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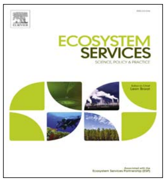

# Assessing mismatches in ecosystem services proficiency across the urban fabric of Porto (Portugal): The influence of structural and socioeconomic variables

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## 1. Introduction

According to UN estimates, it is expected that the world population living in cities will exceed 66% in 2050 (United Nations, 2014). The complex and intense interaction of ecological and socioeconomic systems shaping cities has highlighted the need to foster an interdisciplinary approach to urban issues integrating Natural and Social Sciences (Alberti et al., 2003). Recent research has also stressed the role of urban ecosystems in providing vital services to city dwellers, and the need to embody ecosystem services in urban planning practice (Ahern et al., 2014; Colding, 2011). Ecosystem services (ES) has come to light as one of the most widespread concepts of Ecology in recent years, and refers to the benefits human populations derive from ecosystems (MEA, 2005). Research on ES and the socio-ecological factors that influence their proficiency is essential to allow cities to adopt policies that lead to resource-efficient strategies (Andersson et al., 2007) and greater resilience, which supports ecological, economic and social sustainability (Berkes et al., 2003; McPhearson et al., 2015). Some benefits generated by ecosystems need to be delivered locally to be enjoyed by city inhabitants, such as clean air, runoff regulation, microclimate regulation, erosion control, storm protection and recreation. Urban green areas provide a wide range of these local ecosystem services and thus become very important to sustain human wellbeing in cities (Bolund and Hunhammar, 1999). However, many obstacles prevent ES from being widely operational in urban planning practice. Studies and assessments of urban ES many times lack operability for professionals and planners because they are not developed at a scale relevant for planning and policy decisions (Hölzinger et al., 2014) or do not address the transfer of knowledge and methods in an accessible way to stakeholders, thus providing limited clues for planning and management (Haase et al., 2014). In addition, key concepts remain controversial (Fisher et al., 2009; Hermann et al., 2011), and the lack of consistent methodologies for quantifying, visualizing and valuing ES poses challenges (Seppelt et al., 2011).

Urban ecosystems differ from other ecosystems because they are intensely dominated by human beings, being characterized by high fragmentation and heterogeneity levels. They raise additional questions to researchers and are still poorly understood compared with other types of ecosystems (Gomez-Baggethun and Barton, 2013). Services such as air filtration, thermal regulation, contribution to the perception of the urban environment, sense of place or social cohesion are difficult to assess, and knowledge about the local ES delivery is frequently

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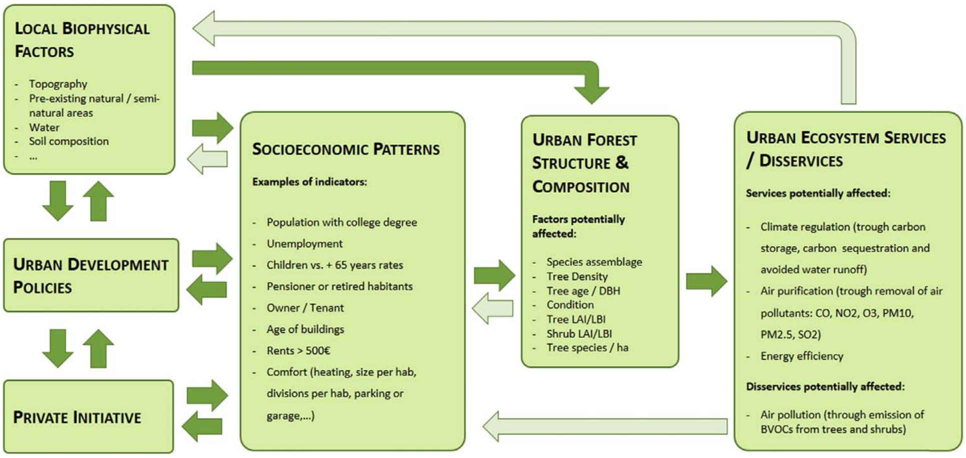

**Fig. 1.** Conceptual framework underlying the impact of socioeconomic patterns in shaping differently the urban forest structure across the urban fabric, thus affecting spatially ecosystem services proficiency. Dark green arrows highlight relationships predominantly direct, and light green stresses connections assumed to be more indirect among components of the framework. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

scarce or not suitable for planners. This knowledge should inform the setting of goals before urban interventions, but usually it cannot be generated within the traditional timeframe of project planning due to time and resource constraints. Because of such difficulties, the structural or functional aspects that sustain urban ES are usually not taken into account in an objective way in the planning and design process, particularly regarding green spaces. Recent investigations suggest a relationship between type and management of green areas and ES provided (Andersson et al., 2007), and that variation in the abundance and layout of vegetation in different types of urban green spaces originates differences in ES delivered (Hayek et al., 2010). There is also evidence of relationships between plant functional diversity and ecosystem processes (Díaz and Cabido, 2001). However, properties like functional redundancy of species are not traditionally taken into account in professional practice regarding planning, design and management of urban green spaces. In addition, biodiversity in green spaces may affect the provision of many services that affect the health and wellbeing of city dwellers, but it is many times seen as having little impact in the urban context, and providing few direct and essential benefits for human beings (Ahern, 2013). Even promoting biodiversity *per se* raises questions about how this can be accomplished, because emerging evidence is revealing that, for example, species richness alone probably does not drive ecosystem function (Cadotte et al., 2011).

