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A method to prioritize and allocate nature-based solutions in urban areas based on ecosystem service demand

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HIGHLIGHTS

- We map the demand for multiple ES to prioritize potential NbS sites.
- To allocate NbS, we assign ES supply scores to 11 NbS types based on the literature.
- Urban forest is the most needed NbS type in Valletta urban area.
- Prioritization of other NbS depends on specific site constraints or demand profiles.
- Coupling ES demand and NbS scores can support performance-based planning of NbS.

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ABSTRACT

Mapping and assessing the demand for ecosystem services (ES) in urban areas can support the allocation of nature-based solutions (NbS) to deliver ES where they are most needed. This study presents a method that combines the spatial assessments of ES demand and numeric scores reflecting the capacity of different typologies of NbS to supply multiple ES. The method was applied in 220 ha of potential NbS sites across the urban area of Valletta, Malta, considering 11 NbS types and 5 priority ES. The proposed approach supports both the prioritization of potential NbS sites and the allocation of the specific NbS types which maximise the benefits by providing the best balance of multiple ES. Results show that urban forest is the most needed NbS type across the study area, being the one with the highest capacity to supply most of the analysed ES. However, there are specific cases in which other typologies are more suitable. These include hotspots of demand for specific ES, such as noise reduction and nature-based recreation; as well as sites where size, shape, or land use constraints hinder the implementation of urban forests. Our approach can be used and adapted to support a variety of planning decisions dealing with the prioritization and spatial allocation of NbS, including the development of performance-based approaches aimed at integrating NbS within urban transformation projects.

1. Introduction

Ecosystem services (ES) mapping and assessment is considered an important tool for policy-makers to better understand the spatial links between ecosystems and their benefits for society (Feurer et al., 2021; Burkhard & Maes, 2017). Hence, advancing mapping and assessment methods is essential for ensuring proper consideration and integration of ES into planning practices (Goldenberg et al., 2017; Mörtberg et al., 2017; Gómez-Baggethun & Barton, 2013). Spatially explicit mapping and assessment of ES supply and demand can be used to “spot problem areas in need of intervention” (Bagstad et al., 2013), thus leading to more informed planning decisions dealing with the spatial allocation and prioritization of interventions to tackle societal challenges and provide socio-environmental benefits through ES (Cortinovis & Geneletti, 2018b). ES supply reflects the capacity of ecosystems to deliver ES, while ES demand focuses on the beneficiaries of such ES and their level

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of need or dependence on them (Yahdjian et al., 2015). Understanding ES demand is therefore fundamental to support decision-making (Chan & Satterfield, 2020) as it can be used to identify where and which ES are most needed in relation to the targeted beneficiaries.

This is especially important in urban areas where the demand for ES is accelerating due to rapid urbanization and population growth (Charoenkit & Piyathamrongchai, 2019; Elmqvist et al., 2015, Gómez-Baggethun et al., 2013). Promoting urban greening through nature-based solutions (NbS), which are purposely designed to deliver multiple ES, is considered one of the key planning actions to address multiple urban challenges (Babí Almenar et al., 2021; Escobedo et al., 2019; Raymond et al., 2017), while enhancing human wellbeing (Frantzeskaki et al., 2019). The implementation of multifunctional NbS in urban areas is thus an opportunity to deliver ES, such as temperature and runoff regulation (Venter et al., 2021), where they are most needed. This requires analysing the spatial variation of the environmental issues and urban pressures (e.g., air pollution, urban heat island effects, reduced soil permeability and access to nature) that determine the demand, as well as the distribution and specific characteristics of the population (Cortinovis & Geneletti, 2020). In this context, the spatial assessment of ES can be used to understand ES flows, i.e. the spatial links between ES supply and demand areas (Bagstad et al., 2013), in order to identify priority sites where the ES supplied by NbS can reach the targeted beneficiaries (Verhagen et al., 2017).

However, real-life planning processes and documents rarely address the demand side of ES (e.g., Cortinovis & Geneletti, 2018a; Longato et al., 2021). Even in studies on ES prioritization, the spatial variation of the demand is not always accounted for (Verhagen et al., 2017). This lack potentially undermines the effectiveness of planning decisions that involve the allocation of NbS to address the specific urban challenges in different areas of the city. Notable exceptions include the work by Langemeyer and colleagues (2020), who mapped the demand for several ES in Barcelona, Spain to prioritize green roof installations in areas characterized by a greater ES demand. Similarly, Cortinovis and Geneletti (2020) spatially assessed the supply of and demand for multiple ES in Trento, Italy, and developed an innovative performance-based planning approach to define requirements for urban transformations in terms of NbS integration. Both studies coupled the mapping of ES demand to identify priority areas with an estimation of the capacity of different types (or design) of NbS to provide the needed ES. This capacity is expressed by numeric scores assigned to the NbS for each ES analysed. However, the former study focuses only on a specific type of NbS, while the latter identifies the preferred NbS based on the most demanded ES, without accounting for their multi-functionality. A multi-criteria analysis tool was recently developed to select suitable NbS based on their potential benefits in terms of multiple ES, thus accounting for their multi-functionality (Croeser et al., 2021). However, the selection of priority ES is made here for the whole city, disregarding the spatial variation of the demand. Studies that combine the spatial assessment of ES demand with a scoring system that accounts for the multi-functionality of different NbS types are still missing, despite their potential usefulness in supporting planning decisions on prioritization and allocation of NbS.

The aim of this study is to develop and test a method to allocate different types of NbS in urban areas to deliver the most demanded ES The method allows to map the demand for multiple ES, as well as to assess the capacity of different types of NbS to supply the selected ES. The results of the two analyses are then combined to allocate different NbS types to a set of areas of intervention. The method is applied to suggest a possible allocation of NbS to potentially available sites in the Valletta urban area, Malta.

The remainder of the paper is organised in four main sections. Section 2 presents the case study area, the input data, and the methodological steps of the proposed approach. Section 3 presents the results, including the maps of the demand scores of potential NbS sites, a look-up table with the supply scores of selected NbS types, and the priority NbS identified in each potential site. Section 4 discusses the results and innovative aspects and limitations of the approach, and provides examples on its possible uses to support planning decisions. Finally, Section 5 provides the conclusions of our study.

2. Materials and methods

2.1. Study area, potential NbS sites, and priority ES

The study area is the urban area around Valletta, the capital city of Malta. With a population density of almost 1,400 inhabitants per km^2 and 21 guest nights per inhabitant (Eurostat, 2017), as well as almost a quarter (23.7%) of land covered by artificial surfaces (Eurostat, 2018), this small island state stands out for having the highest population density, tourism intensity, and share of man-made surfaces in all the EU. The case study area covers around 2,227 ha and is located in the most urbanised part of the island. Its boundaries correspond to those of the two Local Plans (i.e., Grand Harbour Local Plan and North Harbours Local Plan) covering the municipality of Valletta and other 16 municipalities (also called urban localities by the Plans) that form a unique conurbation with scattered agricultural and natural/seminatural areas and urban green spaces (Fig. 1).

To identify potential sites for NbS, we used the map of “physical opportunities” prepared by Longato and colleagues (2022), who mapped the sites that potentially offer an opportunity for implementing NbS based on the map of urban ecosystem types (Balzan et al., 2021). The identified sites include non-urbanized areas where a greening intervention was considered feasible (e.g., excluding watercourses, beaches, cliffs with steep slopes, wetlands, and gardens). To these areas, which cover 207 ha, we added 15 ha of street green areas identified *ex novo* by selecting suitable street green and green verge areas from those classified as “Gardens, parks and landscaping” in the map of ecosystem types by Balzan and colleagues (2021), for a total of 222 ha (Fig. 1).

Most of these areas already contain some green infrastructure elements that provide a range of ES (Balzan et al., 2021), and are located within the urban development boundaries. This constitutes a risk, since future urban development projects may replace them, but it also represents an opportunity to minimise land take and enhance ES supply by integrating NbS that can better address the existing challenges. Operationally, new NbS could be realized either as part of wider transformation projects that include greening interventions or land conservation measures alongside urban development, or through interventions specifically aimed at improving or integrating existing ecosystems (Longato et al., 2022).

