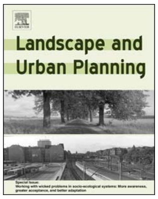
Landscape and Urban Planning 170 (2018) 195–208

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan



Research Paper

Assessing how green space types affect ecosystem services delivery in Porto, Portugal

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ARTICLE INFO

Keywords:
Urban ecosystem services
Green space
Regulating ecosystem services
Urban planning
Urban vegetation
Environmental inequity

ABSTRACT

Significant advances have been made in identifying, quantifying and valuing multiple urban ecosystem services (UES), yet this knowledge remains poorly implemented in urban planning and management. One of the reasons for this low implementation is the insufficient thematic and spatial detail in UES research to provide guidance for urban planners and managers. Acknowledging how patterns of UES delivery are related with vegetation structure and composition in urban green areas could help these stakeholders to target structural variables that increase UES provision. This investigation explored how different types of urban green spaces influence UES delivery in Porto, a Portuguese city, and how this variation is affected by a socioeconomic gradient. A stepwise approach was developed using two stratification schemes and a modelling tool to estimate urban forest structure and UES provision. This approach mapped explicit cold and hotspots of UES provision and discriminated the urban forest structural variables that influence UES at the local scale. Results revealed that different types of green spaces affect UES delivery as a direct result of the influence of structural variables of the urban forest. Furthermore, the uneven distribution of green spaces types across socioeconomic strata alters UES delivery across the city. This case study illustrates how a methodology adaptable to other geographic contexts can be used to map and analyze coupled social and ecological patterns, offering novel insights that are simple to understand and apply by urban planners and managers.

1. Introduction

Recent research has highlighted the capacity of urban ecosystems to provide critical benefits for human wellbeing, and the need to take them into account in urban planning (Gomez-Baggethun & Barton, 2013; Haase et al., 2014). The ecosystem services (ES) concept emerged as a holistic approach that explicitly recognizes these benefits, while integrating the management of biodiversity, natural resources and human needs (Haines-Young & Potschin, 2010). As such, various authors have adopted the ES framework in urban studies to provide relevant insights for urban planning and policy strategies (Ahern, Cilliers, & Niemelä, 2014; McPhearson, Hamstead, & Kremer, 2014). Addressing the local delivery of ES is particularly important in adaptive urban planning, as some benefits crucial for human wellbeing are locally derived, such as rainwater drainage, microclimate regulation, improvement of air quality through pollution removal, noise reduction and recreation (Bolund & Hunhammar, 1999). Urban green areas provide many of these ES, and thus their potential to contribute to human wellbeing in cities is being increasingly acknowledged (De Vries, van Dillen, Groenewegen, & Spreeuwenberg, 2013; Tzoulas et al., 2007).

Several examples illustrate how multiple urban ecosystem services (UES) have been identified, quantified and valuated to inform stakeholders and support decision-making processes (Derkzen, Teeffelen, & Verburg, 2015; Kabisch, 2015; McPhearson, Kremer, & Hamstead, 2013). However, this growing body of knowledge remains poorly implemented in actual urban planning and management (Haase et al.,

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http://dx.doi.org/10.1016/j.landurbplan.2017.10.007
Received 6 February 2017; Received in revised form 13 October 2017; Accepted 18 October 2017

2014; Kabisch, 2015; Kremer et al., 2016). One of the issues contributing to this gap is the lack of sufficient thematic and spatial detail in UES research to provide guidance for urban planning and design (Derkzen et al., 2015). Furthermore, there is a scarcity of studies aiming to analyze urban ecosystems at finer scales, addressing for example, variations in type and function of existing urban green areas (Haase et al., 2014), though some exceptions should be noted (e.g. Derkzen et al., 2015). Yet, different types of urban green areas such as public parks, domestic gardens or wasteland are heterogeneous and reflect diverse social needs and values that affect their performance in terms of UES delivery. These social needs and values are displayed through personal preferences of landowners and other stakeholders in the design and management of private green spaces, as well as strategies and policies defined by public institutions (Andersson, Barthel, & Ahrne, 2007). Selection and maintenance of vegetation in cities mirrors this human influence conspicuously, given its relevance as a major component in the design of urban green spaces (Grove et al., 2006).

Several studies have also exposed links between the spatial variability of UES delivery within the urban fabric and environmental inequity (Escobedo et al., 2006; Escobedo, Clerici, Staudhammer, & Corzo, 2015; Graça et al., 2017; Jenerette, Harlan, Stefanov, & Martin, 2011; Pedlowski, Da Silva, Adell, & Heynen, 2002), even if sometimes authors do not explicitly use the ES framework (Romero et al., 2012). To our knowledge, it remains largely unexplored how such environmental injustice can be mitigated through the proper planning of green spaces. Moreover, Luederitz et al. (2015) highlight as a key challenge for UES research the low transferability of data between contexts, especially in complex urban settings with heterogeneous socioeconomic and ecological backgrounds. This issue adds to the difficulties in providing orientations for urban planners and managers, and underlines the need to develop methodologies that can address local specific conditions and processes. Such process based knowledge is crucial to reveal unique patterns of UES delivery, as well as more generalizable trends already observed in other cross-city comparisons, both of which can contribute to effectively unravel drivers of ecosystem structure, functioning and dynamics (Kremer et al., 2016).

As a key provider of UES, vegetation holds a great potential to enhance urban resilience (Bolund & Hunhammar, 1999; Weber, 2013; Yapp, Walker, & Thackway, 2010). It is, however, necessary to better understand the ecological impacts of vegetation type and structure in cities. Previous research has shown, for example, that species assemblage and functional characteristics of vegetation affect ES provision (e.g. Lundholm, MacIvor, MacDougall, & Ranalli, 2010). In addition, structural variables of the urban forest such as tree density, size and condition impact ecosystem functions such as air pollution removal, carbon sequestration and rainfall interception, thus influencing UES supply (Nowak & Dwyer, 2007). However, trees also emit biogenic volatile organic compounds (BVOC) that can contribute to the formation of ozone (O_3). Some species emit more BVOC than others and their emission rate can be further increased by higher temperatures, potentially degrading air quality especially in an urban heat island context (Calfapietra et al., 2013). Controversy persists regarding the real effect of trees in air quality (Setälä, Viippola, Rantalainen, Pennanen, & Yli-Pelkonen, 2013), supporting the need for more research. Some authors argue, for example that trees reduce air circulation in street canyons, consequently trapping pollutants and decreasing air quality (e.g. Vos, Maiheu, Vankerkom, & Janssen, 2013), while others suggest beneficial effects of trees for mitigation of air pollution (e.g. Irga, Burchett, & Torpy, 2015). Nevertheless, vegetation type and design seem to have a significant role in determining the effect in air quality (Gromke & Ruck, 2007; Janhäll, 2015).

Trees influence microclimate through evapotranspiration, shading, modified air movements and heat exchange, which also affect the urban atmosphere; moreover, urban vegetation intercepts rainfall and reduces water runoff and floods, which avoids stormwater treatment costs and damages (Nowak & Dwyer, 2007). These benefits rely on the structure and composition of vegetation, and are crucial for regulating the urban environment. Thus, acknowledging how vegetation structure and composition in urban green areas affect delivery of regulating UES could help urban planners and managers to target structural variables that enhance their provision. Adaptive design and management of urban green areas could therefore be addressed to explicitly enhance the provision of these UES and help in the implementation of the EU Strategy for Green Infrastructure (European Commission, 2013), as well as to tackle environmental inequities and to promote urban resilience.

However, few studies exist on how choices regarding vegetation use may affect the supply of regulating UES (though some exceptions should be noted, such as Hayek, Neuenschwander, Halatsch, & Grêt-Regamey, 2010; Hunter, 2011; Morani, Nowak, Hirabayashi, & Calfapietra, 2011). Likewise, comparative research concerning UES distribution within the urban fabric has not yet focused upon a full suite of designed types of urban space rather than vegetation types such as trees, shrubs and herbaceous (e.g. Derkzen et al., 2015). This paper aims to explore how different types of urban green spaces influence delivery of regulating UES in Porto, Portugal. The research was designed to answer the following questions:

- How are urban green types distributed in Porto in relation to socioeconomic patterns, and how does this distribution affect UES provision?
- Which structural variables of the vegetation differentiate the urban green types, and how do they impact UES delivery?

The purpose of the research was to assess social-ecological patterns affecting UES provision, with the central objective of identifying key variables that could be targeted through urban planning, planting design and management of green spaces to enhance UES.

