codes 111, 112, 121, 122, 131, and 133. DUSAF identifies 966 such patches (covering 48.6% of the study area), while CLC reports 33 (covering 50.1%).

Suitability assessment

The average suitability of the study areas, estimated using the PSI, is 0.132 (SD=0.204), with values ranging from 0 (Impervious patch) to 0.797 (Hedgerow). The PSI exhibited high statistical significance at both the group level (Level 1) (ANOVA: $F=20150$; $p<0.001$), see Fig. 3 (PSI Graph), and the patch-type level (Level 2) (ANOVA: $F=8002$; $p<<0.001$). Post hoc pairwise comparisons further indicated statistically significant differences across the majority of contrasts (see Table S4b). Specifically, natural patches demonstrated the highest levels of suitability, showing statistically significant differentiation from both urban

and agricultural patches (see Fig. 3, PSI graph). Within this category, permanent crops were further distinguished from temporary crops, indicating a hierarchical structuring of suitability across patch types.

DIS=Disturbance Index; FRA=Floral Resource Availability; NSA=Nesting Site Availability; PSI=Patch Suitability Index; STR=Structural Index; TMC=Thermal Stress Mitigation Capacity.

Scenario analysis

The high resolution of the GSA database enabled the identification of over 14,000 patches to be considered in the scenario analysis for the Implementation of the measures outlined in the Green Areas and Biodiversity Plan. The implementation of the proposed Nature-based Solutions leads to an increase in SIN, FRA, NSA, and TMC values, driven by improvements in vegetation structure and the conversion of impervious surfaces into green areas. In contrast, the value of the DIS (Disturbance) component remains unchanged, as the measures do not involve modifications to the existing road network or infrastructure.

Under the full implementation scenario (100% of the available patches), 12,069 impervious patches would be converted into urban green patches, resulting in a 25.1% increase of PSI. Specifically, 7,741 paved sidewalks would be transformed into 3,871 sidewalk patches and 3,870 tree rows, while 4,328 fully sealed parking areas would be converted into car parks. These interventions would cover a total area of 548 hectares, equivalent to 6% of the study

Table 3 Characteristics (number, mean area, absolute and relative coverage) of patches identified in the municipality of Brescia according to GSA classification

GSA level I	GSA level I	Number of patches	Mean patch area [m ²]	Coverage (total area)	
				Absolute [m ²]	Relative [%]
Urban green patch	Car park	250	732	183,072	0,2%
	Cemetery	314	954	299,501	0,3%
	Industrial estates	762	1,211	922,531	1,0%
	Private garden	15,542	419	6,518,874	7,3%
	Private park	182	11,460	2,085,800	2,3%
	Public garden	1,804	1,121	2,022,331	2,3%
	Public park	127	14,424	1,831,791	2,0%
	Road verge	839	1,240	1,040,271	1,2%
	School garden	206	3,435	707,669	0,8%
	Sidewalk patch	6,085	5,273	1,932,881	2,2%
	Sport and leisure facilities	908	960	871,795	1,0%
	Tree row	1,681	691	1,161,058	1,3%
	Natural green patch	Hedgerow	1,290	336	432,949
Meadow		203	7,856	1,594,859	1,8%
Mixed woodland		530	30,443	16,134,758	18,0%
Crop-land patch	Shrubland	424	3,925	1,664,107	1,9%
	Cropland – Low suitability (e.g. Cereals)	1,636	10,764	17,610,032	19,6%
Permanent crop patch	Permanent crop - Medium suitability (e.g. Orchards)	39	7,168	279,557	0,3%
	Permanent crop - High suitability (e.g. Vineyards)	136	4,935	671,200	0,7%
Impervious patch	Impervious surface	73,665	413	30,445,972	33,9%
Water patch	Water body	234	6257	1,464,033	1,6%

area, and lead to the removal of 12,069 impervious patches. Biodiversity city plan measures 1 and 2 (Table 2) would target larger, more spatially concentrated areas, representing 13.7% of the total number of modified patches and accounting 70.2% of the area affected. In contrast, measures 3, 4, and 5 would involve involved a greater number of smaller, more scattered patches, accounting for 86.2% of the modified patches and 29.8% of the area.

PSI reveals a steady improvement across the four implementation levels (25%, 50%, 75%, and 100%) reveals a steady improvement in PSI, with an average increase of 5.8% between each level. The index shows sensitivity in registering the changes provided by the selected measures (Table 2) which mainly improve nesting site and floral resource availability. This progressive enhancement is consistent with findings in the literature, which highlight the

positive impact of increased floral resources and nesting site availability, particularly in public spaces such as gardens and parks (Baldock et al. 2019).