The selection of the priority ES to analyse is based on the main challenges affecting the area, which were identified and discussed with practitioners from the Malta Planning Authority during a meeting: high levels of air and noise pollution produced by road traffic, climate-related hazards (high temperatures and flooding), and lack of green infrastructure and open spaces in urban core areas (Balzan et al., 2020). Consequently, the ES selected are runoff regulation, microclimate mitigation, air purification, noise reduction, and nature-based recreation.

2.2. Assigning ES demand scores to potential NbS sites

Following the approach proposed by Cortinovis and Geneletti (2020), the demand for each ES is defined by two factors: i) the intensity of the hazard (for regulating services) or level of deprivation (for recreation), and ii) the amount of people or physical assets that are exposed to that condition. To account for the population distribution, we used a refined version of the 100 m-resolution constrained population grid downloaded from the WorldPop database (WorldPop, 2020), which disaggregates population from census data on grid cells using building footprints and/or settlement areas. We adjusted the original version with local land use data to ensure that non-null population corresponded

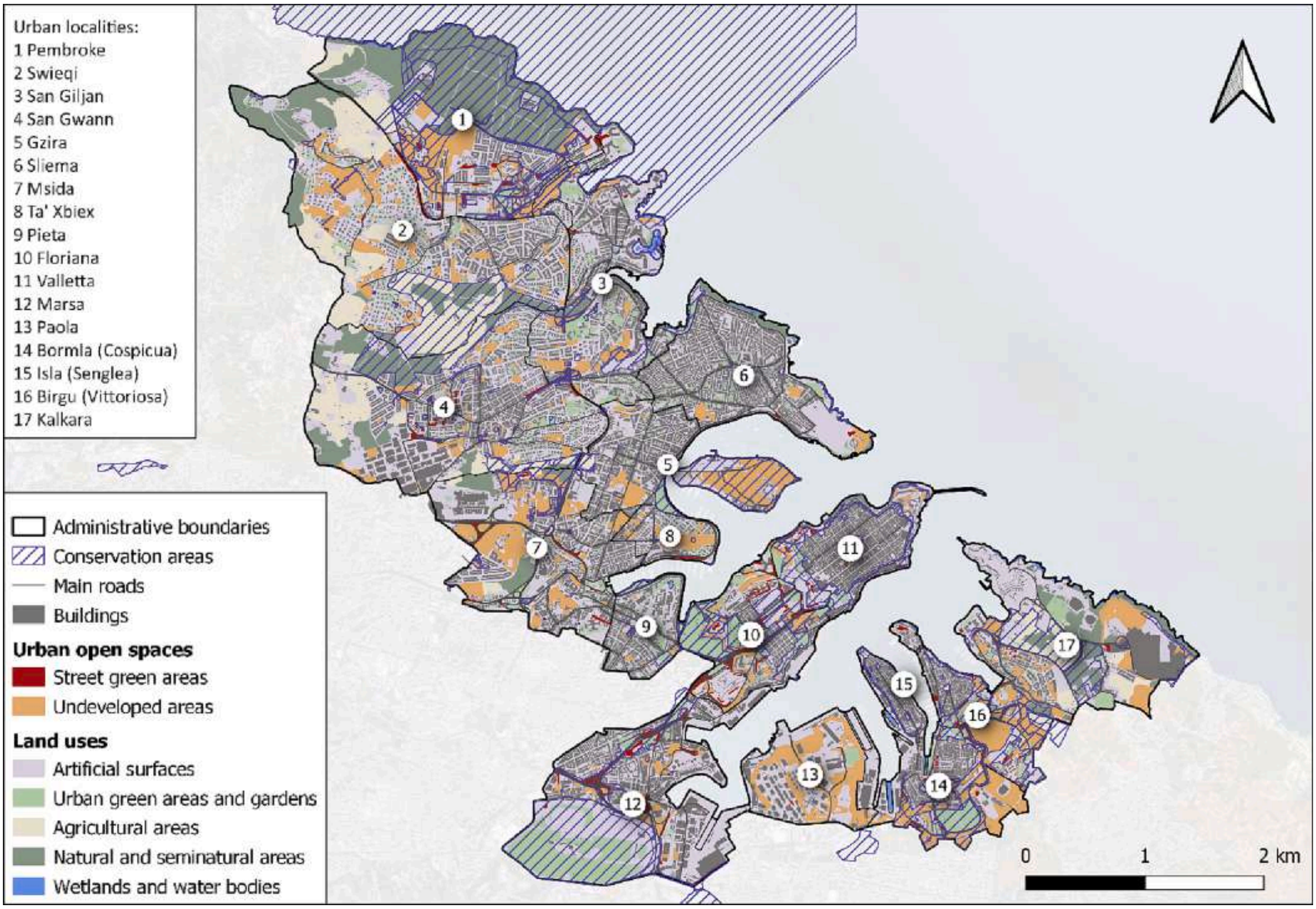

Fig. 1. Administrative boundaries, main land uses, and potential NbS sites in the case study area.

only to those cells containing residential land use patches. The final map of population distribution is shown in the Supplementary Material, together with a detailed description of the methodological steps followed to produce it.

The values of the demand for runoff regulation, microclimate mitigation, air purification, and recreation were spatially assessed in a raster map and subsequently assigned to each cell of the population grid depending on the amount of people and the intensity of the hazard / level of deprivation to which they are exposed. Then, a demand score was assigned to each potential NbS site (i.e., the potential providing area) based on the level of demand in the potential benefitting area, i.e., considering the spatial flows of ES. For runoff regulation and microclimate mitigation, which produce their effects within and in the immediate surroundings of the providing area (Cortinovis & Geneletti, 2019), the benefitting area is accounted by creating a circular neighbourhood (i.e., buffer area) around the potential NbS sites. The same approach was used for recreation, with the circular neighbourhood representing the potential catchment area from which the site is accessible considering a (reasonable) walking distance. The demand score for these three ES was calculated by summing the values of all the pixels of the demand maps that fall within the benefitting (buffer) areas of each potential NbS site. Only for the air purification service, which overall effects are widespread beyond the local scale and the corresponding flow zone can be set at the city level (Verhagen et al., 2017), we did not calculate any benefitting area. In this case, since proximity to pollution sources contributes to increased pollutants uptake (Derkzen et al., 2015), the demand score was calculated by summing the values of the pixels within the potential NbS sites themselves, thus emphasizing the diversified local conditions that can play a role in prioritizing the sites.

The demand for noise reduction was calculated within the potential NbS sites located between noise sources (i.e., traffic roads) and benefitting areas (i.e., the residential buildings exposed to noise). The values are based on the simulated noise levels of the sound beams that connect the main roads to the affected buildings, thus accounting for the directional effects of noise reduction (Fisher et al., 2009). The values were assigned to the sound beams that cross the potential NbS sites depending on the conditions to which buildings are exposed (i.e., on the noise levels affecting them and the capacity to shield noise of the current land covers characterising the sites). The final demand score assigned to each potential NbS site was then calculated by summing the demand values of all the sound beams crossing the site.

Finally, for all the five ES, the demand scores were normalized with respect to the maximum value to obtain a level of priority of the potential NbS sites to be transformed into providing areas of each ES (from 0 = lowest priority to 1 = highest priority). A correlation analysis was conducted to assess the relative contribution of the different factors affecting the demand and the relationship between the five ES demand scores. The Supplementary Material provides a detailed description of the methods and data used for mapping and assessing the demand for the five ES, and reports on the results of the statistical analysis.

2.3. *Estimating ES supply scores for different NbS types*

We selected 11 types of NbS that can address the identified challenges by supplying the selected ES (Table 1). The list includes NbS that can be implemented on the ground, characterized by different management intensities and land covers. When relevant, we identified size, shape, and land use constraints that limit the suitability of certain NbS

Table 1
List of NbS types considered in this study, and size/shape and land use constraints applied to assess their suitability to potential NbS sites.