2. Methods

2.1. Study area

The municipal limits of Porto, a major urban center of Portugal, were used to define the study area in this research (Fig. 1). This municipality covers 41.4 km^2 with 237 591 inhabitants in 2011 (INE, 2011), and it is the nucleus of a metropolitan area comprised of 17 municipalities with 1 759 524 inhabitants in the same year (INE, 2014). Porto is bordered by the Atlantic Ocean at west, and Douro River flowing through the southern limit of the city. The climate is Mediterranean (Csb climate, according to Köppen-Geiger classification), with mild seasons (temperatures typically oscillate between 5.0–16.8 °C in winter and 13.8–25.0 °C in summer) and annual precipitation that averages 1 254 mm (usually occurring from October to April) (IM, 2011). The study area contains a variety of fragmented and discontinuous green areas dispersed throughout the built-up matrix, which reflect the intensity of urban sprawl in the last century (Madureira, Andresen, & Monteiro, 2011). Yet, the singular combination of climate and geographic context have contributed to the establishment of a rich native and non-native flora.

2.2. Classification and distribution of urban green typologies in Porto

In this investigation, green spaces refer to urban areas with more than 35% of vegetated area, including patches with a minimum threshold of 800 m^2, and alignments of street trees (see Appendix A for a synthesis of criteria used for this classification). The classification of green areas was developed by adapting an existing survey and criteria from Farinha-Marques et al. (2011, 2012) to obtain a spatially explicit representation of the eight categories of green spaces found in Porto: *Agricultural areas*, *Allotments & urbanizations*, *Civic & institutional*, *Motorways & tree-lined streets*, *Private gardens & backyards*, *Parks, public*

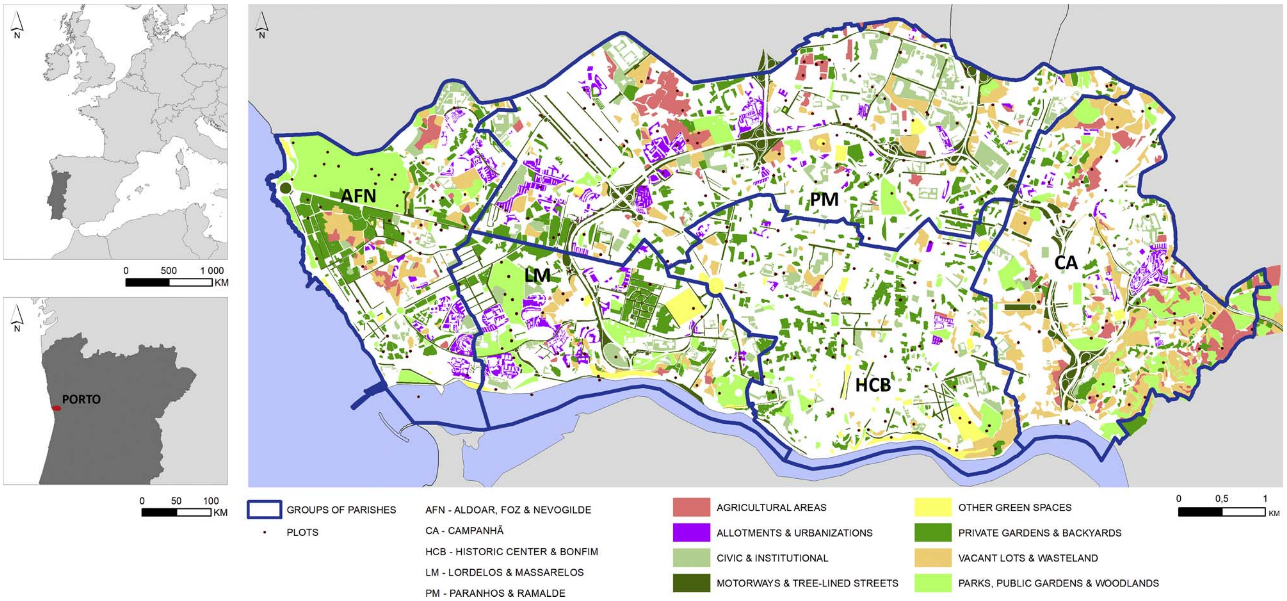


Fig. 1. Location of the city of Porto in the Northwest part of Portugal (left). Groups of parishes and typologies of urban green spaces (Appendix A) in Porto (right) used to, respectively, pre-stratify and post-stratify the 211 field plots used in this investigation (for interpretation of the references to color in this artwork, the reader is referred to the web version of the article).

gardens & woodlands, *Vacant lots & wasteland* and *Other green spaces* (Fig. 1 and Appendix A).

One additional category, *Remaining urban areas*, was created to allow for comparisons between the green spaces and the rest of the urban matrix. This category consists of built-up areas, but also includes scattered isolated trees and small detached patches of green.

The distribution of urban green types across Porto was assessed using a set of socioeconomic strata established by Graça et al. (2017), consisting of 5 groups of parishes of Porto with distinct socioeconomic profiles across a wealth gradient (Fig. 1, Table 1). Parishes are the only mandatory sublevel of administrative units within Portuguese cities. According to Graça et al. (2017) the western and southwestern parish groups *Aldoar, Foz & Nevogilde* (AFN) and *Lordelo & Massarelos* (LM) corresponded to areas with a larger share of population with college degree and younger inhabitants (age ≤14 years), more recent construction, and in which more than half of the dwellings were owned by their occupants. In contrast, the eastern parish *Campanhã* (CA) presented the lowest percentage of population with college degree and dwellings owned by their occupants; CA also had a low rate of recent construction, although urban space availability was not an issue in this part of the city. These indicators suggest that AFN and LM were the wealthiest of the five strata, and CA was considered the most deprived economically; the remaining strata, *Historic Center & Bonfim* (HCB) and *Paranhos & Ramalde* (PM) were in-between in terms of wealth status.

2.3. *i-Tree Eco v5 modelling tool*

i-Tree Eco v5 was used to analyze and quantify four proxies of three UES and one proxy for a potential disservice provided by each of the urban green types. i-Tree Eco is an application of the peer-reviewed software suite i-Tree developed by the USDA Forest Service (www.itreetools.org). It delivers a detailed characterization of the urban forest structure based in field data collected from sample plots or complete inventories, along with local hourly pollution and meteorological information (see Nowak et al., 2008 for a description of the calculations to estimate the overall structure and environmental benefits of urban forests). I-Tree Eco has been widely employed in case studies across the world, usually to estimate UES for whole urban areas without inner stratification (Baró, Haase, Gómez-Baggethun, & Frantzeskaki, 2015), or to compare one single type of strata within an urban area (Escobedo et al., 2006; Yang, McBride, Zhou, & Sun, 2004). According to the i-Tree Eco v5 protocol, it is possible to pre-stratify or post-stratify the study area into smaller parts to better understand differences across the selected strata, keeping in mind that the maximum number of strata should be below 14 (i-Tree, 2014). Our approach proposes an innovative application of i-Tree Eco, using a sample design based in both a pre-stratification and a post-stratification scheme to generate more detailed insights for planning and management (see Section 2.4).

The selected UES for this study were climate regulation (using carbon storage and carbon net sequestration as proxies), water flow regulation (using avoided runoff as proxy) and air purification, considering removal of the following pollutants as UES proxy: carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), particulate matter with diameter of 10 µm or less (PM10), particulate matter with diameter of 2.5 µm or less (PM2.5) and sulphur dioxide (SO_2). Our definition of UES was based in the service cascade proposed by Haines-Young and Potschin (2010), in which ecosystem functions are “capacities” of ecosystems (such as carbon sequestration) which provide useful contributions to humans (services), such as climate regulation (Boerema, Rebelo, Bodi, Esler, & Meire, 2017). The disservice estimated was air pollution using BVOC emissions by trees and shrubs as a surrogate, because they can contribute to ozone and other pollutant formation

The following structural variables of trees were examined: tree density, tree species density, diameter at breast height (DBH), total tree leaf area (TLA), total tree leaf biomass (TLB), Simpson’s diversity/dominance index and tree condition (7 classes ranging from ‘Dead’ to ‘Excellent’).

Following the i-Tree Eco v5 protocol, all woody specimens with DBH ≥ 2.54 cm were considered trees. As such, for example vines were considered trees whenever they reached the threshold in DBH size.

Simpson’s index informs about species dominance effects. i-Tree Eco v5 estimates a non-normalized form of this indicator, Simpson’s inverse index. As such, it is not suitable for comparing different strata. Therefore, in this investigation the complement of Simpson’s index was adopted, which means that greater values denote higher diversity (Magurran, 2004). Since i-Tree Eco delivers significantly more detailed information for trees rather than shrubs, more emphasis was given to trees in this research. Nonetheless, estimates for air pollution removal described in the results section also reflect the positive impact of TLA and TLB of shrubs.