The PSI components - STR, FRA, NSA, and TMC - also exhibit notable variations across the implementation scenarios. Among these, NSA shows the most significant overall increase, rising by 41.2% with an average increment of 9.0%. TMC increases by 24.5% (5.6% on average), followed by FRA with a 22.2% increase (5.1% on average). Changes observed in STR are not due to direct improvements within individual patches. Instead, they result from the conversion of numerous impervious patches under measures 3, 4, and 5 (see Table 2), in green patches, making them contributing in increasing the average surface of these green areas and thus the STR component.(Fig. 4)

Discussion

In this study, individual landscape patches serve as the basic units for evaluating pollinator suitability within urban environments. The framework is designed as a tool to support urban and territorial planning, enabling the quantitative assessment of patch suitability based on currently available knowledge. Contributions of each patch type can be assessed across multiple spatial scales—from individual neighbourhoods to broader urban sectors and the metropolitan landscape—allowing spatially explicit analyses that capture the pronounced heterogeneity inherent in urban systems. The PSI index and its components effectively differentiate among the patch classes and types defined by the GSA protocol, allowing the quantification of contributions from small green patches that are often overlooked by conventional land classification systems (Bowler et al. 2025). Differences in spatial resolution between GSA, DUSAF, and CLC strongly influence their respective abilities to detect these features. While large green areas are consistently identified across all three systems, GSA reveals a substantially higher number of green patches overall, particularly small elements that remain undetected in DUSAF and CLC classifications.

Accurately mapping even smallest urban green patches is essential to support urban planning, as detailed knowledge of their abundance and spatial distribution underpins effective urban planning and management strategies aimed at pollinator conservation (Zhao et al. 2019). These small green spaces provide vital resources such as foraging and nesting sites and thus represent essential components of urban green infrastructure (European Commission: Directorate-General for Environment et al. 2020; Rahimi et al. 2023; Delahay et al. 2023). Detecting such fine-scale elements requires high-resolution topographic tools (Zhao et al. 2019), which enable