NbS main categories	NbS type and description	Size/Shape constraints	Land use constraints
Vegetated areas (low to medium management intensity, no or few man-made features)	**Urban forest** (i.e., "Kyoto forest"): established woodland area with null or very low management intensity that require a minimum size to mimic natural forest habitats with the presence of trees, grasses and other undergrowth layers of vegetation.	Size: > 0.05 ha (UNFCCC, 2001) Shape: > 15 m width	Excluding street greenery areas (where the typologies of tree planting area and street trees are considered more suitable)
	Tree planting area: an area covered by clustered trees that is subject to a higher management intensity than urban forest, with the presence of just a grass layer or permeable soil. It is suitable to all the areas smaller than 0.05 ha, which is the minimum requirement for an urban forest.	Shape: > 15 m width	–
	Vegetation barrier: a linear barrier made of a wooded strip combined with dense shrubs purposely built to shield noise.	Shape: > 15 m width (to ensure at least $\sim$5 dB of noise reduction (Van Renterghem et al., 2015))	–
	Low vegetation area: a permeable area covered by extensive herbaceous vegetation and grasses, possibly with short shrubs.	–	Excluding street greenery areas (where the typology of roadside green is considered more suitable)
	Stormwater infiltration system: a soil depression typically covered by low vegetation that is designed to collect and infiltrate stormwater. It can be an infiltration pond, a rain garden, or a bioswale/infiltration trench, depending on the location and size (e.g., infiltration trenches are usually applied in roadside spaces, rain gardens in small catchment areas, and infiltration ponds in larger catchment areas).	–	–
Parks (open to public use for recreation, medium to high management intensity, often with presence of man-made features, e.g., playground areas, walkway paths)	**Large park**: a neighbourhood park of at least 2 ha (Stessens et al., 2017) with significant tree coverage (approximately 30% of the area covered by clustered trees).	Size: > 2 ha (applied to neighbourhood green spaces (Stessens et al., 2017)) Shape: > 15 m width	–
	Small park: a residential park (Stessens et al., 2017) with less space dedicated to tree planting (approximately 10% of the area covered by clustered trees).	Size: > 0.1 ha (applied to residential green spaces (Stessens et al., 2017)) Shape: > 15 m width	–
Green elements connected to transport infrastructure (medium to high management intensity)	**Street trees**: a linear row of trees (planted in tree pits or strips of land) along streets.	–	Only street greenery areas
	Hedgerow: a row of medium-tall shrubs (of about 2 m width).	–	Only street greenery areas
	Roadside green: a grass strip of amenity grassland, possibly with short shrubs and/or flowerbeds.	–	Only street greenery areas
Other areas (high management intensity)	**Community garden**: a piece of land where citizens can grow vegetables and fruits, among others, with the presence of cultivated plots and ancillary facilities.	Shape: > 15 m width	–

types to specific sites (see Table 1). In particular, minimum sizes are defined for urban forests (i.e., applying the concept of "Kyoto forests" (UNFCCC, 2001)) and parks (depending on park typology). A minimum width is applied to vegetation barriers, to ensure a (perceivable) noise reduction. The same threshold is also applied to urban forests and tree planting areas, to ensure adequate space for planting more than one row of mature trees; to parks, to ensure adequate space to include walking paths, playground areas, and/or other man-made features to the side of a vegetated areas; as well as to community gardens, to ensure adequate space for (linear) plots and ancillary spaces (Table 1).

To each NbS type, we assigned an ES supply score from 0 (no supply) to 5 (highest supply) for each of the analysed ES. The scoring method is grounded on a statistical analysis of ES supply values retrieved from existing studies (see Supplementary Material for more details). We selected studies reporting or assessing (in quantitative or qualitative terms) the level of ES supply of different land covers or typologies of green space, such as parks and woodland, or green element, such as trees and hedgerows. When related to land covers, ES supply values extracted from the identified studies were assigned to each NbS type based on its land cover (e.g., woodland for urban forests). In the case of NbS types characterised by a mix of land covers (e.g., urban parks, which are assumed to have a mix of grassland and woodland areas), the ES supply values were weighted considering the share of the NbS area occupied by each land cover.

To ensure comparability among data provided in studies using different assessment methods and indicators, and applied in different parts of the world, we normalized the ES supply values with respect to the maximum value in each study. This was possible since we retained only studies that included, for each ES, the best-performing NbS or land cover type (i.e., forest/woodlands for regulating ES and parks for recreation), in order to have a common reference for normalization. The normalized ES supply values were then converted into a score from 0 to 5, where 0 corresponds to no supply and values from 1 to 5 corresponds to the intervals 0.01–0.20, 0.21–0.40, 0.41–0.6, 0.61–0.8, 0.81–1. The final ES supply score assigned to each NbS type was the most frequent one across the analysed studies. When two or more scores showed the same frequency, the average was calculated and, if necessary, rounded down to the nearest value to maintain a conservative approach. The Supplementary Material provides the details on the reviewed studies, the ES supply values collected, as well as on their statistical analysis, to derive the ES supply scores of NbS types.

2.4. Combining supply and demand scores to identify priority NbS types in each site

To identify the NbS types that deliver the most needed combination of ES in each site, a priority score was calculated for each combination of NbS types and potential NbS sites. The score is obtained by combining the demand scores assigned to the sites with the supply scores of NbS types using the following formula:

$$P_{NbS,j} = c_{j,NbS}\sum_{i=1}^{5}\left(D_{i,j}{}^{*}S_{i,NbS}\right)$$

where $P_{NbS,j}$ is the priority score of a defined *NbS type* in site *j*, $D_{i,j}$ is the demand score of the site *j* for the *i*-th ES, $S_{i,NbS}$ is the supply score of the *NbS type* for the *i*-th ES, and *c* is a binary factor summarizing the suitability constraints. *c* assumes a value of 0 if the site does not meet the size, shape, or land use constraints reported in Table 1, otherwise it is equal to 1.

The final priority scores potentially range from 0 (no suitability or no demand) to 25 (highest demand score in the site – 1 – for all ES and highest supply score of the selected NbS – 5 – for all the five ES). However, no site shows the maximum values of the demand score for all the ES simultaneously, and no NbS type shows the highest values of the supply score for all the ES analysed. Finally, by comparing the priority scores of the different NbS types, it was possible to identify the one(s) that better address the combination of demand for the five ES in each site. Focusing on the latter NbS, we investigated which factors play a major role in their final selection by constructing a classification and regression tree, using the five ES demand scores and the constraints about size/shape and land use as decision criteria. The tree was created in r using the package ‘rpart’ (Therneau et al., 2022).

3. Results

3.1. ES demand in potential NbS sites

Higher demand for runoff regulation is found in the denser built-up areas characterised by few open spaces. These include a large proportion of the coast and urban areas in the immediate inland, and the industrial and commercial hubs that are located around port areas and in the western side of the case study. For microclimate mitigation, hotspots of ES demand can be identified in the most compact urban areas characterised by higher population density, such as the central coastal zone and the compact historical settlement of Senglea in the southern part. However, high demand values are found in almost all the urbanized areas, including the capital city Valletta, with the exception of those located in the most peripheral urban fringes characterized by lower densities.

The demand for air purification is higher along the main roads, especially where they cross dense residential areas. Here, the rates of pollutants reduced by vegetation can be greater, given that car traffic is the main source of air pollution in the study area. Hotspots of demand for recreation include the areas further away from the existing parks and are mainly located in the central coastal zone towards the interior and within the two fortified compact cities of Valletta and Senglea. Finally, the sites characterised by higher demand for noise reduction are those covered by low vegetation – currently ineffective to shield noise - and located between the main traffic roads that pass through dense residential areas and the residential buildings affected by noise. Most of these sites are distributed along the trunk road crossing north–south the northern part of the urban agglomeration and along the road running from the capital city Valletta towards the West.