Pollution data to run i-Tree Eco v5 were obtained from the national online database *QualAR*, hosted by the Environment Portuguese Agency. Hourly concentrations of NO_2, SO_2, CO_2, O_3, PM_{10} and $PM_{2.5}$ were retrieved for the background station of Porto, *Sobreiras – Lordelo do Ouro,* for 2010 and 2011 (APA, n.d.). Local hourly meteorological data were collected from the National Climatic Data Center (www.ncdc.noaa.gov), excluding precipitation data, which were obtained from a weather station located on the roof of the Faculty of Sciences of the University of Porto building (41°09′N, 8° 38′W, 20 m height).

2.4. Stratification schemes, field survey and data analysis

Field data consisted of records from 211 circular plots covering 404.7 m^2 each (radius = 11.35 m), collected in accordance with the i-Tree Eco V5 protocol (i-Tree, 2014) between mid-May and mid-September 2014. In a previous work, these plots were laid out across the urban fabric in Porto following a pre-stratification scheme to allow comparison between socioeconomic strata (Graça et al., 2017; Fig. 1). In the pre-stratification scheme, the plots were proportionally assigned to five socioeconomic strata according to total area, following a random distribution concentrated within the main green spaces of the city (70% of the plots) to lay emphasis on areas with more vegetation; the remaining plots (30%) were randomly assigned to the rest of the city, to account for the cumulative impact of small green areas to Porto's total UES provision (Graça et al., 2017). The pre-stratification scheme was used in our investigation to explore how urban green types were distributed across socioeconomic strata in Porto, and how this distribution affected UES provision. Structural variables are directly related with the provision of the UES: i) tree size is important as larger specimens can store more biomass and carbon, and total leaf surface area (TLA) affects air pollution removal and rainfall interception; ii) total leaf biomass (TLB), which relates to TLA, affects genera-specific BVOC emissions (Nowak et al., 2008) and iii) species composition and density affect all structural variables and UES, because different species have distinct size profiles and properties. To examine which structural variables of the vegetation differentiated the urban green types, and how they impacted UES delivery, a post-stratification scheme was subsequently developed in our research. For this purpose, the same set of plots from the pre-stratification scheme was used and each plot was assigned to a single category of urban green space. This post-stratification allowed for the quantification of UES supply and structural variables of the urban forest for all types of green space. Care was taken to ensure that the total number of plots per stratum was proportional to the relative abundance of each type of urban green space in the city (Table 2).

The combination of both stratification schemes allowed to analyze the combined effect of urban green types and socioeconomic strata in UES delivery, thus generating detailed multilevel information suitable for urban planning, management and design (Fig. 2).

All measured variables were converted to values per hectare to ensure an unbiased comparison. Average results for each assessed proxy of UES were translated into a proficiency ranking ranging from 1 to 8, in which the urban green type yielding the best result (1) was considered the most proficient. Since four proxies were analyzed, this produced four rankings (for C storage, C net sequestration, pollution removal and avoided runoff). An overall UES proficiency ranking for urban green areas was then calculated by simply averaging rankings for each proxy. This final numeric ranking was then translated into the following classes of UES proficiency: very high, high, moderately high, intermediate, moderately low, low, very low. The UES proficiency classes were mapped according to the location of Porto's corresponding green areas. As BVOC emission was considered a proxy for a disservice, it was mapped independently, using quantitative results. If opposite contributions (positive vs. negative) of vegetation for total UES supply were aggregated in one single ranking, there would be the risk of misrepresenting relevant information for urban planning and

Table 1
Characterization of socioeconomic strata used in a pre-stratification scheme to assess differences in UES provided by urban green spaces in Porto (INE, 2011).

Strata	Area		Population		Occupation of dwellings[a]		Building time of dwellings[a]		Age of residents[a]		Pop with college degree[a] (%)
	Total (ha)	Of municipality (%)	Total	In municipality (%)	Owner or co-owner (%)	Tenant or sub-tenant (%)	Until 1945 (%)	1981–2011 (%)	≤14 yrs (%)	≥65 yrs (%)	
Aldoar, Foz do Douro and Nevogilde (AFN)	627	15,1	28 858	12,1	64,5	27,7	20,1	36,9	13,8	21,4	31,9
Campanhã (CA)	804	19,4	32 659	13,7	36,2	56,4	48,9	13,8	12,3	23,0	8,8
Historic Center and Bonfim (HCB)	853	20,6	64 705	27,2	42,1	51,4	51,6	11,4	9,8	27,0	21,8
Lordelo and Massarelos (LM)	559	13,5	29 059	12,2	52,3	40,5	32,4	19,3	13,3	20,7	26,6
Paranhos and Ramalde (PM)	1 299	31,4	82 310	34,6	54,4	39,3	29,7	16,5	12,4	21,8	23,2
City Total	4 142	100,0	237 591	100,0	49,3	43,9	39,7	16,8	11,9	23,2	22,3

[a] Indicators used by Graça et al. (2017) to investigate associations between variables of the urban forest and socioeconomic variables in Porto.

Table 2
I-Tree Eco results per type of green space in the city of Porto (Portugal), estimated from sample means.

Type	Number of plots	Total estimated area of city (%)	Tree density (n ha^{-1})	Tree species richness (n ha^{-1})	Simpson Index	Tree Leaf Area (m^2 ha^{-1})	Tree Leaf Biomass (kg ha^{-1})	C storage (kg ha^{-1})	C net sequestration (kg ha^{-1} yr^{-1})	Top tree species density	
										Species	n ha^{-1}
Agricultural areas	8	1.6	131.7	21.9	0.80	5,426.1	417.0	11,009.1	455.2	*Vitis vinifera* *Actinidia deliciosa* *Prunus cerasifera*	47.0 25.1 21.9
Allotments & urbanizations	13	2.9	190.7	53.5	0.85	15,420.1	1,265.1	22,910.5	1,082.1	*Populus nigra* 'Italica' *Pittosporum tobira* *Metrosideros excelsa*	60.5 41.9 18.6
Civic & institutional	13	3.1	201.0	52.6	0.80	14,352.5	1,529.6	22,338.1	680.5	*Acacia melanoxylon* *Ligustrum lucidum* *Prunus laurocerasus*	81.3 28.7 16.7
Motorways & tree-lined streets	19	4.1	130.4	50.9	0.96	23,104.4	1,541.7	25,789.6	892.5	*Platanus x acerifolia* *Thuja plicata* *Sequoia sempervirens*	15.9 14.3 9.5
Private gardens & backyards	22	7.8	133.8	63.6	0.97	9,660.4	1,212.5	12,801.4	684.5	*Camellia japonica* *Prunus persica* *Laurus nobilis*	16.9 9.1 7.8
Parks, public gardens & woodlands	30	6.3	250.4	48.2	0.94	23,439.4	2,164.4	40,520.8	1,195.4	*Quercus robur* *Quercus suber* *Cornus* sp.	37.0 30.1 27.5
Vacant lots & Wasteland	30	12.1	50.6	12.4	0.66	3,105.8	334.9	5,296.1	152.1	*Populus nigra* *Pinus pinaster* *Quercus suber* *Robinia pseudoacacia*	29.3 5.3 2.7 2.7
Other green spaces	6	2.1	153.2	27.0	0.69	15,344.9	1,539.5	16,765.8	656.8	*Magnolia x soulangiana* *Cupressus sempervirens* 'Stricta' *Camellia japonica*	76.6 31.5 27.0
Remaining urban areas	70	60.1	20.1	11.8	0.94	955.3	79,1	1,402.1	97.6	*Cupressus sempervirens* 'Stricta' *Pyracantha coccinea* *Acer negundo* *Nerium oleander*	3.8 2.7 1.5 1.5
City Total	211		64.0	17.0		4,857.6	453.1	7,152.9	293.0	*Quercus robur* *Populus nigra* *Quercus suber*	3.7 2.9 2.7

management. Increasing UES supply can be achieved by actively promoting positive effects of vegetation, but also through the deliberate decrease of potential disservices. Therefore, addressing simultaneously both these strategies requires separate supporting information.

3. Results

3.1. Distribution of urban green types across the city

Green areas in Porto covered about 40% of the urban area. Considering only the eight green types, the type with the highest coverage in the city was *Vacant lots & wastelands* (12.1%), followed by *Private gardens & backyards* (7.8%) and *Parks, public gardens & woodlands* (6.3%) (Table 2).