Delivery of ES is also greatly determined by socioeconomic factors and reflects urban patterns. Examples include dissimilarities of provision of urban green spaces by demographic variables like immigrant status and age (Kabisch and Haase, 2014), relationships between public urban forest structure and socioeconomic strata (Escobedo et al., 2006), increased exposure towards urban flooding according to indices of social segregation (Romero et al., 2012), spatial variation in urban plant diversity across low to high-income areas (Hope et al., 2003), inequity in the spatial distribution of public right-of-way street trees (Landry and Chakraborty, 2009) and the impact of lifestyle behavior and housing characteristics in species composition and configuration (Grove et al., 2006). However, to our knowledge these findings have seldom been translated into objective guidelines that can help to inform planning and design practice.

All these considerations could mean that it is not enough to include green areas in urban settings, without addressing their specific characteristics and ability to sustain the well-being of city's inhabitants. Urban green areas can be designed to contribute for the provision of specific ES such as microclimate regulation (Jenerette et al., 2011), mental wellbeing (Kuo, 2001), physical and psychological health (Lachowycz and Jones, 2013), water quality control and storm protection (Windhager et al., 2010), just to name a few.

As one of the matrix elements of urban ecological structure, vegetation may play a major role in promoting ES proficiency through planting design. Although a few examples have explicitly applied the ES approach to urban planting design (Hayek et al., 2010; Hunter, 2011) or to urban forestry (Morani et al., 2011), these are very recent and still emerging. To our knowledge, very few studies address how composition and configuration of urban vegetation might enhance ES proficiency, though this need has been identified (James et al., 2009). It is also important to better understand the relationships between ES and socioeconomic factors, because these can impact urban ecosystems. Acknowledging these topics can provide useful insights to urban planning, planting design and management.

This paper addresses the heterogeneity of urban ES proficiency, and aims to:

- test a conceptual framework relating socioeconomic urban patterns and the shaping of the urban forest structure;
- present a methodology to investigate associations between socioeconomic indicators and structural variables of the urban forest;
- investigate which structural variables of the urban forest, if any, differ along a socioeconomic gradient, to objectively set planning and management goals and contribute to the effective implementation of the ES approach in urban issues.

The city of Porto (located in mainland NW Portugal) is used as a case study, but the methodology can be adapted to other geographical locations and contexts to provide information easily usable by stakeholders and practitioners with responsibilities regarding urban planning and management.

## 2. Methods

A conceptual framework was developed to underlie the impact of socioeconomic patterns in shaping the urban forest structure across the urban fabric, thus affecting spatially ecosystem services proficiency (Fig. 1).

This investigation was developed in two phases, with methods and objectives built upon this framework. The first phase aimed to measure the patterns of delivery of some regulating ES provided by trees and shrubs across the city of Porto, using the i-Tree Eco tool to reveal the heterogeneity of ES proficiency in the urban forest (defined here as the relative ability of trees and shrubs to deliver ES). The second phase consisted of a statistical analysis conducted to investigate potential associations between the urban patterns of ES delivery and socioeconomic indicators, and also to find which structural variables of the urban forest of Porto are more associated with the proficiency of regulating ES. Multimodel inference over one set of generalized linear models was used to analyze associations with socioeconomic indicators, and generalized additive models were developed to investigate relations between structural variables and ES proficiency.

### *2.1. Study-area description*

This research was developed within the municipal boundaries of Porto, the second largest Portuguese city.

Porto is located in the northwest of Portugal, facing the Atlantic Ocean at west and Douro River at south and covers 41.42 km$^2$.

The city is the center of a metropolitan area composed by 17 municipalities adding up to about 1,759,524 inhabitants (INE, 2014) and is currently structured in 7 parishes. Porto has a Mediterranean type climate (Csb climate, according to Köppen-Geiger classification) with winter temperatures usually between 5.0 and 16.8 °C, rarely stepping below 0 °C, and summer temperatures typically between 13.8 and 25.0 °C (but reaching sometimes 36.0 °C or even more); annual precipitation averages 1254 mm usually concentrated between October to March (IM, 2011).

During the late 19th century green spaces totalized about 75% of the city. However, after a century of intense urbanization, in 2000 the green areas amounted to less than 30% of the city and were characterized by high levels of fragmentation and discontinuity (Madureira et al., 2011).