The pairwise Pearson’s correlation analysis (see Supplementary Material for the analysis results) between the different ES demand components and the ES demand values reveals that the distribution of the demand for the five ES analysed (Fig. 2) is mainly influenced by the spatial distribution of the exposure component (i.e., population in the case of air purification, microclimate mitigation, recreation, with a correlation value of 0.97, 1.00, and 0.82, respectively; population in combination with industrial and commercial areas in the case of runoff regulation with a correlation value of 0.89; residential buildings that area exposed to noise levels from roads in the case of noise reduction with a correlation value of 0.89).

Fig. 3 shows the demand scores for the five ES calculated for some exemplary potential NbS sites using the values from the demand maps (Fig. 2) and considering the ES flow (i.e., areas potentially benefitting from the NbS intervention).

3.2. ES supply scores of proposed NbS types

The ES supply scores derived from the literature for the 11 proposed NbS types are reported in Table 2.

The scores show that urban forests and tree planting areas are the NbS types that in general provide the best overall balance in the supply of all the five ES. However, in the case of noise reduction and recreation, vegetation barriers and parks, respectively, perform better. Concerning NbS types that can be implemented in roadside spaces, street trees demonstrate good performances in supplying all the ES except noise reduction. In this case a hedgerow – if there is not enough space for a proper vegetation barrier – is the best solution.

3.3. Allocation of NbS

At the site level, most of the priority NbS types identified within the 222 ha of potential NbS sites (Fig. 4), namely the one that gained the highest priority score among the eleven considered, fall within the category of “vegetated areas”. Urban forests (170 ha) are mostly concentrated in larger peri-urban sites and scattered in some larger sites within the urban cores, while tree planting areas (6,7 ha), cover especially small infill sites and larger street green areas (e.g., road junctions, roundabouts) that are not suitable for urban forests. Vegetation barriers (2 ha) are predominantly located along the main roads and road junctions nearby residential neighbourhoods. Sites where low vegetation areas are the priority are few (1,7 ha) and mostly scattered within some infill sites in residential areas. Stormwater infiltration systems cover 26,8 ha, especially concentrated in high-impervious industrial areas and along streets in the southern part of the study area. Of these, 2,5 ha are

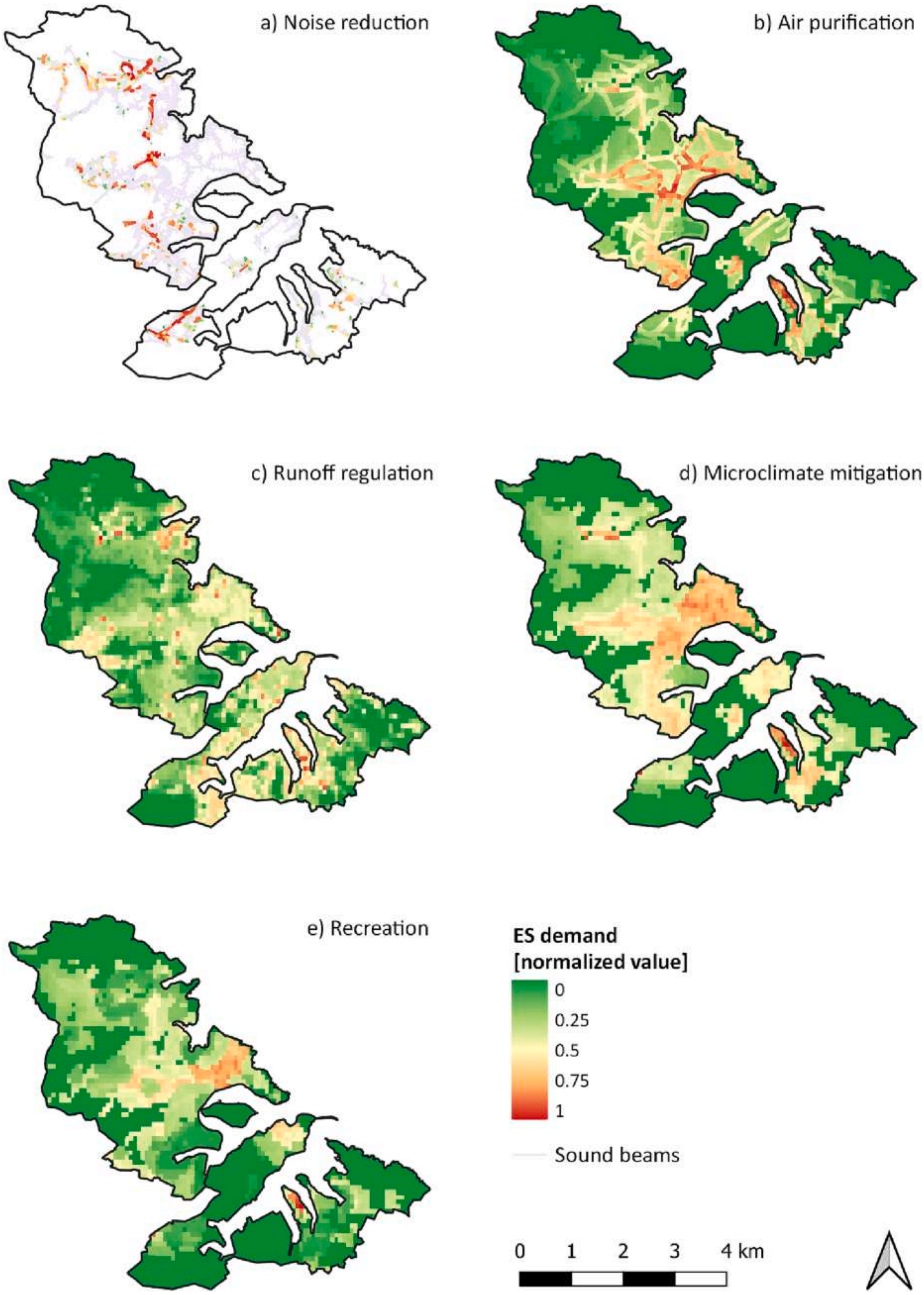

Fig. 2. Maps of the demand for the five ES analysed.