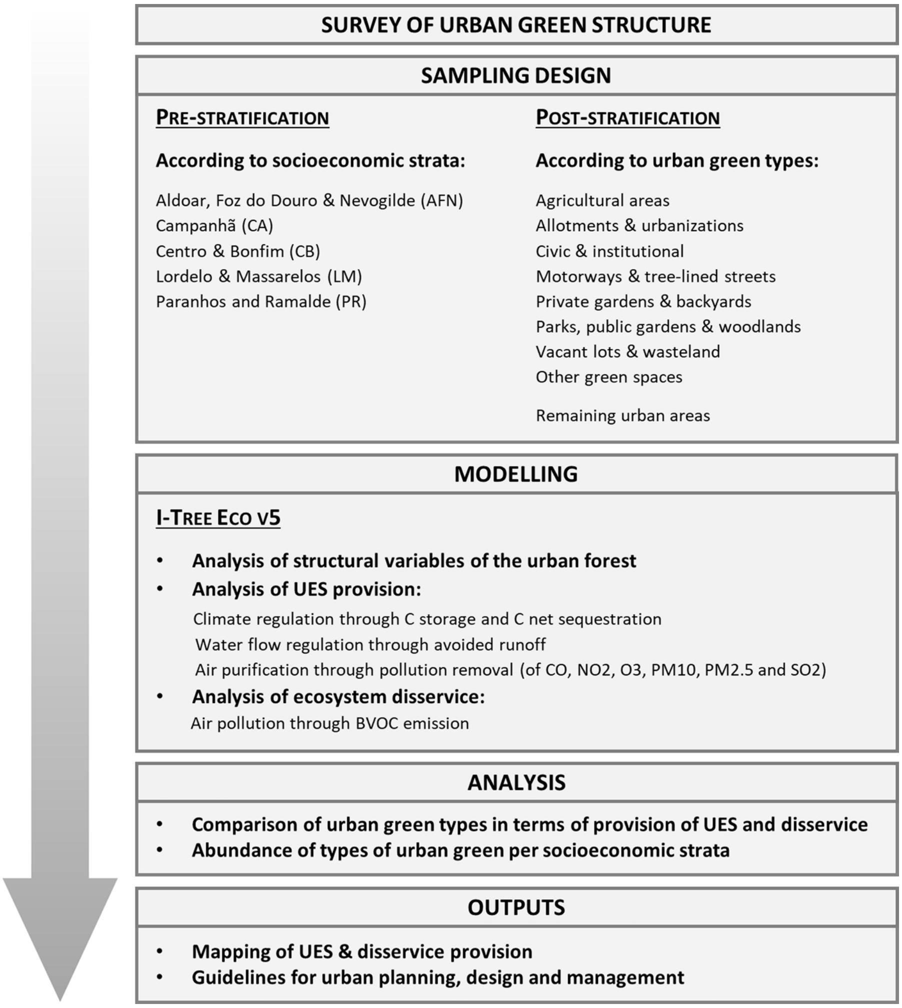
The urban green types were not evenly distributed throughout Porto or among the socioeconomic strata (Fig. 3).

The greenest socioeconomic stratum was CA (48.6% of the stratum area), which is the most economically deprived area of the city (Graça et al., 2017). More than half of the green areas of CA were classified as *Vacant lots & wastelands* or *Agricultural areas*. AFN and LM, the two wealthier strata, also had a high amount of green areas (over 46% of each stratum). These areas showcased a much more balanced composition of urban green types. *Parks, public gardens & woodlands* dominated these areas of Porto, along with *Private gardens & backyards* for LM. AFN also contained numerous private gardens and backyards, but they covered a slightly smaller area than *Vacant lots & wastelands*. HCB, the urban center of Porto, was the area of the city with lower proportion of green areas; PM presented the second lowest share of green space, and the smallest proportion of *Parks, public gardens & woodlands* (Fig. 3).

3.2. Structural variables and UES delivery for urban green types

Results show considerable differences among green types in terms of structural variables. The highest average tree density was found in *Parks, public gardens & woodlands* (250.4 trees ha^{-1}), followed by *Civic & institutional* (201.0 trees ha^{-1}) and *Allotments & urbanizations* (190.7 trees ha^{-1}). The least treed green areas were *Vacant lots & wastelands* (50.6 trees ha^{-1}), *Motorways & tree-lined streets* (130.4 trees ha^{-1}), *Agricultural areas* (131.7 trees ha^{-1}), and *Private gardens & backyards* (133.8 trees ha^{-1}), (Table 2).

In terms of species richness per hectare, *Vacant lots & wastelands* and *Agricultural areas* had the lowest richness with 12.4 and 21.9 species ha^{-1} respectively. *Private gardens & backyards* had the highest richness (63.6 species ha^{-1}). The highest Simpson's index, representing



SURVEY OF URBAN GREEN STRUCTURE

SAMPLING DESIGN

PRE-STRATIFICATION

According to socioeconomic strata:

Aldoar, Foz do Douro & Nevogilde (AFN)
Campanhã (CA)
Centro & Bonfim (CB)
Lordelo & Massarelos (LM)
Paranhos and Ramalde (PR)

POST-STRATIFICATION

According to urban green types:

Agricultural areas
Allotments & urbanizations
Civic & institutional
Motorways & tree-lined streets
Private gardens & backyards
Parks, public gardens & woodlands
Vacant lots & wasteland
Other green spaces

Remaining urban areas

MODELLING

I-TREE ECO V5

- **Analysis of structural variables of the urban forest**
- **Analysis of UES provision:**
  Climate regulation through C storage and C net sequestration
  Water flow regulation through avoided runoff
  Air purification through pollution removal (of CO, NO2, O3, PM10, PM2.5 and SO2)
- **Analysis of ecosystem disservice:**
  Air pollution through BVOC emission

ANALYSIS

- **Comparison of urban green types in terms of provision of UES and disservice**
- **Abundance of types of urban green per socioeconomic strata**

OUTPUTS

- **Mapping of UES & disservice provision**
- **Guidelines for urban planning, design and management**

Fig. 2. Diagram of the methodology developed to investigate how different types of urban green spaces influence urban ecosystem services (UES) delivery across a socioeconomic gradient in Porto (Portugal).

greater species diversity, was found in *Private gardens & backyards* (0.97), followed by *Motorways & tree-lined streets* (0.96) and *Parks, public gardens & woodlands* (0.94). *Vacant lots & wastelands* (0.66) and *Other green spaces* (0.69) had the lowest diversity values.

TLA and TLB revealed a similar ranking, with *Parks, public gardens & woodlands* yielding the highest values per hectare, followed by *Motorways & tree-lined streets*. Lowest leaf density values were found on *Vacant lots & wastelands, Agricultural areas* and *Private gardens & backyards* (Table 2).

Agricultural areas (57%) and *Vacant lots & wastelands* (42%) had the

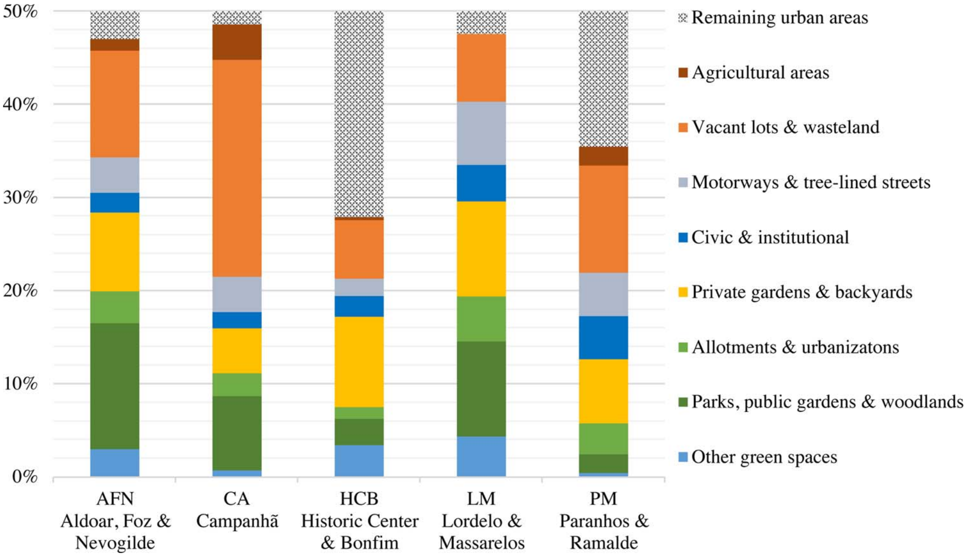


Fig. 3. Proportion of types of green spaces in total urban area per group of parishes in Porto. Graph bars illustrate only 50% of total area in each strata because the sum of green areas is below this percentage in all cases.