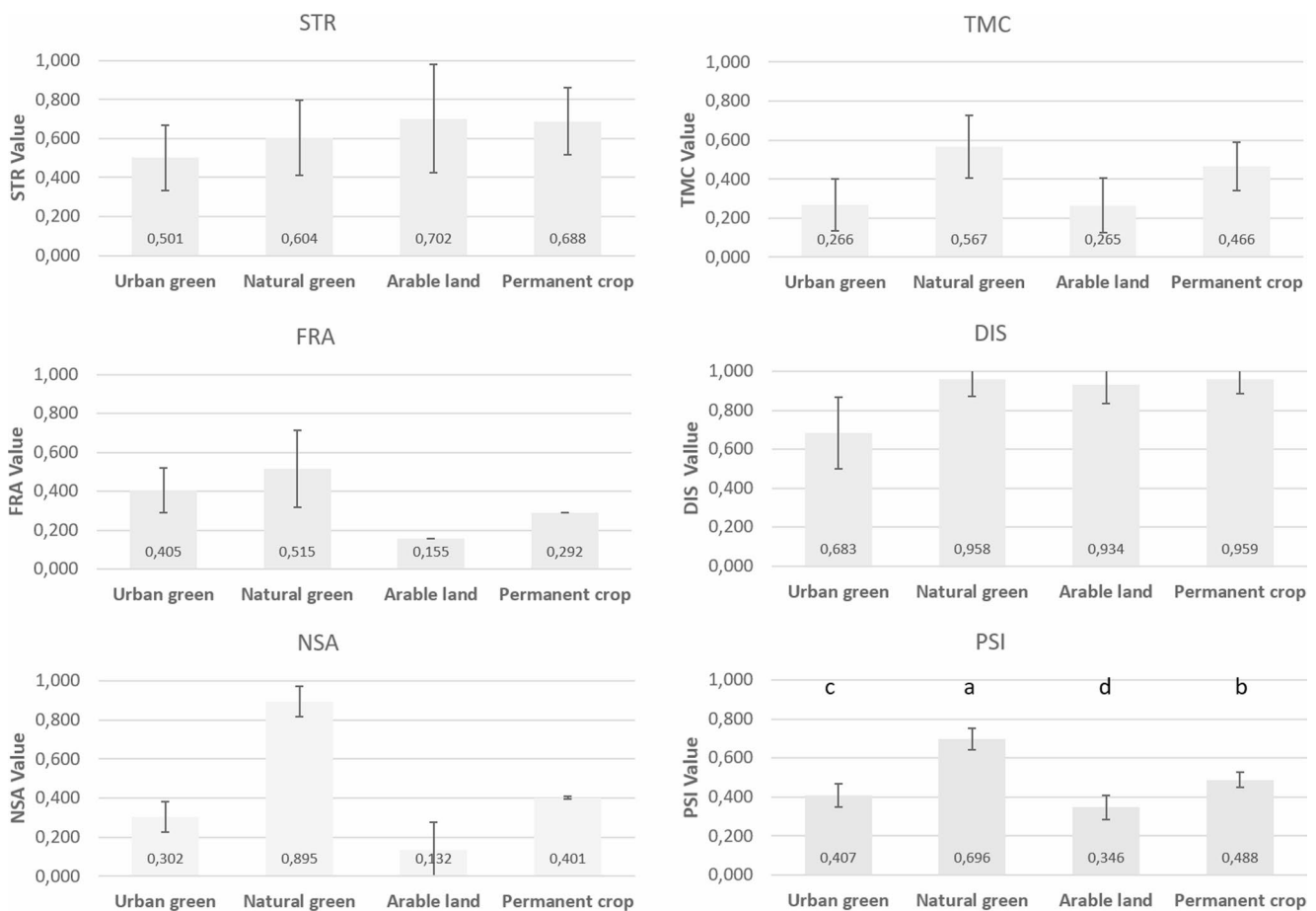


Fig. 3 Mean values of the Patch Suitability Index (PSI) and its components across the four first-level GSA suitable classes. Error bars represent standard deviation; letters indicate the significant differences

among the groups. Impervious and water bodies are excluded as their suitability is zero by definition

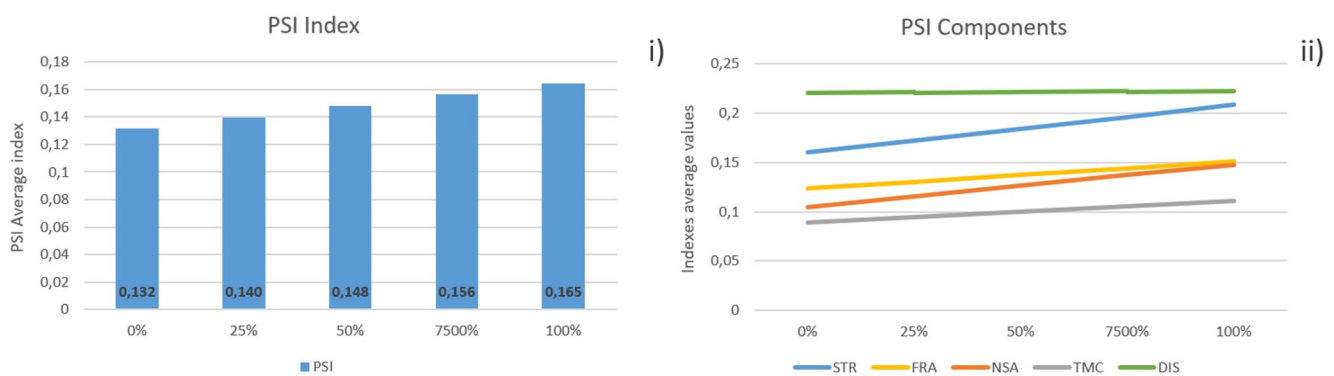


Fig. 4 Changes in the Patch Suitability Index (PSI) (right) and its individual components (left) across the four implementation scenarios of nature-based solutions in the Municipality of Brescia. The baseline

scenario (0%) represents the current condition without any nature-based solutions implemented

a more precise understanding of urban ecological networks. Furthermore, these fine-scale green elements could enhance ecological connectivity between fragmented habitats and surrounding natural areas, functioning as key nodes within broader green infrastructure networks. The GSA framework is specifically designed to capture and evaluate these small

yet significant features, providing planners with a quantitative tool to inform decisions and optimize the ecological function of urban green spaces.

Differences among GSA, DUSAF, and CLC are particularly pronounced within urban land-use classes (CLC codes 111, 112, 121, and 122), both in terms of the number and size

of identified patches. Low-resolution classification systems such as DUSAF and CLC tend to aggregate heterogeneous land cover types— combining green and impervious surfaces—into broad, homogeneous polygons. This generalization reduces classification granularity and compromises the accuracy of habitat suitability assessments, particularly in densely urbanized contexts (Grafius et al. 2016). Unlike DUSAF and CLC, which typically identify only large, urbanized polygons, GSA captures a much greater number of small-area patches (mean size: 0.09 ha), including fine-scale features such as private gardens, sidewalks, and tree rows— elements largely absent from coarser-resolution datasets.