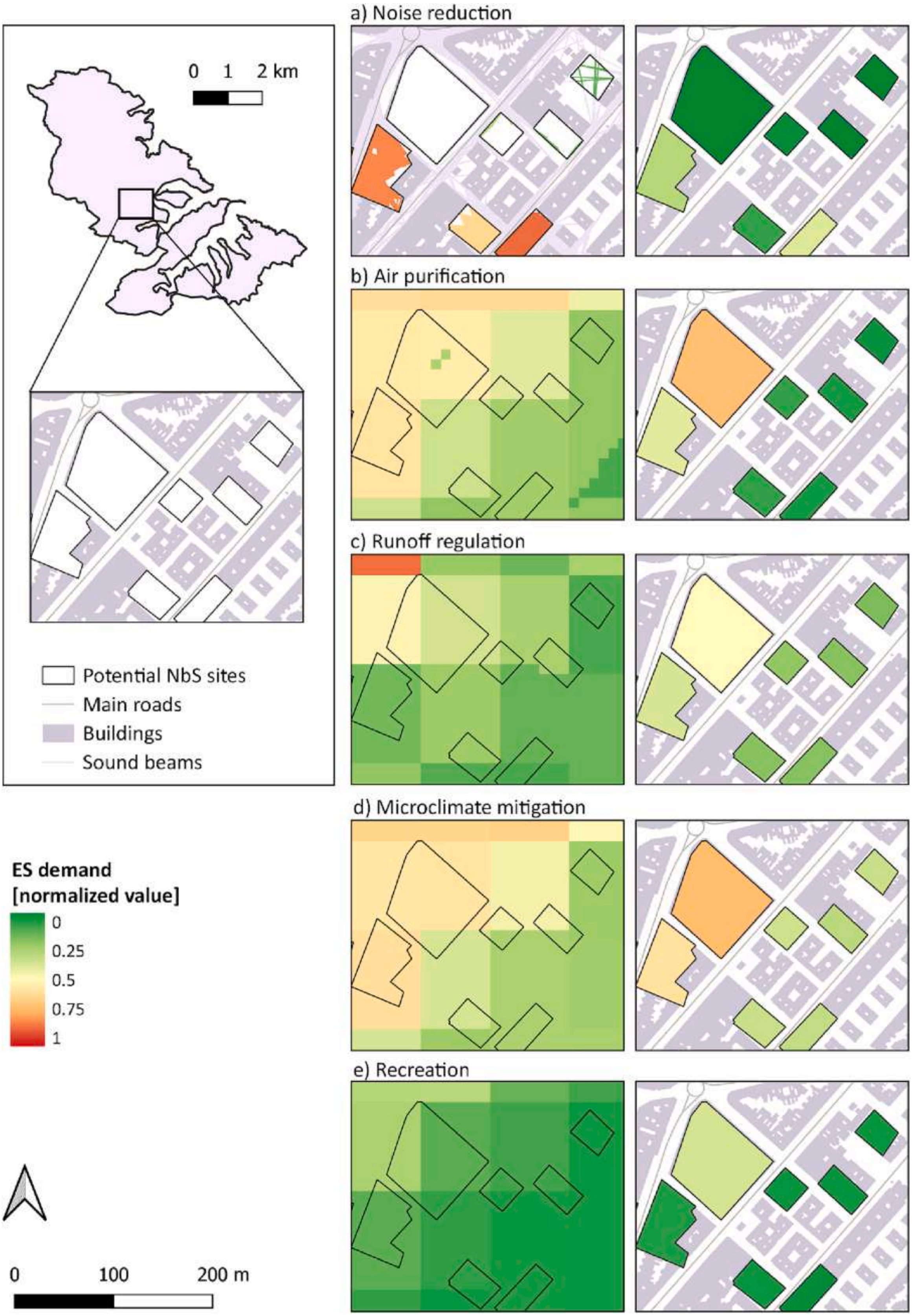

Fig. 3. Example of the assessment of ES demand for selected potential NbS sites. Left side: boundaries of the potential NbS sites superimposed on the ES demand maps (Fig. 2). Right: ES demand scores calculated for the same sites by accounting for the potential ES flows from provisioning (the sites) to benefitting areas (see Section 2.2 for methods).

Table 2
ES supply scores for the five ES analysed for each NbS type.

NbS type	ES supply scores				
	Runoff regulation	Microclimate mitigation*	Air purification	Noise reduction	Recreation
Urban forest	5	5 (> 2 ha) 4 (< 2 ha)	5	3	3
Tree planting area	5	4	5	3	3
Vegetation barrier	4	3	4	5	2
Low vegetation area	4	2	1	1	3
Stormwater infiltration system	5	2	1	1	0
Large park	4	4	2	2	5
Small park	4	3	2	2	5
Street trees	5	4	5	0	3
Hedgerow	4	3	4	2	2
Roadside green	4	2	1	1	3
Community garden	3	3 (> 2 ha) 1 (< 2 ha)	1	1	3

* The scores are calculated for two different sizes (<2 ha and >2 ha) for those (non-linear) NbS types that may exceed 2 ha, since the cooling capacity of areas larger than 2 ha is greater than the one of smaller areas (Majekodunmi et al., 2020; Zardo et al., 2017). Large parks are assumed to be larger than 2 ha. For low vegetation areas, the final score was the same in the two cases. More information can be found in the Supplementary Material.

street green areas in which bioswales/infiltration trenches are the suitable solutions among the typologies of stormwater infiltration systems.

Large (23,5 ha) and small parks (4 ha) are the priority NbS type assigned to some peri-urban spaces close to the denser urban areas, where the availability of green spaces is scarce. Street trees (12,4 ha) are quite homogeneously distributed along roadside spaces within the residential areas, while hedges (0,9 ha) are predominantly located within some narrow street green areas where other more performing NbS types, such as vegetation barriers, cannot be implemented due to size and shape constraints. Roadside green and community gardens are not a priority in any space. In some sites (covering a total of 25,9 ha) more than one NbS type obtained the same priority score. Examples include sites with two priority NbS types, such as stormwater infiltration systems and urban forests, low vegetation areas, or street trees; as well as urban forests and small parks. In some cases, three NbS types received the same priority score, for example, stormwater infiltration systems, tree planting areas, and street trees.

At the level of the whole study area, an overall indication of the need for NbS implementation can be obtained by comparing the highest priority score among those gained by the different NbS types in each potential NbS site. The highest scores range from a minimum of 0 (no need for NbS) to a maximum of 14,22 (highest need) (Fig. 5). These scores can support the identification of sites where NbS implementation should be prioritized in order to target areas characterised by a high demand for multiple ES.

We analysed the distribution of the values of the priority scores corresponding to the different priority NbS type(s) identified in each site (see Supplementary Material for the complete results). The analysis reveals that vegetation barriers, hedgerows, and large parks are generally associated with sites characterized by a high total demand score, although urban forests and tree planting areas are the NbS with the highest priority scores. Small parks, rain gardens, and low vegetation areas are the priority NbS types in sites characterized by a lower total demand. The Supplementary Material also shows the detailed results about the distribution of the five ES demand scores corresponding to the different priority NbS types. Finally, Fig. 6 shows a classification and regression tree that identifies the main factors affecting the selection of the priority NbS types in the potential NbS sites. The tree reveals that size/shape (i.e., minimum width or area) and land use (i.e., street green or open space area) constraints are decisive factors in the selection (at various "hierarchical" levels). Among ES demand scores, those for noise reduction, microclimate mitigation, and recreation plays a main role, while the demand for runoff regulation and air purification is less critical in the decision.

4. Discussion

4.1. Factors affecting NbS allocation

Planting trees, through urban forestry/afforestation or street trees, is often seen as the best solution to tackle multiple urban environmental challenges (Cortinovis et al., 2022; Pataki et al., 2021). This is partly confirmed by the ES supply scores we developed and by the results of NbS allocation, showing urban forests as the priority NbS typology in most sites across the urban area of Valletta. Moreover, it is consistent with previous analysis of the study area which prioritised tree cover increase to improve ES supply (Balzan et al., 2021). This depends on the fact that the difference in supplying microclimate mitigation and air purification – among the most demanded ES in the study area – between high and low vegetation is significant. Evapotranspiration and shading functions of tall vegetation and canopy cover (Duncan et al., 2019; Livesley et al., 2016; Coutts et al., 2012; Shashua-Bar & Hoffman, 2000), and the absorption of gaseous air pollutant by leaves and deposition of particles resulting from increased surface roughness by vegetation (Tiwari et al., 2019; Escobedo & Nowak, 2009; Nowak et al., 2006), are the main factors respectively affecting the supply of the two ES. For this reason, urban forests and street trees are much better in cooling down temperatures and purify the air than the other NbS.

In some cases, urban forests or street trees obtained the same priority as stormwater infiltration systems. This happened in areas with high demand for runoff regulation and relatively low demand for the other ES, such as in commercial/industrial sites and in several street green areas along residential roads. Actually, our ES supply scores show that in general there is little difference in the capacity to regulate runoff between NbS characterised by low (e.g., grass) and high vegetation (e.g., tall shrubs, trees). This is because the supply of runoff regulation depends on a number of functions that are not exclusively related to the presence of tall plants, including water retention and infiltration in soil by permeable surfaces, reduction of flood velocities by vegetated surfaces, and water storage and infiltration by floodplains, besides rainfall interception by canopy cover (Livesley et al., 2016; Ossola et al., 2015; Yang et al., 2015; Nisbet & Thomas, 2006; Blackwell & Maltby, 2006; Xiao & McPherson, 2002).