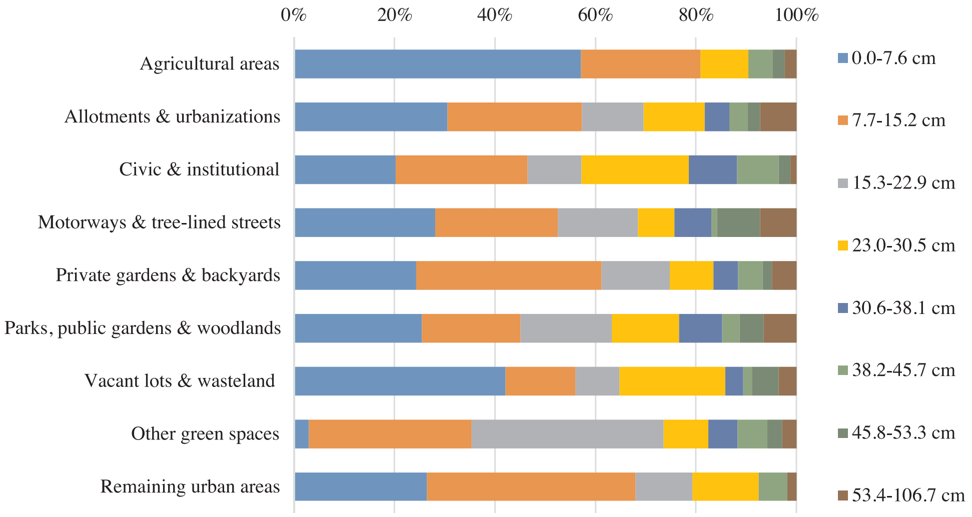


Fig. 4. Composition of tree population according to Diameter at Breast Height (DBH) class, per typology of urban green areas in Porto, estimated from sample means.

highest proportion of small trees (0 < DBH ≤ 7.6 cm) (Fig. 4). *Motorways & tree-lined streets* (24%) and *Parks, public gardens & woodlands* (24%) had the highest proportion of large trees with DBH ≥ 30.6 cm.

These results for structural variables of the urban forest were in line with findings for UES delivery in Porto. C storage and C net sequestration densities were the lowest in *Vacant lots & wastelands* followed by *Agricultural areas*, and the maximum value was estimated for *Parks, public gardens & woodlands* (Table 2). A very similar pattern occurred when analyzing pollution removal and avoided runoff, with *Parks, public gardens & woodlands* rendering the best outcome, followed by *Motorways & tree-lined streets* (Figs. 5 and 6). *Vacant lots & wastelands* emerged again with the lowest estimates, behind *Agricultural areas* and *Private gardens & backyards*. Avoided runoff for all categories was higher in 2010, due to higher precipitation, highlighting how ES supply is dependent of temporal dynamics.

UES performance varied across green spaces in Porto, with *Parks, public gardens & woodlands* and *Motorways & tree-lined streets* exhibiting the highest overall performance and *Vacant lots & wastelands* and *Agricultural areas* exhibiting the lowest overall performance (Table 3; Fig. 7a).

As expected, *Remaining urban areas* had considerably less trees than any of the green strata, thus presenting the lowest performance of UES per hectare.

In terms of disservices, total BVOC emission per hectare was highest for *Civic & institutional* and *Parks, public gardens & woodlands* (Fig. 7b). *Agricultural areas* had the lowest BVOC densities.

Parks, public gardens & woodlands had the highest values among all strata for tree density, TLA and TLB, presenting also the second highest proportion of trees with DBH ≥30.6 cm. As UES provided by vegetation are directly dependent of the density, size and condition of specimens, these results explain, without surprise, the high delivery of UES in this green type. *Motorways & tree-lined streets,* however, recorded the second lowest tree density of all green types, but ranked in the second highest in terms of delivery of all UES except for climate regulation through C

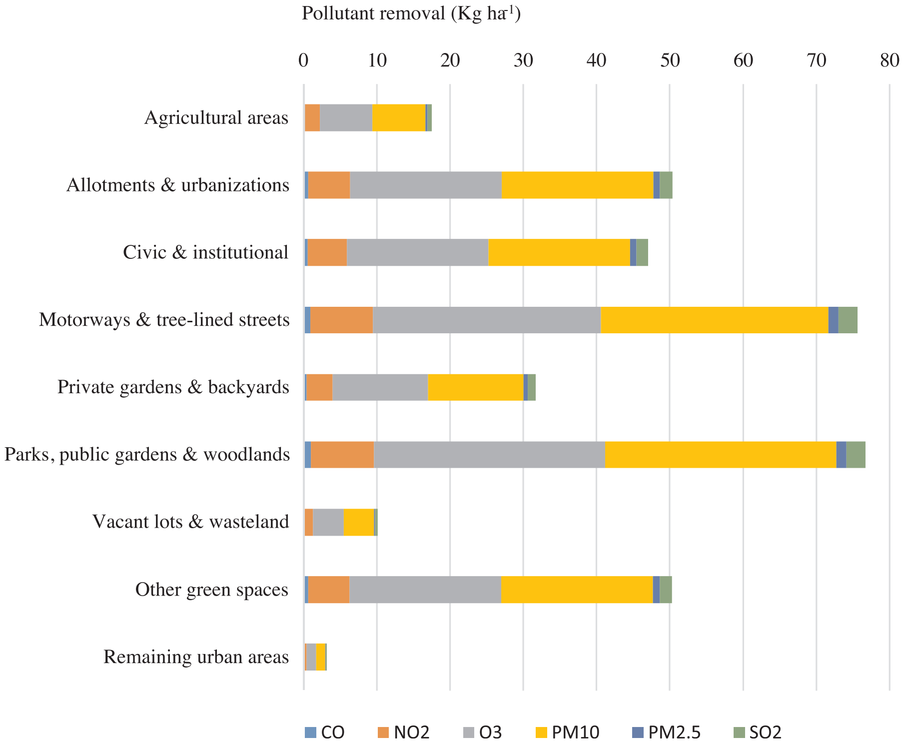


Fig. 5. Pollution removal per typology of urban green areas in Porto in 2011, estimated from sample means.

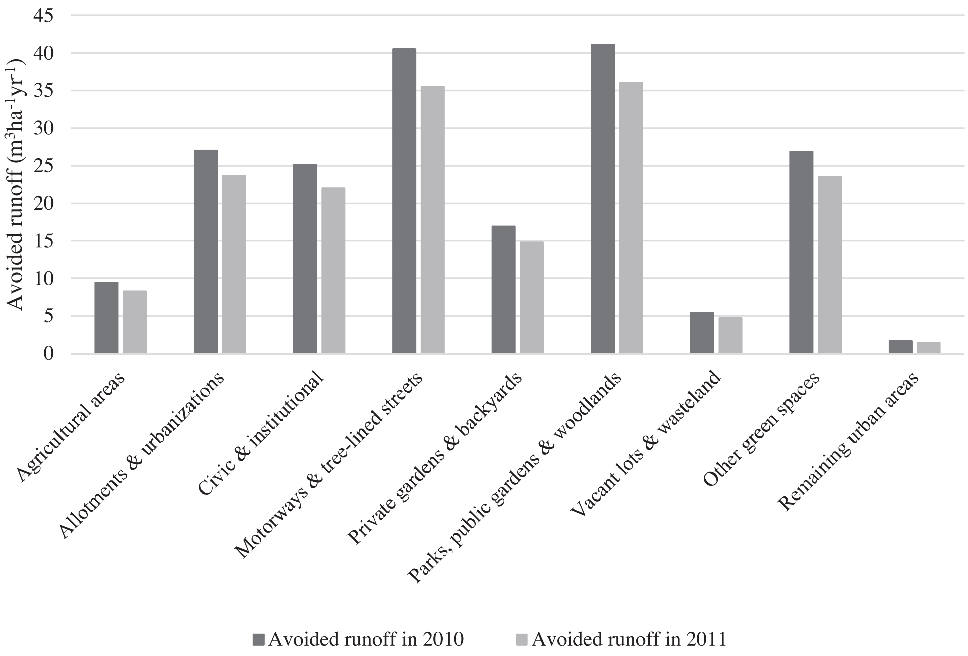


Fig. 6. Comparison of avoided runoff in 2010 and 2011 for trees in Porto, per typology of urban green areas (estimated from sample means).

Table 3
Numeric ranking proficiency for different urban ecosystem services (UES) derived from I-Tree Eco per type of green space in the city of Porto (Portugal).