### *2.2. Ecosystem services estimation, sampling design and field protocol*

i-Tree Eco was used to characterize Porto's urban forest structure and to estimate carbon sequestration, pollution removal (of CO, $NO_2$, $O_3$, $PM_{10}$, $PM_{2.5}$ and $SO_2$), avoided runoff, energy effects in residential buildings and emission of biogenic volatile organic compounds (BVOCs) by trees and shrubs. i-Tree (www.itreetools.org) is a peer-reviewed software suite developed by the USDA Forest Service and cooperators to analyze the urban forest and the benefits it provides to communities. i-Tree Eco was originated from the Urban Forest Effects Model UFORE, and requires field data from complete inventories or sample plots, hourly pollution and meteorological information to produce outputs. It provides an extensive characterization of the whole urban forest using a bottom-up approach, as described in Nowak et al. (2008a) along with methods to estimate its structure and benefits.

Following guidelines for plot number and size determination (Nowak et al., 2008b), a set of 255 plots with 404.7 m$^2$ each (radius=11.35 m) was set up to obtain field data for the city of Porto (Fig. 2).

A pre-stratification scheme was delimited to assign these plots, with the purpose of obtaining more data to investigate potential differences and causes behind ecosystem services proficiency in green areas among the parish strata. A limit of 10 strata was set to avoid analysis issues during i-Tree Eco data processing, and to ensure that each stratum analyzed contained at least 20 plots. More strata would oblige to allocate more time and resources to collect data, which was not feasible for this research. The pre-stratification consisted in grouping the 7 parishes of Porto into 5 groups of similar socioeconomic and urban characteristics, obtained using variables derived from the 2011 Census database (INE, 2011), a preliminary analysis of other urban and socioeconomic available data and the author's knowledge of the study area. Each of the 5 groups was then subdivided into a GREEN layer, adapted from a survey from Farinha-Marques et al. (2011), and a GREY layer. GREEN refers to the main green structure of the city, and includes diverse areas such as public and private parks and gardens, green spaces from allotments and urbanizations, tree lined streets and motorway's green strips, wasteland, vacant lots and agricultural areas. GREY refers to the remaining area, consisting of mainly impermeable and densely built areas punctuated by very small green patches and isolated trees. This pre-stratification scheme resulted in 10 strata, which are mapped in Fig. 2. The 255 plots were assigned to the area of each of the five parish groups, totaling 70% in the green strata and 30% in the grey strata, to ensure that the biggest effort in field data collection was targeting green areas (generally with higher amount and diversity in terms of vegetation composition and structure).

Field data were collected for 863 trees and shrub cover during the leaf-on season, between mid-May and mid-September 2014. According to the i-Tree Eco field guidelines, vegetation was recorded as tree when the diameter of trunk or bole at breast height (DBH) is greater than or equal to 2.54 cm.

A total of 19 plots was considered inaccessible due to lack of access authorization, security constraints or high density of wild vegetation in abandoned areas. In this last case, field teams could not access the interior of green masses to collect data. To address the lack of data for dense vegetation areas, these were removed from the analysis of Porto. The area of dense vegetation in Porto was calculated using photo-interpretation of 1,500 random points within the city limits using i-Tree Canopy. Inaccessible areas due to high density of vegetation totaled about 1.2% of the total city area.

Local hourly pollution and weather data were input into the i-Tree Eco model. Hourly air concentrations for $NO_2$, $SO_2$, CO, $O_3$, $PM_{10}$ and $PM_{2.5}$ for 2010 and 2011 were retrieved from the national online database QualAR provided by the Environment Portuguese Agency, for the station of *Sobreiras – Lordelo do Ouro*, which is the background

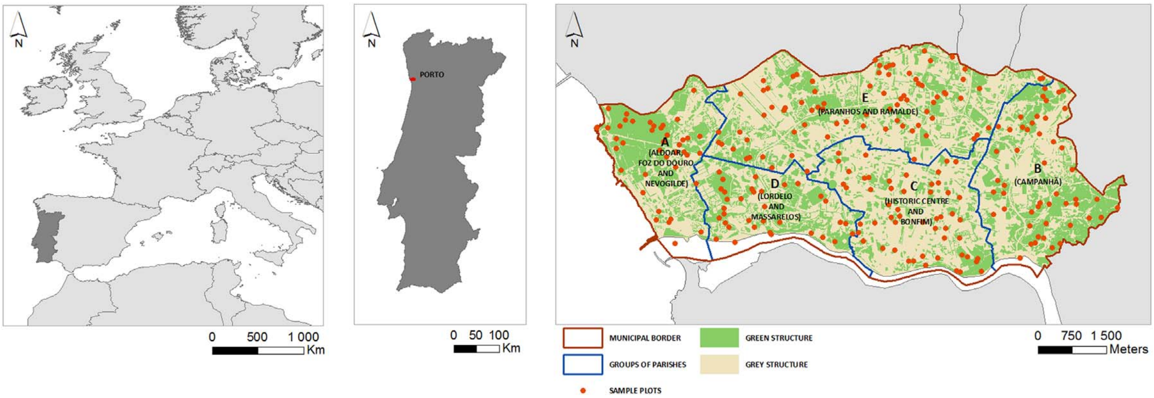

**Fig. 2.** Location of the study area (left and center) and pre-stratification scheme used in this investigation for sampling design (right). The green infrastructure was used to subdivide each parish group in two layers: GREEN refers to refers to the main green structure of the city (e.g. parks and gardens, tree lined streets and motorway's green strips, wasteland, agricultural areas, …); GREY refers to the remaining area (mainly impermeable and densely built areas punctuated by very small green patches and isolated trees). The capital letters A, B, C, D and E are the short names used to refer parish strata in text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