Furthermore, GSA improves the delineation of impervious surface patches, whose extent plays a pivotal role in shaping habitat suitability for pollinator communities ((Larson et al. 2014; Bennett and Lovell 2019; Birdshire et al. 2020). By providing a more accurate and detailed classification, GSA supports more targeted and effective urban biodiversity planning and monitoring.

Suitability assessment

In this study, individual landscape patches are used as the basic units of analysis for evaluating the pollinator suitability within urban environments.

The suitability index, along with its individual components, significantly differentiates among the patch classes and types defined by the GSA protocol. The contribution of each patch type can be quantitatively assessed across multiple spatial scales—ranging from individual neighbourhoods to broader urban sectors and the metropolitan landscape—thereby facilitating spatially explicit analyses that incorporate the pronounced heterogeneity inherent to urban systems. This analytical resolution allows for the identification of specific landscape features with limited ecological performance, whether due to their intrinsic characteristics or their spatial context. Such insights are essential for informing targeted and evidence-based interventions aimed at improving ecological quality and functional connectivity across urban environments.

While our methodology confirms the key role of natural areas in supporting pollinators, it also highlights the contribution of urban patches, particularly features such as tree rows, sidewalk patches, or public gardens. In densely urbanized areas of Brescia, where green space is otherwise scarce, these small patches play an outsized role due to their abundance rather than their individual size (Donkersley et al. 2023; Bowler et al. 2025).

Ultimately, the patch-level information generated through this assessment supports more precise decision-making in the planning and implementation of urban green

infrastructure strategies. Hedgerows may receive higher suitability scores than some natural habitats, such as meadows or shrublands, because the GSA framework retains the estimates proposed by the original authors used to construct the indicators. Their combination of accessible nesting surfaces and dense floral resources at the patch scale results in higher values for nesting site availability (Zulian et al. 2013) and floral density (Montero-Castaño et al. 2016; Lynch et al. 2021). These indices do not fully capture floral diversity, phenological spread, or the complete range of nesting habitats, which may explain why some natural habitats appear lower. The GSA framework can accommodate refinements, including additional indicators and experimental validation linking scores to actual pollinator presence, allowing continuous improvement in both accuracy and ecological relevance (see Table S4a).

It should be emphasized that the primary objective of this study is not to provide definitive assessments of patch suitability, but rather to demonstrate the utility of the GSA as a planning tool. By leveraging the best available knowledge, it enables planners to quantitatively evaluate urban patches, compare their relative contribution to pollinator support, and guide informed decisions for the design and implementation of urban green infrastructure strategies.

Scenario analysis

The scenario analysis conducted with the GSA framework demonstrates the potential of the Green and Biodiversity Plan to enhance the suitability of both individual patches and the broader urban landscape. By relying on the multi-dimensional structure of the PSI, the tool allows planner to identify which ecological components are most responsive to different levels of intervention. The results indicate that improvements in patch suitability are primarily driven by increases in floral resource availability, nesting site availability, and thermal stress mitigation capacity. Among these, enhancements in floral resources emerge as particularly influential, consistent with their well-established role in sustaining pollinator populations. However, achieving stable and long-term improvements requires complementary actions that address additional ecological dimensions (Baldock et al. 2019). In this perspective, the capacity of the GSA to highlight changes in nesting opportunities and thermal regulation provides valuable insights into the broader ecological functionality of urban green infrastructure.

Conversely, disturbance-related components showed little or no variation under the proposed measures. Addressing these aspects would require structural modifications to patch configuration and surrounding road infrastructure, which are often impractical in consolidated urban areas due to the scale of spatial reorganization involved. This underscores

the importance of integrating ecological design principles into new urban developments from the outset, while using tools such as the GSA to quantitatively assess the expected contribution of planned interventions and guide strategic decision-making in territorial planning.

Measures targeting the conversion of impermeable surfaces, such as fully sealed parking lots or sidewalks, emerged as particularly effective, as they increase landscape heterogeneity and thereby promote pollinator communities (Liang et al. 2023). Similarly, the ecological enhancement of public parks and gardens was shown to substantially improve patch suitability by providing additional nesting opportunities and expanding the availability of floral resources (Bennett and Lovell 2019). These results highlight the capacity of the GSA framework to quantify the expected ecological benefits of specific interventions, offering urban planners an evidence-based tool to prioritize actions with the greatest potential impact on pollinator support.