Type	Climate regulation through C storage	Climate regulation through C net sequestration	Water flow regulation through avoided runoff	Air purification through pollution removal	Average ranking	UES provision
Agricultural areas	7	7	7	7	7	Low
Allotments & urbanizations	3	2	3	3	3	Moderately high
Civic & institutional	4	5	5	5	5	Intermediate
Motorways & tree- −lined streets	2	3	2	2	2	High
Private gardens & backyards	6	4	6	6	6	Moderately low
Parks, public gardens & woodlands	1	1	1	1	1	Very high
Vacant lots & Wasteland	8	8	8	8	8	Very low
Other green spaces	5	6	4	4	5	Intermediate

Numeric classes refer to the level of proficiency for each analyzed UES: very high (1), high (2), moderately high (3), intermediate/high (4), intermediate/low (5), moderately low (6), low (7), very low (8). In the final UES provision ranking the intermediate/low and intermediate/high classes were merged into one single class, corresponding to the numeric average ranking of 4.75.

net sequestration. This green type category contained the greatest proportion of trees with DBH ≥ 30.6 cm (particularly trees between 45.8-106.7 cm), and ranked in the second highest in TLA and TLB, which explains the relatively high performance in UES delivery. *Vacant lots & wastelands* provided the lowest provision of UES, followed by *Agricultural areas*. In these two types, poor UES provision was mainly due to low tree densities combined with small DBH, which impacted TLA and TLB densities. Consequently, the investigated UES were negatively affected by these structural variables.

Tree species composition (Table 2) was dominated by autochthonous species in *Parks, public gardens & woodlands* and by non-native species in *Private gardens & backyards, Motorways & tree-lined streets, Allotments & urbanizations* and *Other green spaces.* Surprisingly, the most abundant species for *Civic & institutional* was *Acacia melanoxylon*, which is classified as an invasive species by the Portuguese legislation. *Vacant lots & wastelands* revealed a prevalence of autochthonous and spontaneous species.

UES performance also varied across socioeconomic patterns, as a consequence of their heterogeneous distribution of green space types (Fig. 8) The affluent socioeconomic strata LM and AFN contained the highest proportion of urban green spaces with the best UES performances, particularly *Parks, public gardens & woodlands* (Figs. 3 and 8). The most economically deprived area of the city (CA) was the greenest amongst socioeconomic strata, but it was dominated by green space types with the lowest estimates for UES delivery, with about half of its total green area being covered with *Vacant lots & wastelands.*

4. Discussion

4.1. Analysis and implications of results

This research revealed that socioeconomic strata in Porto had distinct composition of urban green types, and that this strongly affected UES supply. The wealthier strata LM and AFN revealed a much better UES performance compared with the most economically deprived area (CA). LM and AFN also had by far the greatest share per hectare of managed green spaces, suggesting considerable more private and public investment than in the rest of the city. CA covers about one fifth of Porto and is home for nearly 14% of its inhabitants (INE, 2011), which arise in this investigation as having less access to quality green spaces and to UES provision, even though this was the greenest socioeconomic strata. The inhabitants of CA also have less opportunities to benefit from other well-documented cultural and psychological benefits of green spaces (Tzoulas

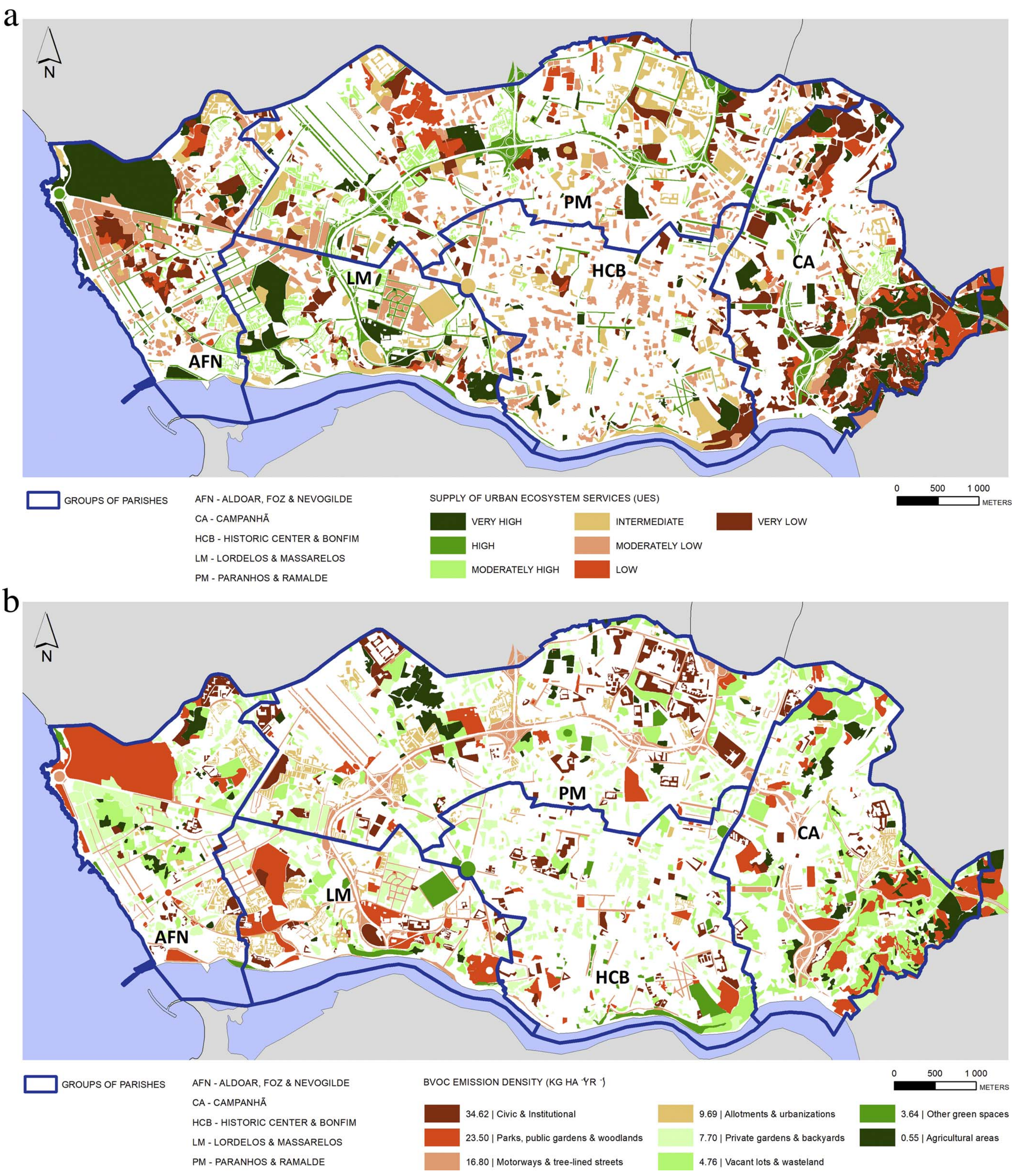


Fig. 7. (a) Performance of urban green areas per group of parishes of Porto, according to the average provision of four urban ecosystem services (UES): climate regulation through carbon storage and carbon sequestration; water flow regulation through avoided runoff; air purification through pollution removal. (b) Supply of urban ecosystem disservices: average density of biogenic volatile organic compounds (BVOC) by vegetation in urban green areas of Porto, according to groups of parishes.

et al., 2007), because the most abundant green type in this part of the city corresponds to areas frequently neglected or inaccessible. These considerations underline a pattern of environmental injustice already noted by Graça et al. (2017), which established a statistical association between the five socioeconomic strata adopted in our case study and the structural variables of the urban forest in Porto, exploring the consequences for UES provision. Building from the findings of Graça et al. (2017), our results suggest that the differences between socioeconomic strata are due to the heterogeneity of the distribution of urban green types across the city, and underline the critical role of the quality of urban ecosystems in mitigating environmental injustice.