station collecting data for Porto (APA, n.d.). Hourly weather data for Porto (2010 and 2011) was retrieved from the National Climatic Data Center (www.ncdc.noaa.gov) except precipitation, which was collected in a weather station placed on the roof of the Faculty of Sciences of the University of Porto building (41°11'N, 8°39' W; height: 20 m).

The impact of trees on energy use for residential buildings is estimated in i-Tree Eco using U.S. parameters. For this reason, the energy component of i-Tree Eco was adapted to local parameters for Porto, by adjusting values for frost free length, home vintage percentages, primary energy use per type of fuel in residential buildings, energy use in residential buildings for heating, and emission factors for electricity, natural gas and liquefied petroleum gas. The US climate region equivalent chosen for Porto was California Coast.

As i-Tree Eco provides a more exhaustive characterization of tree variables compared to shrubs, only tree data was used in the statistical analysis for this investigation. However, ES estimates presented in the results section also include the contribution of shrubs.

### *2.3. Modelling the association of structural variables of the urban forest and socioeconomic indicators*

Socioeconomic variables used for this analysis were selected from the 2011 national census database, after determining which ones accounted for potentially significant differences between parish strata. To assess relationships between structural and socioeconomic variables (dependent and independent variables, respectively) at parish strata level, Spearman correlation coefficients were calculated between the best available socioeconomic variables, and four of them (the least correlated) were selected to represent four different dimensions of socioeconomic patterns: i) Population with college degree; ii) Population age; iii) Time of construction of buildings; and, iv) Building owners vs. tenant percentages (Table 1).

The structural variables selected were: DBH; tree density; total tree leaf area (TLA), total tree leaf biomass (TLB), tree species density, Simpson's index and tree condition (7 classes ranging from Dead to Excellent). As DBH and tree condition are categorical variables with many classes, only the class having greater Spearman correlation with socioeconomic variables was used to represent each of these two variables. Simpson's index is an indicator of species dominance. i-Tree Eco calculates Simpson's inverse index, which is not a normalized value, and therefore cannot be used to compare different strata. For this research, the complement of Simpson's index was used, corresponding to the probability that any two individuals drawn at random from a finite community belong to different species. Thus, greater values correspond to higher diversity (Magurran, 2004).

Generalized linear models (GLM) were developed to relate each structural variable with the set of socioeconomic variables. GLM are an extension of linear models which allow for non-linearity and non-constant variance structures in data, and thus provide more flexibility to analyze ecological relationships (Guisan et al., 2002).

Each of the five parish strata was disaggregated into their respective GREEN and GREY substrata to increase the number of case units to ten. For each structural variable, four univariate models for each socioeconomic variable were developed; a second set of four models per structural variable was also considered, including the interaction between socioeconomic variables and the type of substrata (GREEN or GREY) thus allowing to separate the effects of socioeconomic conditions for each sub-stratum.

### *2.4. Modelling the association of the urban forest structure and ES proficiency*

The second goal of the statistical analysis was to find which structural variables of the urban forest of Porto are associated with the proficiency of ES. For this purpose, a set of Generalized Additive Models (GAM) was built. Several ES were considered the response and

**Table 1**
Socioeconomic indicators of parish groups of Porto.

| Parish strata | Area | | Number of dwellings | | 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* (A) | 627 | 15,1 | 11 280 | 11,4 | 64,5 | 27,7 | 20,1 | 36,9 | 13,8 | 21,4 | 31,9 |
| *Campanhã* (B) | 804 | 19,4 | 12 763 | 12,9 | 36,2 | 56,4 | 48,9 | 13,8 | 12,3 | 23,0 | 8,8 |
| *Historic Center and Bonfim* (C) | 853 | 20,6 | 28 944 | 29,3 | 42,1 | 51,4 | 51,6 | 11,4 | 9,8 | 27,0 | 21,8 |
| *Lordelo and Massarelos* (D) | 559 | 13,5 | 11 536 | 11,7 | 52,3 | 40,5 | 32,4 | 19,3 | 13,3 | 20,7 | 26,6 |
| *Paranhos and Ramalde* (E) | 1 299 | 31,4 | 34 146 | 34,6 | 54,4 | 39,3 | 29,7 | 16,5 | 12,4 | 21,8 | 23,2 |
| City Total | 4 142 | 100,0 | 98 669 | 100,0 | 49,3 | 43,9 | 39,7 | 16,8 | 11,9 | 23,2 | 22,3 |

[a] Variables used for GLM multimodel inference (Section 2.3).