Limitations and future improvements

The GSA framework was developed and tested primarily for its ability to discriminate among patch types and to evaluate different biodiversity planning scenarios. However, several limitations must be acknowledged. Some components of the index rely on simplified assumptions and literature-derived estimates rather than direct and precise measurements, due to the lack of fine-scale data. As a consequence, the resulting suitability scores should not be interpreted as predictive, but rather as indicative of the relative suitability of patches as determined by the integrated contribution of all index components.

Future improvements will require targeted field validation, specifically aimed at directly linking PSI scores with observed pollinator community composition and abundance, in order to consolidate the predictive capacity of the framework. Once validated, additional refinements should include the integration of landscape connectivity metrics into patch-level analyses, thereby moving towards a metapopulation perspective in which urban pollinator communities are evaluated as part of a broader ecological network. Such advancements would provide a more comprehensive understanding of how individual patch suitability interacts with landscape structure to shape the distribution and persistence of pollinators in urban systems.

Conclusion

High-resolution cartographic data provide valuable insights into the spatial configuration of green areas across urban and rural landscapes, highlighting their crucial role in

sustaining pollinator presence and abundance. By distinguishing vegetated from impervious surfaces and characterizing individual patches through ecological attributes, this study illustrates how urban systems can be conceived as heterogeneous mosaics of habitat patches rather than uniformly unsuitable matrices. Within this context, the GSA framework—through its multidimensional suitability index—offers a standardized and quantitative means to assess habitat quality across multiple components and patch types, thereby outlining their relative contributions to the ecological suitability of municipal areas. The approach is intended as a decision-support tool for urban and territorial planners, enabling the evaluation of green areas and the potential effects of proposed interventions on pollinator suitability. Furthermore, the fine-scale patch characterization generated by the framework provides a basis for future connectivity analyses, which could conceptualize pollinator populations as metapopulations distributed across urban green networks. Such perspectives can improve understanding of how spatial structure influences pollinator persistence and inform biodiversity-oriented planning strategies. Ultimately, the GSA framework supports the integration of pollinator conservation objectives into urban development, contributing to greener, more resilient, and ecologically functional cities.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11252-025-01821-4>.

Acknowledgements We are grateful to Mr. Graziano Lazzaroni, director of the Urban Green areas management division of Brescia Municipality who helped the improvement of the integrated database by providing the topographic database about public green areas and trees in the municipality area.

Author contributions FG, AS and GG contributed to the study conception and design. FG managed Material preparation, data collection. FG, AS and GG developed the framework models and performed data analysis. FG wrote the first draft of the manuscript and AS and GG commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work has been supported by “Fondazione Cariplo” (Italy) and “Regione Lombardia” (Italy) under the project: “Biodiversità, suolo e servizi ecosistemici. Strategie, metodi e tecniche per la realizzazione di food system robusti, resilienti e sostenibili” (ref. 2020–4135, CUP D75F21002990009).