As carbon sequestration and storage affect mainly climate

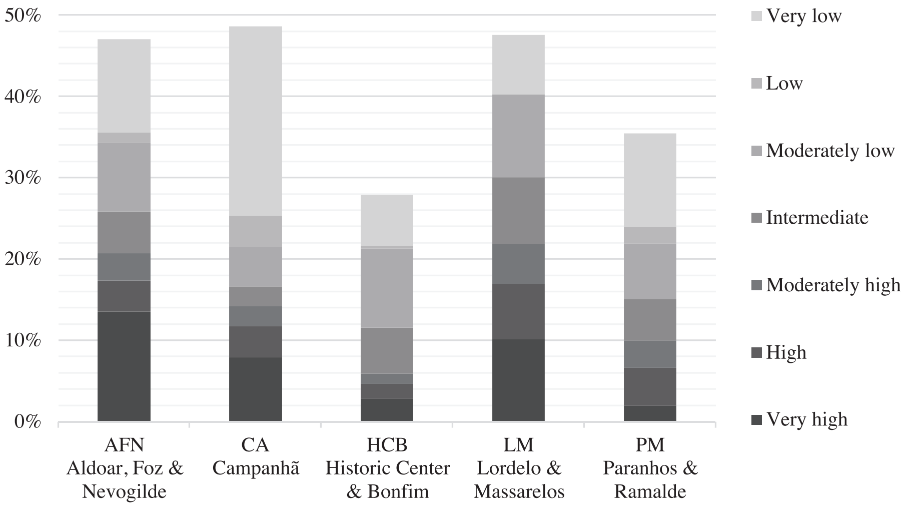


Fig. 8. Proportion of green spaces per group of parishes in Porto, according to the performance regarding delivery of regulating urban ecosystem services (UES). Ranking classes refer to the overall level of proficiency assigned to each type of green space: very high, high, moderately high, intermediate, moderately low, low, very low.

regulation at the global scale, the heterogeneity of these variables within Porto does not evidence environmental injustice, even though Graça et al. (2017) concluded that CA presented the lowest densities in both. Nevertheless, carbon sequestration and storage patterns reflect tree size, density and condition across the city, which affect many other critical UES (such as water flow regulation, air purification, microclimate regulation, energy efficiency …) with direct local impact in the wellbeing of inhabitants. In addition, acknowledging carbon sequestration and storage patterns in urban settings could help local institutions to devise informed actions for carbon footprint mitigation through tree plantation and adequate management.

The results also confirmed previous research highlighting environmental inequity in other cities (Escobedo et al., 2015; Jenerette et al., 2011; Romero et al., 2012). Pedlowski et al. (2002) observed that socioeconomic and education levels were associated with tree density in a case study in Rio de Janeiro (Brazil), which was likewise confirmed for Porto by Graça et al. (2017). If effective improvements in UES provision to increase environmental justice are to be achieved by urban planning and management, characteristics of green spaces must be acknowledged and addressed in relation with socioeconomic patterns. However, Conway and Bourne (2013) concluded that in residential land within Peel Region (Ontario, Canada) canopy cover, stem density and species richness had a week relationship with socioeconomic variables, and that multiple tree variables should be assessed when exploring associations between social aspects in urban patterns and the urban forest. For Porto, results showed that the characteristics of urban green areas were more important than their size in UES supply, which is relevant for urban planning and management regardless of socioeconomic patterns eventually detected in a given study area. However, results for Porto did reveal an increased need to reinforce resilience in the less privileged areas. This change could be accomplished through private and public investment for creating new green spaces and increasing tree density in existing vacant lots and wastelands in CA, as well as promoting good practices in other types of green spaces (e.g. proper design and management of vegetation to allow full growth).

One possible explanation for decreased tree quantity and size in *Vacant lots & wastelands* could be the frequency of land use changes or vegetation clearing, hence limiting trees from reaching maturity. Even though this category revealed an overall poor performance, this finding might also be partially a consequence of our selection of UES for analysis. For example, a recent study by McPhearson et al. (2013) revealed that vacant areas in New York City can be very important for runoff mitigation and habitat provision for biodiversity. These authors found that vacant lots could retain as much as 37% of the rain in a 24 h, 5 inches rain event, based in combinations of hydrological soil groups and landcover. In our investigation, we considered avoided runoff by trees, but not runoff mitigation through absorption of rain in soils. This emphasizes the need to expand research assessments in more ecosystem services and variables than those analyzed in this study.

Given that some research has highlighted the importance of private gardens to total urban tree cover (Davies et al., 2009), it was expected that this investigation could reveal a good performance for *Private gardens & backyards* compared to the other studied green types. However, this was not the case. *Private gardens & backyards* had a tree density slightly higher than *Motorways & tree-lined streets*, but presented some of the lowest values for TLA and TLB, only above *Agricultural areas* and *Vacant lots & wastelands*. It also presented the third highest proportion of small trees with DBH ≤ 15.2 cm, adding up to more than 60% of all trees (Fig. 4). Climate regulation through C storage and C net sequestration was negatively influenced by this structure, because smaller trees store less carbon, and lower amounts of TLA and TLB decrease the capacity of specimens for photosynthesis. Lower TLA and TLB also reduce air purification through pollution removal and avoided runoff, because there is less interception area (Nowak and Dwyer, 2007). Graça et al. (2017) noted that in Porto very few sampled trees had the required height and distance to residential buildings to affect their energy efficiency. A large quantity of the trees that could have impacts on building energy use are located in *Private gardens & backyards* and fit in classes of smaller DBH, suggesting that homeowners tend to avoid big trees near buildings. These small trees will produce less energy effects near buildings. Other studies have also pointed out the scarcity of large trees in domestic gardens in Leicester (Davies, Edmondson, Heinemeyer, Leake, & Gaston, 2011) and in residential neighborhoods in Melbourne (Threlfall et al., 2016). These outcomes indicate a considerable opportunity to increase citizen awareness and engagement towards UES provision, for example, by promoting inclusive initiatives with the potential to foster a new societal dialogue about biodiversity, ecosystem services and sustainable living environments (Beumer & Martens, 2015). Municipal incentives (e.g. reduced taxes) might also promote proactive involvement from landowners (Kirkpatrick, Daniels, & Davison, 2009).

It is worthwhile to stress, nevertheless, that *Private gardens & backyards* had the greatest species richness per hectare, and the highest Simpson Index, which is in line with findings from other studies analyzing vegetation diversity in gardens (Loram, Thompson, Warren, & Gaston, 2008).

Greater DBH and TLA lead to higher UES supply, which explains why UES provision was higher in *Allotments & urbanizations* than in *Civic & institutional*, for all the services analyzed.

BOVC emission density was by far the highest for *Civic & institutional* among all strata, even though TLB was much higher for other green typologies. This result is explained by the occurrence of more high

BVOC-emitter species in *Civic & institutional* (data not shown), combined with the larger size of specimens. Even though *Acacia melanoxylon* is not a high BVOC-emitter (Benjamin, Sudol, Bloch, & Winer, 1996), it is alarming that an invasive species was the top species in this green type. Invasive species did not thrive in the other green types, not even in *Vacant lots & wastelands,* where spaces are typically unmanaged and covered by spontaneous vegetation. Such findings further reinforce the necessity to improve knowledge of those in charge of urban planning and management about the impact of their choices in biodiversity and UES provision. Invasive species may contribute positively for some UES, but they represent a severe menace to autochthonous species and supporting ES that underpin overall UES provision (Vilà et al., 2010). Hence, programs to monitor and control proliferation of invasive species in *Civic & institutional* are highly recommended for Porto. Also, trade-offs between UES and disservices such as air pollution due to BVOC emission should be acknowledged in decision processes affecting urban green areas, especially in more polluted areas. In the case of Porto, municipal regulations and incentives can help to promote the use of low emitting species.

Another interesting result in this study was the relatively low BVOC emission on *Motorways & tree-lined streets*, considering the high delivery of UES associated with this typology, almost matching *Parks, public gardens & woodlands*. The general good performance of *Motorways & tree-lined streets* is particularly important to increase Porto's UES provision in the future, because implementation of new green spaces is difficult in the densely built urban matrix, similarly to many other cities from Southern and East Europe (Fuller & Gaston, 2009). Trees can more easily be planted along existing streets, thus promoting urban resilience. Moreover, street trees can substantially reduce air concentration of pollutants (e.g. Pugh, MacKenzie, Whyatt, & Hewitt, 2012; Vailshery, Jaganmohan, & Nagendra, 2013). However, possible negative effects due to pollutant trapping in street canyons should be considered when deciding the location and type of tree to plant (Pugh et al., 2012). Hence, recommendations for Porto stemming from this research include carefully planned tree plantation in streets and motorways to increase UES provision, especially in the denser urban areas where new gardens and parks might be unfeasible.

In addition, performance of green spaces relies upon proper establishment of trees, which should be given appropriate conditions to fully grow. Severe pruning is still fairly common in many cities of Portugal including Porto (Fabião, 2009), and causes the destruction of the natural shape of trees, reduction of the crown size and leaf area. Besides safety issues from unbalanced architecture of branches, this practice reduces TLA/TLB in trees of considerable DBH, and consequently reduces UES provision. Xiao and McPherson (2002) showed that more intense pruning of sweetgum in Santa Monica originated only 46% of the annual intreception of rainfall for the same species in Modesto, for 40-old specimens, due to reduced crown size. Hence, investing in wide awareness strategies targeting urban populations and administrations could shape the management practices that determine where and how trees will grow (Roman et al., 2015) and affect future UES.

Derkzen et al. (2015) commented that one shortcoming of i-Tree Eco is that it does not discriminate between types of urban green spaces. However, our approach showed how defining an appropriate stratification scheme to assign field plots enables i-Tree Eco to compare UES supply across different urban green types.