**Table 2**
Comparison of i-Tree Eco results for several cities across the world.

| City | Country | Total study area (ha)[*] | Tree Cover (%) | Number of trees | Trees/ha | Source |
|---|---|---|---|---|---|---|
| **PORTO** | Portugal | 4,091 | 10.6 | 281,359 | 68.8 | |
| **New York** | USA | 78,949[a] | 21.0 | 5,212,000 | 65.2[1] | Nowak et al. (2007); [a] DCPNY (n.d.) |
| **Toronto** | Canada | 66,140[c] | 26.6[b] | 10,220,000[b] | 160.4[b] | [b] Nowak et al. (2013); [c] PFR (n.d.) |
| **Jersey City** | USA | 3,859[d] | 11.5[1] | 136,000[1] | 35.3[1] | Nowak et al. (2007); [d] CJC (n.d.) |
| **Edinburgh** | UK | 11,468[e] | 17.0 [e] | 638,000[e] | 56.0 [f] | [e] Hutchings et al. (2012)<br>[f] Rumble et al. (2015) |
| **Glasgow** | UK | 17,643 | 15.0 | 20,000,000 | 112 | Rumble et al. (2015) |
| **Wrexham** | UK | 3,833[2] | 17.0 | 364,000 | 95 | Rumble et al. (2014) |
| **Torbay** | UK | 6,375[g] | 11.8[g] | 818,000[g] | 105.0[f] | [f] Rumble et al. (2015); [g] Rogers et al. (2011) |
| **Barcelona** | Spain | 10,121 | 25.2 | 1,419,823 | 141 | Chaparro and Terradas (2009) |
| **Berlin** | Germany | 89,110 | 42.7 | – | – | Baró et al. (2015) |
| **Rotterdam** | Netherlands | 27,740 | 12.2 | – | – | Baró et al. (2015) |
| **Salzburg** | Austria | 6,570 | 28.6 | – | – | Baró et al. (2015) |
| **Stockholm** | Sweden | 21,580 | 37.5 | – | – | Baró et al. (2015) |

[*] Refers to total analyzed area in study, except New York, Toronto and Jersey City. In these cases there was no information available, and total study area was assumed to match the city official limits.

[1] Information provided automatically by i-Tree Eco software.

[2] Neighboring cities were also considered in this case study.

the structural variables were the explanatory variables. GAM are data-driven rather than model-driven, which means that the fitted values do not come from a model previously assumed (Yee and Mitchell, 1991). They are more suitable for data exploration and dealing with highly non-linear relationships between the response and explanatory variables (Guisan et al., 2002). Each model related one single response variable (ES) to one explanatory (structural variable), and no interaction effects were considered. Case units corresponded to single tree species in a given GREEN or GREY strata per parish level, totalizing 264 cases. Tree species was a categorical variable with 148 levels in this case. To facilitate modelling, it was converted to a quantitative variable using a “shading factor” as proxy. This factor is used in i-Tree Eco to adjust calculations taking into account the fact that some species have denser canopies than others, which translates into more or less TLA / TLB.

ES considered included stored C and net sequestered C per year. Pollution removal and avoided runoff were also considered, using TLA as a proxy because these ES are estimated in i-Tree Eco through a direct relationship with this variable (Hirabayashi et al., 2011). The selected structural variables were: DBH, tree density, tree condition, shading factor and TLB; TLB was not used as an explanatory for TLA because of the high autocorrelation between these variables.

### *2.5. Model selection and performance evaluation*

The strength of the association between socioeconomic patterns and the urban forest structure, and between the latter and ES proficiency, was assessed in a trifold process. First, GLM and GAM models were compared and ranked using a Multimodel Inference (MMI) framework based on Akaike Information Criterion with a correction for small sample sizes (AICc) (Burnham et al., 2011). AICc provides a measure that allows comparison of different models, inference about how confident we can be that a given model is the best approximation to reality, and accounting for model selection uncertainty (Symonds and Moussalli, 2011). MMI together with AICc allowed to calculate the ΔAICc measure which consists in the difference in AICc values between the best model and each single model. From this, a $\Delta\text{AICc} < 2$ suggests substantial evidence for the model, values between 2 and 4 indicate some support, while ΔAICc values between 4 and 7 indicate that the model has considerably less support and a $\Delta\text{AICc} > 10$ indicates that the model is very unlikely (adapted from Burnham and Anderson (2002)). It is also possible to calculate Akaike weights ($w_i$) which provide an indication of the probability that a given model is the best among the entire set of candidate models which can be translated into a measure of model uncertainty.

This statistical methodology relies on an Information-Theoretic (I-T) approach, which is intrinsically different from methods based on significance testing and model selection based on stepwise or stepdown techniques and presents several advantages for analyzing complex ecological processes (see Burnham et al. (2011) and Garamszegi (2011)).