However, there are two specific cases in which other NbS are to be prioritized over urban forests and street trees. The first case concerns sites along main roads, where the demand for noise reduction is particularly relevant. Here, a vegetation barrier made of trees and large shrubs is the preferred solution. In fact, although the reduction of noise levels also depends on the reflection, diffraction, and absorption effects of vegetation and soil in general (Van Renterghem et al., 2012), it is mainly determined by the noise shielding function. This function is

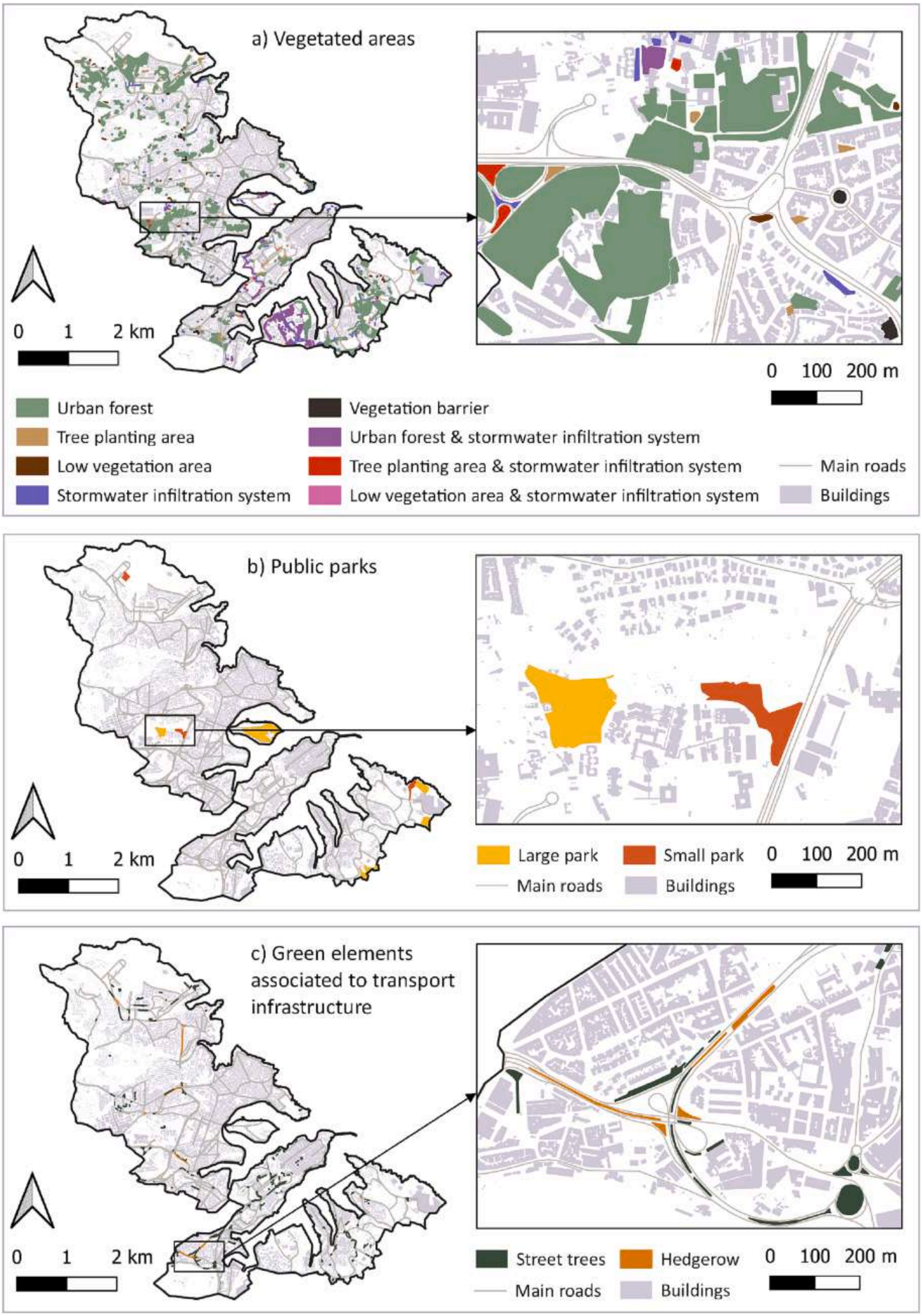

Fig. 4. Allocation of priority NbS types within the potential NbS sites, broken down by main category: vegetated areas (a), urban parks (b), and green elements associated to transport infrastructure (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

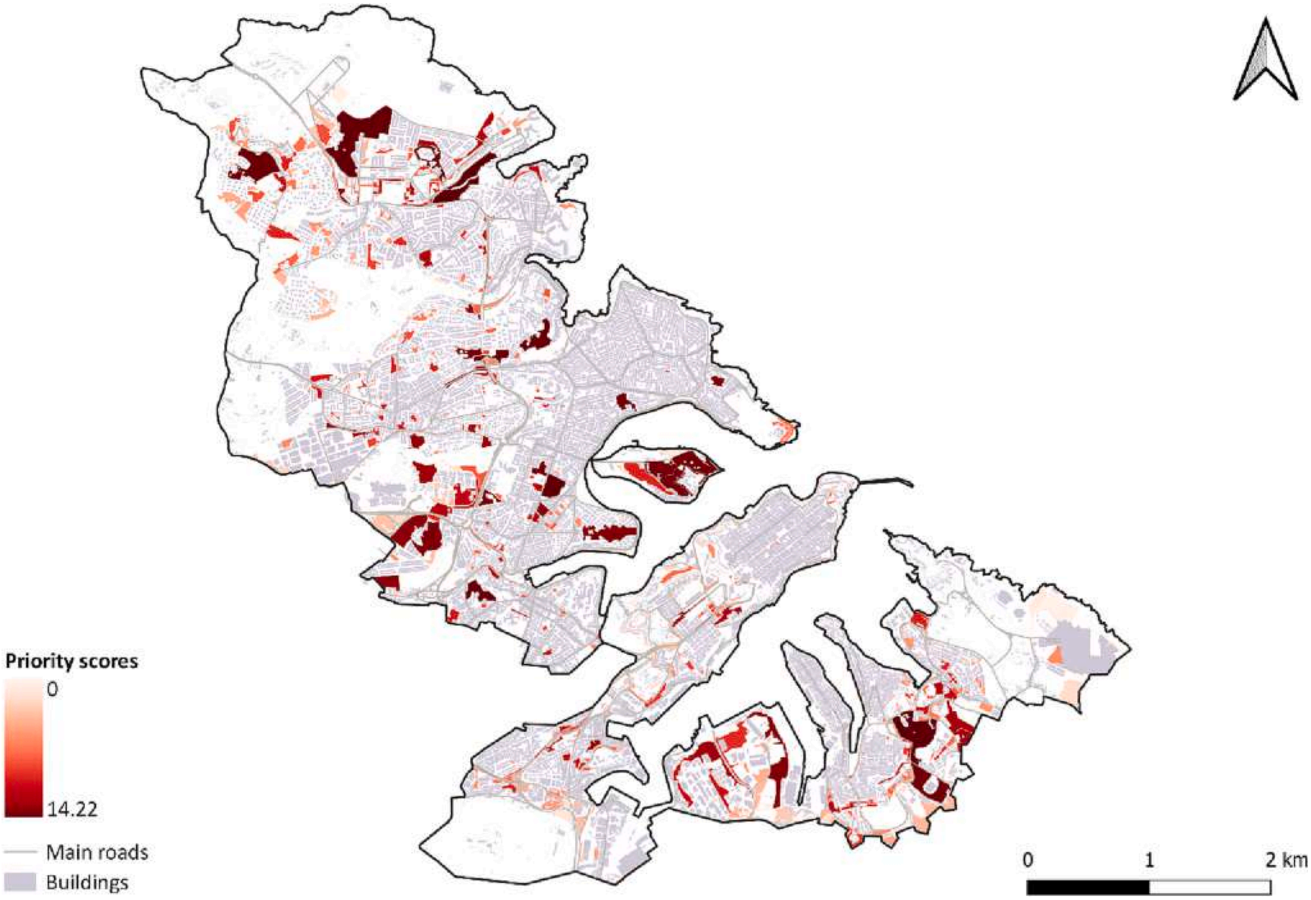

Fig. 5. Highest scores obtained in each potential NbS site among the ones gained by the 11 types of NbS included in the analysis.

delivered most effectively by vegetation with higher and more homogeneous distribution of foliage densities along the height compared to urban forests, which usually consist of trees with no or little understory. The second case involves areas characterised by a high demand for recreation. This in fact depends on the opportunities for active and passive recreation offered by accessible NbS (Davern et al., 2017; McCormick, 2017), which are mostly provided by urban parks, whether characterised by (more or less) short or tall vegetation.