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Altieri MA (1999) The ecological role of biodiversity in agroecosystems. *Agric Ecosyst Environ* 31. [https://doi.org/10.1016/S0167-809\(99\)00028-6](https://doi.org/10.1016/S0167-809(99)00028-6)
- Baldock KCR, Goddard MA, Hicks DM et al (2015) Where is the uk's pollinator biodiversity? The importance of urban areas for flower-visiting insects. *Proc R Soc B-Biol Sci* 282:20142849. <https://doi.org/10.1098/rspb.2014.2849>
- Baldock KCR, Goddard MA, Hicks DM et al (2019) A systems approach reveals urban pollinator hotspots and conservation opportunities. *Nat Ecol Evol* 3:363–373. <https://doi.org/10.1038/s41559-018-0769-y>
- Baldock KC (2020) Opportunities and threats for pollinator conservation in global towns and cities. *Curr Opin Insect Sci* 38:63–71. <https://doi.org/10.1016/j.cois.2020.01.006>
- Bartholomée O, Aullo A, Becquet J et al (2020) Pollinator presence in orchards depends on landscape-scale habitats more than in-field flower resources. *Agric Ecosyst Environ* 293:106806. <https://doi.org/10.1016/j.agee.2019.106806>
- Bennett AB, Lovell S (2019) Landscape and local site variables differentially influence pollinators and pollination services in urban agricultural sites. *PLoS ONE* 14:e0212034. <https://doi.org/10.1371/journal.pone.0212034>
- Biella P, Tommasi N, Guzzetti L et al (2022) City climate and landscape structure shape pollinators, nectar and transported pollen along a gradient of urbanization. *J Appl Ecol* 59:1586–1595. <https://doi.org/10.1111/1365-2664.14168>
- Birdshire KR, Carper AL, Briles CE (2020) Bee community response to local and landscape factors along an urban-rural gradient. *Urban Ecosyst* 23:689–702. <https://doi.org/10.1007/s11252-020-00956-w>
- Bommarco R, Lindström SAM, Raderschall CA et al (2021) Flower strips enhance abundance of bumble bee queens and males in landscapes with few honey bee hives. *Biol Conserv* 263:109363. <https://doi.org/10.1016/j.biocon.2021.109363>
- Bowler DE, Callaghan CT, Felappi JF et al (2025) Evidence-base for urban green-blue infrastructure to support insect diversity. *Urban Ecosyst* 28:54. <https://doi.org/10.1007/s11252-024-01649-4>
- Brescia municipality (2024) Green areas and biodiversity city plan. <https://www.comune.brescia.it/aree-tematiche/verde-e-parchi/piano-del-verde-e-della-biodiversita>
- Burr A, Hall DM, Schaege N (2018) The perfect lawn: exploring neighborhood socio-cultural drivers for insect pollinator habitat. *Urban Ecosyst* 21:1123–1137. <https://doi.org/10.1007/s11252-018-0798-y>
- Cohen H, Philpott SM, Liere H et al (2021) The relationship between pollinator community and pollination services is mediated by floral abundance in urban landscapes. *Urban Ecosyst* 24:275–290. <https://doi.org/10.1007/s11252-020-01024-z>
- Cohen H, Egerer M, Thomas S-S, Philpott SM (2022) Local and landscape features constrain the trait and taxonomic diversity of urban bees. *Landsc Ecol* 37:583–599. <https://doi.org/10.1007/s10980-021-01370-z>
- Davis AY, Lonsdorf EV, Shierk CR et al (2017) Enhancing pollination supply in an urban ecosystem through landscape modifications. *Landsc Urban Plann* 162:157–166. <https://doi.org/10.1016/j.landurbplan.2017.02.011>
- Delahay RJ, Sherman D, Soyalan B, Gaston KJ (2023) Biodiversity in residential gardens: a review of the evidence base. *Biodivers Conserv*. <https://doi.org/10.1007/s10531-023-02694-9>
- Dmitruk M, Wrzesień M, Strzałkowska-Abramek M, Denisow B (2021) Pollen food resources to help pollinators. A study of five Ranunculaceae species in urban forest. *Urban For Urban Green* 60:127051. <https://doi.org/10.1016/j.ufug.2021.127051>
- Donkersley P, Witchalls S, Bloom EH, Crowder DW (2023) A little does a lot: can small-scale planting for pollinators make a difference? *Agric Ecosyst Environ* 343:108254. <https://doi.org/10.1016/j.agee.2022.108254>
- Doroski DA, Duguid MC, Ashton MS (2021) Forest patch size predicts seed bank composition in urban areas. *Appl Veg Sci*. <https://doi.org/10.1111/avsc.12534>
- Dylewski Ł, Białas JT, Szymysł A, Banaszak-Cibicka W (2024) Pollinator assemblages in grasslands along river valleys depend on the urban matrix and local habitat scale variables. *Ecol Ind* 159:111687. <https://doi.org/10.1016/j.ecolind.2024.111687>
- Dylewski Ł, Maćkowiak Ł, Banaszak-Cibicka W (2019) Are all urban green spaces a favourable habitat for pollinator communities? Bees, butterflies and hoverflies in different urban green areas. *Ecol Entomol* 44:678–689. <https://doi.org/10.1111/een.12744>
- Egerer MH, Wagner B, Lin BB et al (2020) New methods of spatial analysis in urban gardens inform future vegetation surveying. *Landsc Ecol* 35:761–778. <https://doi.org/10.1007/s10980-020-0974-1>
- Essenberg CJ (2012) Explaining variation in the effect of floral density on pollinator visitation. *Am Nat* 180:153–166. <https://doi.org/10.1086/666610>
- European Commission: Directorate-General for Environment, Wilk B, Rebollo V, Hanania S (2020) A guide for pollinator-friendly cities – How can spatial planners and land-use managers create favourable urban environments for pollinators?, Publications Office of the European Union. <https://doi.org/10.2779/87169>
- European Environment Agency (EEA) (2018) Urban atlas. https://www.eea.europa.eu/en/urban-atlas/copernicus_v_3035_10_m_ua-2018_p_2017-2019_v01_r03
- Grafius DR, Corstanje R, Warren PH et al (2016) The impact of land use/land cover scale on modelling urban ecosystem services. *Landsc Ecol* 31:1509–1522. <https://doi.org/10.1007/s10980-015-0337-7>
- Hall MA, Nimmo DG, Cunningham SA et al (2019) The response of wild bees to tree cover and rural land use is mediated by species' traits. *Biol Conserv* 231:1–12. <https://doi.org/10.1016/j.biocon.2018.12.032>
- Henriksen CI, Langer V (2013) Road verges and winter wheat fields as resources for wild bees in agricultural landscapes. *Agric Ecosyst Environ* 173:66–71. <https://doi.org/10.1016/j.agee.2013.04.008>
- Hicks DM, Ouvrard P, Baldock KCR et al (2016) Food for pollinators: quantifying the nectar and pollen resources of urban flower meadows. *PLoS ONE* 11:e0158117. <https://doi.org/10.1371/journal.pone.0158117>
- Jeanneret Ph, Aviron S, Alignier A et al (2021) Agroecology landscapes. *Landsc Ecol* 36:2235–2257. <https://doi.org/10.1007/s10980-021-01248-0>
- Kennedy CM, Lonsdorf E, Neel MC et al (2013) A global quantitative synthesis of local and landscape effects on wild bee pollinators