Secondly, the adjusted R-squared was used to assess the explained variance of each model. Lastly, a Null Model ($M_0$) in which the structural variable under study was always equal to 1was included in the candidate set and compared with the remaining models. The purpose was to test if a nonsense model could provide more incremental explanatory power than GAM or GLM models.

In each of the three steps described above the strength of the associations under study was independently verified, providing additional evidence for inference.

All statistical analyses were conducted in R v.3.1.0 (R Development Core Team, 2014).

## 3. Results

### *3.1. Global results at city level*

Porto was found to have a considerably low tree cover (10.6%) and tree density (68 trees ha$^{-1}$) comparably to most cities reported in Table 2. About 57% of all trees had DBH less than 15.2 cm, and about 19% were between 15.3 cm and 25.4 cm.

Only 13 sampled specimens were considered to have impact in energy efficiency of residential dwellings, meaning they were at least 5.5 m height and closer than 18.28 m to construction (adapted from McPherson and Simpson (1999)). This small sample size limited the estimation of energy use impact at city level and comparison between groups of parishes, but revealed that not many trees in Porto are in energy-affecting positions around buildings. Still, the estimated overall impact in the city based on this small sample was an increase in energy use and costs due to tree positions around residential buildings.

*Quercus robur* was the most common tree species (5.3% of all estimated trees), followed by *Populus nigra* (4.2%) and *Quercus suber* (3.9%). This is surprising because these species are not typically planted in the city, nor are they abundant in public green areas. They are very common in vacant lots, given their spontaneous nature. However, many times they do not reach mature age because of land use changes.

The species contributing the most to the total TLA of the city were the ornamental trees *Platanus x acerifolia* (9.7%) and *Acer negundo* (6.8%), even though their total population was not very high (respectively 1.9% and 2.4%). *Quercus robur* accounted only for 3.5% of the total TLA.

### 3.2. Results at parish level

The selected socioeconomic indicators revealed that western and southwestern parish groups ("*A*" and "*D*") had a higher proportion of population with college degree and young residents (age ≤14 years); they also corresponded to areas of more recent construction, where more than half of the dwellings were owned by their occupants. The eastern parish ("*B*"), on the other side, had the lowest proportion of residents with college degree and of dwellings owned by their occupants; it also had a low rate of recent construction, even though this area of the city does not lack space availability, as is the case in the dense city center ("*C*"). These results suggest that "A" and "D" are wealthier parish groups, and "B" is the most deprived one; the remaining two parish groups ("*C*" and "*E*") had intermediate wealth conditions (Table 1).

In terms of urban forest structure, emphasis was placed in the comparison of the five GREEN substrata results because these were obtained from much more field information, collected mostly in green area, which was considered to yield the highest amount of regulating ES provided by vegetation (Table 3).

The wealthy parishes revealed much better results for tree density than the rest of the groups (Fig. 3).

Stratum "*B*" stood out as the parish with fewer trees. However, in most structural indicators (tree species density, TLA, TLB and DBH composition) one of the wealthy parish groups ("*A*") did not perform as expected, showing results sometimes below both intermediate parish groups (Table 3 and Fig. 4).

In the case of DBH composition, it was expected that parish groups with higher proportions of trees with low diameters (in classes 0–12.7 and 12.8–25.4 cm) would have lower TLA and TLB per tree. Stratum "*B*" had the lowest diversity of species, composed mainly of autochthonous species and others with agricultural value, and the lowest Simpson's index value, revealing higher dominance effect of some species than in other strata. On the opposite side, the wealthier parishes had higher prevalence of ornamental species typical of gardens and parks. In the intermediate parish groups, the most striking result was the clear dominance of *Acacia melanoxylon*, listed as an invasive species by the Portuguese legislation. Strata "A" and "E" had the highest values for Simpson index, reflecting less dominance of species. The most deprived parish consistently revealed poor results in structural variables when compared with the remaining parishes, and the same overall pattern of results was maintained when analyzing ES results. For climate regulation (considering stored C, net sequestered C and avoided runoff) and air purification through pollution removal, the wealthy parish group "*D*" always presented the highest results, while "*B*" always showed the worst performance (Table 3, Figs. 5 and 6).

The other 3 parish groups had similar performances, though the two intermediate-wealthy parish groups had better results than the wealthy parish group "*A*". In any case, stratum "*C*" always presented better results than "*A*" and "*E*".

Parish groups with less TLB had lower BVOC emission density and thus were less affected by the potentially negative impact of BVOC emissions (Fig. 7).

However, it should be noted that many of the dominant tree species found in Porto are high BVOC-emitters, such as *Quercus robur* (Donovan et al., 2005), *Platanus x acerifolia* (Aydin et al., 2014), *Liquidambar styraciflua* (Benjamin et al., 1996) and *Populus nigra* (Owen et al., 2001).