Our methodology allowed mapping UES provision across the city of Porto in a scale compatible with municipal planning, and can be adapted to other cities to explore UES provision as a consequence of structural variables of the urban forest and socioeconomic patterns. Though the case study of Porto was built upon socioeconomic strata based in groups of parishes, this was because it was an inherent condition of the pre-stratification of our dataset. The suitability of this set of strata to represent accurately socioeconomic patterns in Porto was documented in Graça et al. (2017). Nevertheless, socioeconomic strata based in other classes may be used in future studies, as well as other types or categories of urban green spaces.

Results from this investigation evidenced hot and cold spots of UES provision, and revealed a high spatial discontinuity in terms of performance of green areas according to socioeconomic patterns. These findings can establish the base for the development of a green plan for the city, which is currently lacking, addressing particularly the environmental inequity observed across the city. Though equal weighting was given to each UES when calculating the overall proficiency ranking, the weight of certain services could be adjusted by urban planners and managers to better address local needs and demands, as suggested in multi-criteria decision analysis studies (Langemeyer, Gómez-Baggethun, Haase, Scheuer, & Elmqvist, 2016). For example, avoided runoff might be considered more relevant to inform a municipal strategy for flood control. In light of specific local problems of cities, it is also crucial to assess provision of UES in relation to demand, as facing some urban challenges might rely more in other strategies beyond UES enhancement.

4.2. Limitations and caveats

Some limitations in our investigation should be recognized. In i-Tree Eco v5, pollution data is derived from one single station or aggregated values of more than one station, hence pollutant concentrations are assumed to be the same across all the city (even though hourly variations are considered to generate results). This is a limitation when assessing the efficacy of vegetation to remove air pollutants at the local scale, because the effect is dependent of pollution concentrations. Also, pollution removal is calculated in i-Tree Eco based on a deposition velocity estimated from amount of tree cover, daily leaf area index, and local hourly weather data. The model calculates an average deposition velocity for trees in the area of analysis. For individual tree estimates, it prorates the total removal back to tree based on proportion of total leaf area in the analysis. Thus, while tree species will have an impact on pollutant removal (Sæbø et al., 2012), in the model only the leaf area attribute of species is considered.

Using a post-stratification scheme for plots allowed the use of an existing dataset, but it likely has less precision in representing the relative proportions of urban green types compared to pre-stratification, in which strata definition occurs prior to plot distribution. In addition, some urban green types that covered a very small percentage of Porto were clustered into more general types to ensure minimum plot sample size. Such clustering likely increased the heterogeneity and lowered precision of the estimates of the structural variables within clustered categories. One way to partially overcome these issues in future research could be to create a pre-stratification scheme based solely on the urban green area. By excluding the remaining urban areas, field plots would be located exclusively in green spaces. This design would oblige to collect new field data, but it would also increase the relative representability of each type of urban green. As such, this new design would considerably optimize time and resources in the field.

Performances in UES delivery represent average estimates because i-Tree results were estimated from sample plots and aggregated in urban green types (thus clustering different types of vegetation). Nevertheless, subsequent analysis can focus in more detail some types of green spaces or some urban areas, in order to address the potentially high variability of vegetation structure and composition within these.

Lastly, this investigation focused in a small set of UES particularly affected by the structure and composition of vegetation. However, urban planning and management also require information regarding other types of assessments acknowledging crucial contributions of ecosystems, as for example cultural ES. Future studies should integrate these different types of information in order to better support decision-making processes.

5. Conclusions

This work revealed that different types of green spaces affect UES delivery as a direct result of the influence of structural variables such as tree density, species richness, DBH, TLA and TLB. Furthermore, the uneven distribution of types of green spaces across socioeconomic strata might exacerbate this effect in some parts of the city, as observed in Porto. Urban planning can be a powerful way to address such environmental inequity, by efficiently allocating resources to the cold hotspots of reduced UES provision. Full development of trees and proper selection of species should be pursued through good design and management of urban green spaces. Our results suggest that site-specific preferences and practices might have adverse effects in UES delivery. Therefore, before setting planning and management targets, it is critical to acknowledge local patterns of UES provision, and features or drivers determining such patterns. Fostering awareness about how local human action might hinder or boost UES provision is probably one powerful way to substantially increase urban resilience.

If the ES framework is to be effectively implemented in urban issues, UES research should focus more on the effect of specific variables at the local scale that contribute to a greater appropriation of the ES framework by urban planners and managers.

The approach developed in this investigation revealed how spatially explicit cold and hotspots of UES provision can emerge from social-ecological patterns. This method also discriminates the structural variables that may be tackled by local administrations at the local scale, and thus provides them with means to effectively incorporate UES enhancement in urban planning, management and design. Methods that capture the full scope of UES should also be developed in future research to help analyze trade-offs between ES and disservices of urban green areas.

Acknowledgments

We are grateful to the Institute of Earth Sciences (University of Porto) for providing precipitation data to run i-Tree Eco v5, and to three anonymous reviewers for their valuable comments. This research was partially funded by the Portuguese Agency for Science and Technology (FCT) through PhD grant of M. Graça SFRH/BD/91028/2012 and PhD grant of J. Gonçalves SFRH/BD/90112/2012, both financed by national funds of the Ministry for Science and Education and by the European Social Fund through POPH – QREN – Tipology 4.1 – Advanced Training.

Appendix A. – Criteria for classification of urban green areas in Porto

- *General notes*

Green areas of Porto were classified adapting an existing survey and criteria from Farinha-Marques et al. (2011, 2012), in order to obtain a spatially explicit representation of the main categories found in the city. The original survey contained 16 classes of green spaces (Table A1), but for this investigation two of these were considered not green, because they do not contain vegetation. This was the case for *Beaches & Coastal Area* and for *Margins of Rio Douro*, which consisted in sandy areas, rocks and retention walls. The remaining 14 classes were clustered into 8 categories (Table A1).

The final classification of green spaces was validated and corrected using field data and photo-interpretation of 1500 randomly distributed points across Porto.

For this investigation, the following conditions were observed:

- Photo-interpretation and classification was only carried out for continuous green spaces greater than 800 m^2 at a spatial scale equal to 1:2500; clusters of adjacent smaller green spaces (e.g. backyards of residential areas) totaling the required threshold area were also considered;
- Streets were considered green corridors if they contained 3 or more street trees aligned in at least one of the sidewalks, visible at scale 1:1500, framed by the facade of nearby buildings or by the outer limit of tree crowns, and by the outer limit of the driving lane immediately next to the sidewalk where trees were planted (as such, if a street had 2 lanes and trees planted in both sidewalks, the whole driving corridor was considered a green area); in streets with more than 2 driving lanes, all lanes covered by tree crowns were included in the green corridor. The ends of the

Table A1
Typologies and criteria for the classification of urban green areas in Porto into eight classes, resulting from clustering a broader set of classes used in a survey by Farinha-Marques et al. (2011, 2012). Criteria were adapted for research purposes.

Categories in original survey	Clustered categories	Specific Criteria for classification
Agricultural areas	*Agricultural areas*	Active continuous agricultural areas greater than 2000 m^2; smaller areas were considered private gardens & backyards
Allotments & urbanizations	*Allotments & urbanizations*	Green areas associated with multi-residential buildings, generally publicly accessible
Civic & institutional	*Civic & institutional*	Green spaces associated with institutional buildings or lots
Motorways *Tree-lined streets*	*Motorways & tree-lined streets*	Green corridors associated with motorways and tree-lined streets, including green separators and roundabouts
Private gardens *Backyards*	*Private gardens & backyards*	Private green areas with restricted access, associated with single-family housing or inside residential blocks
Woodlands *Public parks & gardens*	*Woodlands, parks & gardens*	Woodlands consisting in continuous green areas with high tree density (roughly 70%), greater than 2000 m^2, with no explicit spatial arrangement and not included in public parks or private gardens; public parks and gardens comprising designed areas publicly accessible with at least 35% of vegetation cover in permeable soil
Vacant lots & wasteland	*Vacant lots & wasteland*	Public or private permeable unbuilt areas with no evident use, usually covered with ruderal vegetation or in early stages of ecological succession
Watercourses *Cemeteries* *Squares* *Scarps*	*Other green spaces*	Vegetated margins and water bodies associated with watercourses; green spaces with slopes higher than 45°; squares with vegetation cover greater than 35%; cemeteries

corridor were defined by the insertion of stems of the trees located at the extremities, to which a measure equal to that tree's crown was added. If trees were planted in a traffic green separator narrower than the adjacent lanes, the green corridor included both lanes; if the separator was larger and tree crowns did not cover the driving lanes, only the former was considered green area;

- Permeable playing fields were considered green spaces if they had the minimum threshold area of 800 m^2 or if they were contained in larger green areas.

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