- in agroecosystems. *Ecol Lett* 16:584–599. <https://doi.org/10.1111/ele.12082>
- Langellotto G, Melathopoulos A, Messer I et al (2018) Garden pollinators and the potential for ecosystem service flow to urban and peri-urban agriculture. *Sustainability* 10:2047. <https://doi.org/10.3390/su10062047>
- Larson JL, Kesheimer AJ, Potter DA (2014) Pollinator assemblages on dandelions and white clover in urban and suburban lawns. *J Insect Conserv* 18:863–873. <https://doi.org/10.1007/s10841-014-9694-9>
- Li E, Parker SS, Pauly GB et al (2019) An urban biodiversity assessment framework that combines an urban habitat classification scheme and citizen science data. *Front Ecol Evol* 7:277. <https://doi.org/10.3389/fevo.2019.00277>
- Liang H, He Y, Theodorou P, Yang C (2023) The effects of urbanization on pollinators and pollination: a meta-analysis. *Ecol Lett* 26:1629–1642. <https://doi.org/10.1111/ele.14277>
- Lombardy, Region (2018) Dusaf 6.0 – Land Use. Accessed: Jul. 27, 2023. [Online]. Available: <https://www.dati.lombardia.it/Territorio/Dusaf-6-0-Usa-del-suolo-2018/7rae-fng6>
- Lombardy R (2025) Regional Forest Database. https://www.geoportale.regione.lombardia.it/metadati?p_p_id=detailSheetMetadati_WAR_gptmetadataportlet&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&_detailSheetMetadati_WAR_gptmetadataportlet_identifier=r_lombar%3A7ceabf1c-28b2-4c0b-b4ba-4be3d17afa33&_jsfBridgeRedirect=true
- Lombardy Region (2020) Regional Topographic Geodatabase (DBTR). https://www.regione.lombardia.it/https://www.geoportale.regione.lombardia.it/download-pacchetti?p_p_id=dwnpackageportlet_WAR_gptdownloadportlet&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&_dwnpackageportlet_WAR_gptdownloadportlet_metadatiid=r_lombar%3A0092b7ba-c697-433b-b5f2-9f9d9b8694e3&_jsfBridgeRedirect=true
- Lowenstein DM, Matteson KC, Minor ES (2019) Evaluating the dependence of urban pollinators on ornamental, non-native, and ‘weedy’ floral resources. *Urban Ecosyst* 22:293–302. <https://doi.org/10.1007/s11252-018-0817-z>
- Lynch L, Kangas M, Ballut N et al (2021) Changes in land use and land cover along an urban-rural gradient influence floral resource availability. *Curr Landscape Ecol Rep* 6:46–70. <https://doi.org/10.1007/s40823-021-00064-1>
- McKINNEY ML (2002) Urbanization, biodiversity, and conservation. *Bioscience* 52(10):883. [https://doi.org/10.1641/0006-3568\(2002\)052\[0883:UBAC\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2002)052[0883:UBAC]2.0.CO;2)
- Meyer S, Unternährer D, Arlettaz R et al (2017) Promoting diverse communities of wild bees and hoverflies requires a landscape approach to managing meadows. *Agric Ecosyst Environ* 239:376–384. <https://doi.org/10.1016/j.agee.2017.01.037>
- Montero-Castaño A, Ortiz-Sánchez FJ, Vilà M (2016) Mass flowering crops in a patchy agricultural landscape can reduce bee abundance in adjacent shrublands. *Agric Ecosyst Environ* 223:22–30. <https://doi.org/10.1016/j.agee.2016.02.019>
- Ollerton J (2021) Pollinators and pollination: nature and society. Pelagic Publishing Ltd. <https://doi.org/10.1016/j.baee.2021.04.006>
- Phillips BB, Wallace C, Roberts BR et al (2020) Enhancing road verges to aid pollinator conservation: a review. *Biol Conserv* 250:108687. <https://doi.org/10.1016/j.biocon.2020.108687>