### 3.3. Relation between the urban forest structure and socioeconomic indicators

Model selection based on AICc and GLM revealed a strong support for associations between socioeconomic and all structural variables considered, as shown by the ΔAICc ranking presented in Table 4 (models with the strongest support had the lowest ΔAICc value of 0.00, and generally higher adjusted R-squared values).

The performance of the Null Model ($M_{0)}$ further reinforced this observation, since it was consistently ranked below models including socioeconomic variables. Some of the structural variables revealed stronger associations for models considering the interaction between socioeconomic variables and the type of substrata (GREEN or GREY). This was the case for tree density, for which the best explanatory model was $M_{B2i}$, which considered the interaction between "Population with College Degree" and "Type of substratum" as explanatory. The same applied to TLA (best model: $M_{D2i}$), TLB (best model: $M_{E2i}$) and tree species per hectare (best model: $M_{F2i}$), all revealing that "Population with College Degree" and "Type of substratum" yielded the maximum explanatory power for the response considered. The best model for Simpson's index ($M_{G4i}$) was sensitive to the interaction between the type of Subtrata, and the variable "Built until 1945", considered in the socioeconomic dimension of "Time of construction of buildings" referred in Section 2.3. DBH and tree condition were less benefited in terms of model performance by the inclusion of the interaction term, as revealed by the ΔAICc ranking. For DBH, the best model was $M_{A1}$, with only "Owner or co-owner" as explanatory variable (which was considered in the socioeconomic dimension of "Building owners vs. tenant percentages"), followed at a short distance by "Built until 1945". Tree condition revealed a stronger association with "Building time between 1981 and 2011".

### 3.4. Relation between structural variables of the urban forest and ES proficiency

Tree DBH was the structural variable with the highest support for explaining climate regulation through Stored C (ΔAICc=0.00, $R^2$ adjusted=0.72). However, for C Net Sequestration the TLB variable recorded by far the strongest predictive support (ΔAICc=0.00, $R^2$ adjusted=0.46). TLA was used as a proxy to assess both air purification through removal of air pollutants and also climate regulation through avoided water runoff. In this case again, Tree DBH was the variable with the strongest explanatory power (ΔAICc=0.00, $R^2$ adjusted =0.51). TLA was used as a response variable only, and TLB as explanatory just for the other response variables. Otherwise, it is expected that TLA would have similar results to TLB in terms of impact in ES proficiency, because these variables were highly correlated. For all the four ES analyzed through model selection based on AICc using GAM, the Null model was the one with higher values of ΔAIC (between 157.12 and 325.87), thus revealing no support among all the response variables in the candidate set (Table 5).

Results suggest that tree DBH and TLB are of major importance to the proficiency of ES provided by urban trees in Porto, and that tree density has a moderate effect in C Net Sequestration (ΔAICc >10 but reasonable adjusted R-squared value), to low impact in the other response variables analyzed (ΔAICc >100 and low adjusted R-squared value). Shading Factor (used as a proxy to analyze species effects) emerged as having very low impact in proficiency of regulating ES in Porto, thus suggesting that tree DBH and leaf biomass have a much more important role than the type of species.

## 4. Discussion

Overall, results from GLM and MMI analyses revealed a strong association between spatial patterns of wealth and structural variables of Porto's urban forest, highlighted by better indicator values in the western and southwestern parish groups, and the poorest values in the less wealthy stratum "*B*". Some structural variables emerged as being also dependent of the type of substratum considered for data collection. This was the case for tree density, TLA, TLB and tree species per

**Table 3**
I-Tree Eco results for GREEN and GREY strata per parish group. GREEN refers to the main green structure of the city and GREY to the remaining area.