Finally, there are two NbS types that based on the results obtained from this study are not a priority in any site: roadside green and community gardens. For the former, the reason is that it provides fewer benefits than the other NbS types that can be implemented within the same street green areas (i.e., street trees and hedgerows), meaning that all areas that are currently covered by a strip of amenity grassland (i.e., the typical surface cover characterising roadside green areas) could be improved, for example planting street trees. For the latter, which capacity to supply ES is lower than most of the other solutions, especially concerning regulating services, its implementation needs to be promoted in the context of the wider social benefits that community gardens provide, such as social learning, cohesion, and well-being, in addition to food production (Dennis & James, 2017). Including some of these aspects among the analysed ES would have probably resulted in their prioritization in some areas of the city.

Overall, the prioritization of the potential NbS sites – in accordance to the priority scores of NbS to be implemented therein – is linked both to the level of ES demand in the surroundings (or within the site in the case of noise reduction), which in turn has been shown to be highly correlated to the presence of the exposed factors (e.g., population, buildings); and to the size of the site, since to larger sites correspond larger benefitting areas and, potentially, more beneficiaries. The decision tree also showed that constraints are a critical factor in NbS prioritization. While the prevalence of binary vs. continuous variables in the highest hierarchical levels of the trees is generally expected, different constraints have different relevance in the case study, with the width being a critical factor that affects the possibilities of NbS implementation in the case study. On the other hand, the level of demand for some ES also appears in the top branches of the tree. The demand for recreation is critical in eliminating stormwater infiltration systems from the preferred options, while a combination of the demand for microclimate regulation and noise reduction is decisive in selecting the priority NbS types in street green areas.

Planning practitioners were involved in the initial stages of the work to co-identify the main problems affecting the study area, and the main challenges that can be addressed through ecosystem services. In a follow-up step, it would be very important to engage them again in order to assess the validity of the proposed method, as well as to evaluate whether the spatial distribution of NbS suggested by our model fits the scores assigned by local experts and does not conflict with other local needs (e.g., road safety).

4.2. Potential of the proposed approach to advance performance-based planning of NbS

The approach presented in this study can be applied to support a variety of planning decisions related to NbS. Various options to implement the analysed types of NbS exist depending on the current land uses and covers, considering that typologies of intervention on urban ecosystems include conservation, restoration, and enhancement of existing ecosystems, and creation of new ones (Cortinovis & Geneletti, 2018a). Their implementation can be secured by applying appropriate

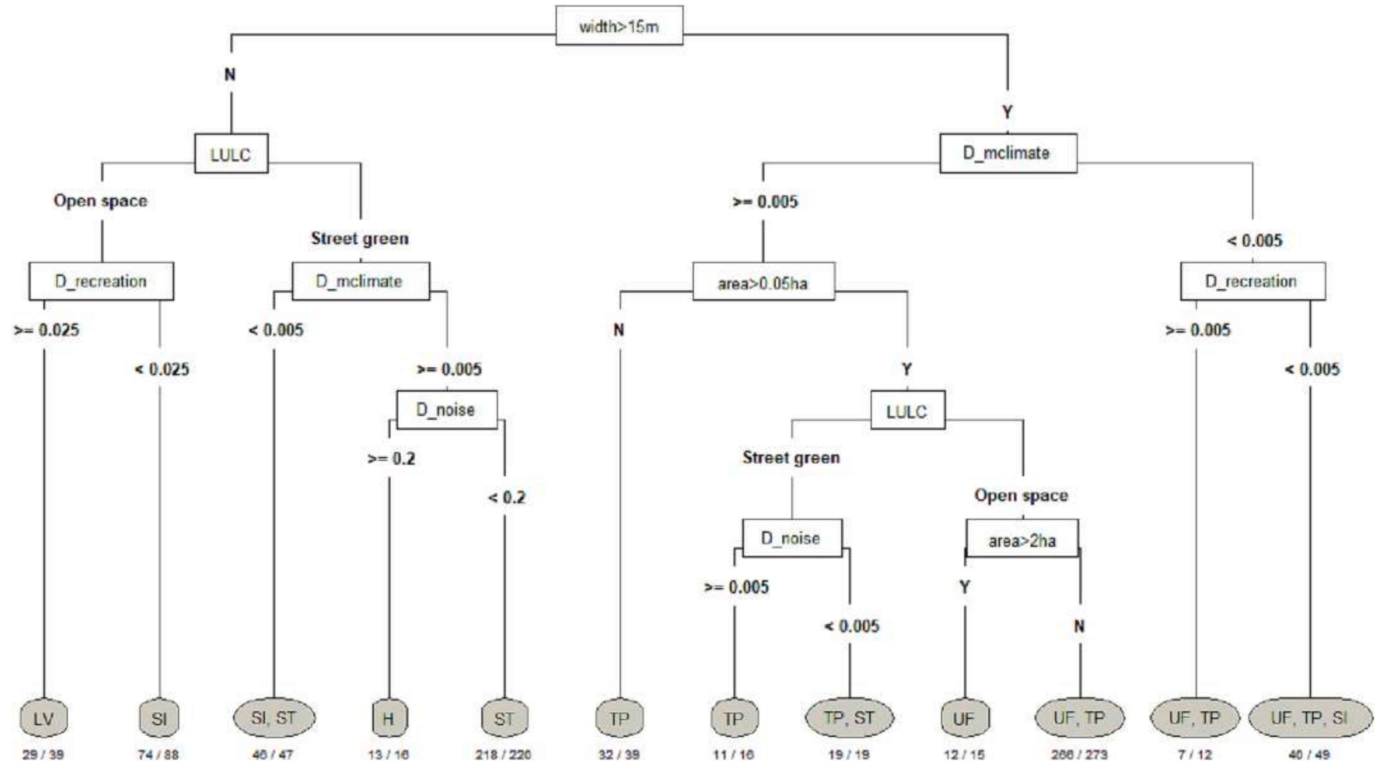

Fig. 6. Classification and regression tree showing the main factors that affect the selection of priority NbS in the potential NbS sites. Each box indicates a factor and the branches departing from it are alternative options. The grey "leaves" indicates the NbS type (or types) selected by each branch, while the ratios underneath display the classification rate at the node, i.e., the number of correct classifications vs. the number of observations in the node. Legend: LV = low vegetation area, SI = stormwater infiltration system, ST = street trees, H = hedgerow, TP = tree planting area, UF = urban forest. Large parks, small parks, and vegetation barriers are not included in the decision tree due to their low frequency of selection (respectively 6, 3 and 11 times).

instruments to allocate proper space for and promote NbS early on in the planning process for new development projects, to preserve the undeveloped land from future urban expansions, or to promote the implementation of NbS in public spaces such as street green areas (Longato et al., 2022).

For example, besides the application tested in the case study of Valletta, the proposed approach can be adapted and used for identifying the most suitable NbS to implement in areas where direct government provision is possible, for selecting the most beneficial areas for a specific NbS type (e.g., areas showing urban forest as a priority and, among these, the ones showing the higher scores to concentrate afforestation programmes), and for defining the type of out-of-kind compensation measures to enforce when an area is about to be developed, or redeveloped such as in brownfield redevelopment projects, and that developers must respect.

Most notably, the methodology we proposed can be used to develop innovative performance-based approaches that are grounded on ES-based scoring systems to assess urban development projects, which have recently been proposed as a suitable way to promote and integrate NbS in new developments due to their flexibility in embracing multifunctionality and urban complexity (Dorst et al., 2019). Actually, our approach that combines ES demand mapping and assessment and NbS performance scores (i.e., the ES supply scores) can support the implementation of scoring systems (i.e., through defining scores/weights and thresholds) that establish locally-specific NbS requirements, or can be used to integrate/improve existing approaches and tools that usually make use of them separately (i.e., only ES demand mapping and assessment without NbS performance scores or the contrary) and/or through scoring systems that do not account for NbS multifunctionality. Examples of existing approaches and tools include the "performance-based green area indicators" (Stange et al., 2022) adopted in various cities, including the blue-green factor of Oslo (Oslo Kommune, 2018), the green factor of Helsinki (Juhola, 2018), the biotope area factor of Berlin, the green factor of Seattle, the green space factor of Malmo (Szulczewska et al., 2014), and the green factor tool of Melbourne (Bush et al., 2021).