- Potts SG, Biesmeijer JC, Kremen C et al (2010) Global pollinator declines: trends, impacts and drivers. *Trends Ecol Evol* 25:345–353. <https://doi.org/10.1016/j.tree.2010.01.007>
- Prendergast KS, Tomlinson S, Dixon KW et al (2022) Urban native vegetation remnants support more diverse native bee communities than residential gardens in Australia’s Southwest biodiversity hotspot. *Biol Conserv* 265:109408. <https://doi.org/10.1016/j.biocon.2021.109408>
- Rahimi E, Barghjelveh S, Dong P (2023) Estimating the pollination supply of urban green spaces to determine suitable areas for urban agriculture in the city of Tehran. *Urban Ecosyst* 26:19–30. <https://doi.org/10.1007/s11252-022-01289-6>
- Semerdzheva L, Borisova B (2021) Urban ecosystems assessment: an integrated approach to maintenance of habitats and their biodiversity. *JBGS* 45:99–106. <https://doi.org/10.3897/jbgs.e78975>
- Silva JLS, De Oliveira MTP, Cruz-Neto O et al (2021) Plant–pollinator interactions in urban ecosystems worldwide: a comprehensive review including research funding and policy actions. *Ambio* 50:884–900. <https://doi.org/10.1007/s13280-020-01410-z>
- Stange E, Zulian G, Rusch G et al (2017) Ecosystem services mapping for municipal policy: ESTIMAP and zoning for urban beekeeping. *OE* 2:e14014. <https://doi.org/10.3897/oneeco.2.e14014>
- Twerd L, Sobieraj-Betlińska A, Kilińska B et al (2022) Unexpectedly, creation of temporary water bodies has increased the availability of food and nesting sites for bees (Apiformes). *Forests* 13:1410. <https://doi.org/10.3390/f13091410>
- Wenzel A, Grass I, Belavadi VV, Tschardt T (2020) How urbanization is driving pollinator diversity and pollination – a systematic review. *Biol Conserv* 241:108321. <https://doi.org/10.1016/j.biocon.2019.108321>
- Winfrey R, Griswold T, Kremen C (2007) Effect of human disturbance on bee communities in a forested ecosystem. *Conserv Biol* 21:213–223. <https://doi.org/10.1111/j.1523-1739.2006.00574.x>
- Wray JC, Elle E (2015) Flowering phenology and nesting resources influence pollinator community composition in a fragmented ecosystem. *Landsc Ecol* 30:261–272. <https://doi.org/10.1007/s10980-014-0121-0>
- Yang J, Luo X, Lu S et al (2022) Effects of compositional and configurational heterogeneity of the urban matrix on the species richness of woody plants in urban remnant forest patches. *Landsc Ecol* 37:619–632. <https://doi.org/10.1007/s10980-021-01368-7>
- Zawadzka JE, Harris JA, Corstanje R (2021) Assessment of heat mitigation capacity of urban greenspaces with the use of invest urban cooling model, verified with day-time land surface temperature data. *Landsc Urban Plann* 214:104163. <https://doi.org/10.1016/j.landurbplan.2021.104163>
- Zhao C, Sander HA, Hendrix SD (2019) Wild bees and urban agriculture: assessing pollinator supply and demand across urban landscapes. *Urban Ecosyst* 22:455–470. <https://doi.org/10.1007/s11252-019-0826-6>
- Zulian (2013) ESTIMAP: ecosystem services mapping at European scale. Publications Office, LU
- Zulian G, Paracchini ML, Maes J, Lique C (2013) ESTIMAP: Ecosystem services mapping at European scale. Publications Office of the European Union, Luxembourg. <https://doi.org/10.2788/64713>

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.