Such tools use a scoring system that combines performance scores of different green-blue surfaces (usually defined by experts according to their capacity to support ecosystem functions and/or deliver ES) to assess if urban transformation projects achieve a pre-defined threshold (i.e., the required performance) that is necessary for granting the development permit (Stange et al., 2022). However, they do not include spatial assessment of ES demand to define context-specific requirements that better meet the ES needed in each area, contributing to one of their main limitations, namely the non-inclusion or accounting for the character or quality of the area surrounding the development site (Stange et al., 2022). Actually, the methods we used to assess the demand for ES that account for the spatial flows from the providing to the benefitting areas may help to (partially) overcome this limitation by supporting the definition of ES-demand-based weights that can be used to adjust such performance-based indicators and define green area requirements according to local conditions and needs.

While a more innovative performance-based approach grounded on spatial assessments of ES demand for defining the performance requirements of urban transformations have been proposed by Cortinovis and Geneletti (2020), the scoring method they adopted to define NbS requirements and scoring criteria is not grounded on NbS performance scores and favours NbS that deliver the single most needed ES (Geneletti et al., 2022), thus often not allowing to harness NbS multifunctionality that can address the demand of multiple ES simultaneously. Our approach can be used to refine the scoring method by defining NbS requirements and scoring criteria based on the calculation of NbS priority scores that capture the multiple benefits delivered according to the demand profiles of each area. For example, in the approach previously proposed a vegetation barrier is usually selected when noise reduction is (or is among) the most needed service(s) (Geneletti et al., 2022). Nevertheless, in some cases, selecting an urban forest instead of a vegetation barrier could provide the best compromise between a slightly lower capacity to shield noise and a higher capacity to supply other ES such as air purification and microclimate mitigation. The presented approach is able to capture this compromise. This is especially important when the available space forces to select one or another solution, and when the demand for air purification and microclimate regulation is significant – even if not as much as noise reduction.

Finally, the look-up table(s) we developed provide performance scores that are based on quantitative estimates of ES supply, which can be used instead of (or in combination with) expert scores to limit the risk of subjectivity, as suggested by Campagne and colleagues (2020). Integrating such scores would promote a more evidence-based decision-making where data from the literature are explicitly used to score/weight the different green elements included in urban transformation projects. This would be more straightforward in approaches using scoring criteria related to NbS types or land covers (e.g., Cortinovis & Geneletti, 2020). For scoring systems that also include detailed design criteria for green areas and elements (e.g., related to tree species, tree size, or green-grey surface combinations), the integration of expert opinion and local knowledge to adjust the scores would remain crucial.

4.3. Strengths and limitations

The data and methods we used to map and assess ES demand to prioritize NbS allowed to directly account for the benefits (in terms of ES) provided by existing vegetation, hence the ES demand mapped corresponds to the actual demand by residents (i.e., the current supply of ES in the study area is already discounted from the demand assessments). Instead, other approaches usually map and assess ES demand and supply separately, possibly combining them only at a second stage to quantify mismatches (e.g., Chen et al., 2019; Larondelle & Lauf, 2016). For example, in the assessment of runoff regulation, imperviousness density is used as a proxy to exemplify the risk potential (i.e., the more impervious is an area, the more runoff is potentially generated), but it also describes the ES supply side that is associated to the density of permeable surfaces, which support rainwater infiltration and runoff velocity reduction. In the assessment of microclimate mitigation and air purification, the use of data derived from near real-time monitoring platforms (i.e., satellite data and air pollution values from monitoring stations) allows depicting the current situation in which the mitigation effects of existing vegetation are already accounted. Finally, the methods applied for assessing the demand for noise reduction and recreation instead directly incorporated the ES supply component in the determination of the demand.

The approaches used for mapping and assessing ES demand are in general replicable in other areas, with some limitations. While for assessing the demand for some ES we used data that are in principle available worldwide (e.g., satellite data) or at continental scale (e.g., imperviousness density data at pan-European level), for other ES local data are needed (e.g., air pollution map, distribution of public green spaces, noise levels from roads). However, some ES assessment methods can be used with different input data (e.g., generic noise parameters can be set if specific data on noise levels from roads is not available).

The list of NbS types used in this study is non-exhaustive and only includes NbS that can be implemented on the ground. Other types of NbS exist and can be added to our list for specific planning applications that involve, for example, the implementation of NbS on buildings (e.g., green roofs), such as in performance-based planning approaches. These solutions would require the analysis of additional suitability criteria for identifying constraints for NbS implementation (e.g., building-related constraints), as well as the assessment of their capacity to supply ES. In addition, different design typologies exist for these solutions (e.g., extensive and intensive green roofs), which involve different vegetation types and mixes to be installed that deliver more or less ES. A number of standard design criteria need therefore to be introduced to allow for assessing their capacity to supply ES and, consequently, for assigning the ES supply scores to NbS using the same method we applied to NbS types characterised by a combination of land covers can be used (e.g., a standardised proportion of different land covers for urban parks), which can be also further used to define some minimum design requirements for that type of solution. However, the attribution of a standardised proportion of land covers to NbS does not always correspond to the reality, where the same NbS type can be designed in different ways (even if meeting possible minimum design requirements). In any case, the ES supply scores can be adjusted relatively easily to reflect the capacity to supply ES of NbS with different land cover characteristics/proportions.

In addition, the potential NbS sites that were used in this study do not always correspond to the space that in reality is to be transformed. This in fact depends on a variety of factors such as the fragmentation of land properties. The NbS priority scores calculated in this study instead reflect the transformation of the whole site area. However, the main purpose of the study is to provide the methodological details of our approach and test a possible use to provide spatial indications on the priority NbS types using the available data on the potential sites for NbS on the ground. Different mapping methods and input data can be applied according to the various needs without affecting the rationale of the proposed approach, such as working on pixels to provide the priority NbS needed in each pixel area or using, when available, land parcel data to identify the ES demand profiles and the priority NbS needed in light of single parcel transformations.

Finally, our approach does not provide ready-to-use outcomes that can be automatically applied to planning decisions, but spatial indications (and indicators) that can support decision-making processes and the related negotiations that are required to balance the different interests (e.g., privates versus public, costs versus benefits, etc.) at stake. For example, weighting factors can be introduced to additionally weight the different ES based on their relative importance when calculating the priority scores of NbS to reveal specific local conditions and policy orientations (Cortinovis & Geneletti, 2020).

5. Conclusions

The approach presented in this study highlights the potential of combining the mapping and assessment of ES demand with the analysis of the potential ES supply of selected NbS types. It is aimed to support planning decisions towards the reduction of urban pressures and alleviation of socio-environmental challenges in cities, allowing decision-makers not only to identify priority locations but also the specific NbS that maximise the benefits to residents, which is paramount to promote more effective outcomes within a context of competing demands for budgets and for the use of land. Compared to existing approaches, the strength of our approach is that it suggests the NbS types that provide the best balance between the supply of multiple ES, accounting for their demand in each area. With our method, we have tried to address two of the elements that are deemed as essential for the next generation of ES research (Chan & Satterfield, 2020), namely the integration of biophysical and social information that couples multi-metric valuations towards ES provision for human wellbeing, and the provision of a decision-support approach that can be adapted and applied to context-appropriate decision-making for both the NbS planning and design phases. Further applications with the involvement of local practitioners and decision-makers will test its relevance and usability to support decisions about NbS implementation in real-life planning contexts.

CRediT authorship contribution statement

D. Longato: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **C. Cortinovis:** Conceptualization, Methodology,

Validation, Investigation, Writing – review & editing, Supervision. **M. Balzan:** Validation, Investigation, Writing – review & editing. **D. Geneletti:** Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2023.104743.

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