| Parish group*Name* (stratum id) | Sub-stratum | Stratum area in each parish (%) | Trees (n ha$^{-1}$) | Tree species (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 abundance (n ha$^{1}$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Species | n ha$^{-1}$ |
| *Aldoar, Foz do Douro and Nevogilde*(A) | GREEN | 45.82 | 190.0 | 41.0 | 0.95 | 14,041.1 | 1,239.2 | 16,299.2 | 627.4 | *Pittosporum tobira Populus nigra Arbutus unedo* | 20.5 15.9 15.9 |
| | GREY | 54.18 | 27.6 | 25.1 | 0.98 | 1,120.2 | 94.2 | 3,029.2 | 165.1 | *Eriobotrya japonica Castanea sativa Citrus sinensis* | 5.0 2.5 2.5 |
| *Campanhã*(B) | GREEN | 46.80 | 97.1 | 23.0 | 0.87 | 3,837.7 | 455.7 | 7,093.6 | 309.6 | *Quercus robur Quercus suber Actinidia deliciosa* | 29.2 14.6 7.3 |
| | GREY | 53.20 | 30.2 | 10.8 | 0.50 | 490.7 | 73.8 | 426.8 | 65.1 | *Cupressus sempervirens 'Stricta' Abies nordmanniana Citrus lemon* | 21.6 2.2 2.2 |
| *Historic Center and Bonfim*(C) | GREEN | 26.05 | 167.5 | 47.1 | 0.92 | 16,226.9 | 1,721.5 | 24,316.1 | 788.6 | *Acacia melanoxylon Magnolia x soulangiana Camellia japonica* | 37.7 22.0 13.6 |
| | GREY | 73.95 | 1.6 | 1.7 | 0.00 | 118.7 | 8.9 | 51.1 | 8.8 | *Ficus carica* | 1.6 |
| *Lordelo and Massarelos*(D) | GREEN | 43.60 | 208.0 | 58.0 | 0.90 | 21,149.4 | 2,129.5 | 40,579.7 | 1,218.4 | *Weigela sp. Populus nigra* 'Italica' *Crataegus laevigata* | 47.5 38.6 13.4 |
| | GREY | 56.40 | 7.6 | 5.1 | 0.67 | 1,402.3 | 127.9 | 409.8 | 44.6 | *Acer negundo Prunus lusitanica* | 5.1 2.5 |
| *Paranhos and Ramalde*(E) | GREEN | 35.76 | 133.4 | 41.6 | 0.97 | 15,339.0 | 1,153.6 | 21,030.2 | 786.9 | *Populus nigra Quercus suber Platanus x acerifolia* | 11.8 10.5 8.7 |
| | GREY | 64.24 | 31.1 | 18.2 | 0.90 | 1,580.5 | 104.9 | 2,716.4 | 179.2 | *Pyracantha coccinea Nerium oleander Acer negundo* | 9.1 5.2 2.6 |
| City Total | | | 68.8 | 4.3 | | 5,307.6 | 486.3 | 8,100.7 | 315.9 | *Quercus robur Populus nigra Quercus suber* | 3.7 2.9 2.7 |

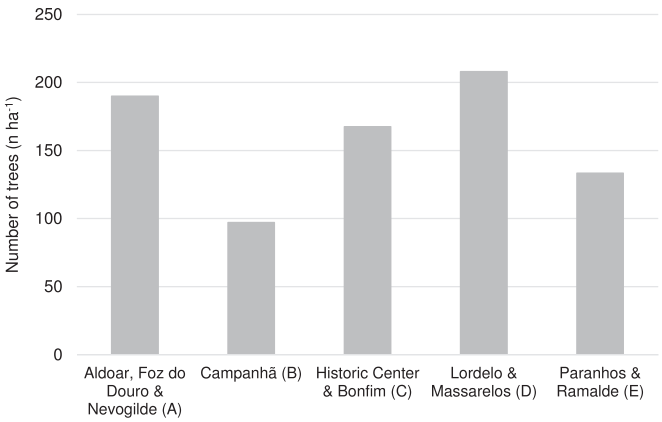

**Fig. 3.** Tree density in GREEN strata, according to parish groups in Porto.

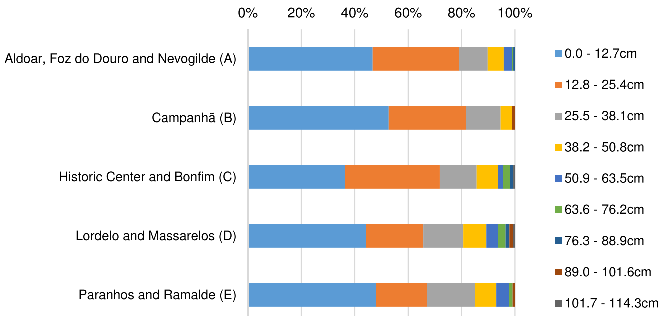

**Fig. 4.** Composition of tree population in GREEN strata according to Diameter at Breast Height (DBH) class, per parish group of Porto. The smallest trees (class 0.0–12.7 cm) account for the higher proportion of trees in all parish groups. (For interpretation of the references to color in this artwork, the reader is referred to the web version of the article).

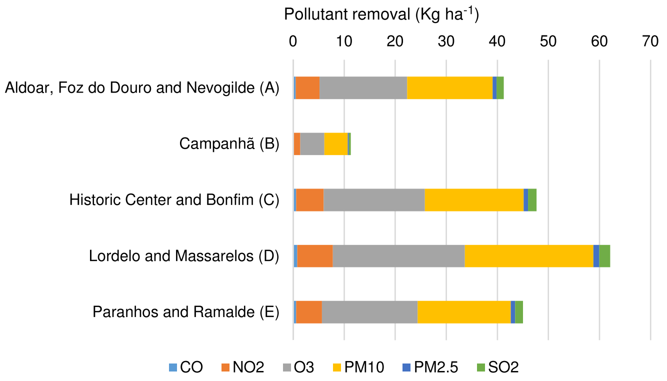

**Fig. 5.** Mean pollution removal for trees and shrubs in GREEN strata, per parish group in Porto (for 2011). (For interpretation of the references to color in this artwork, the reader is referred to the web version of the article).

hectare, which were naturally much higher in GREEN substrata, where the highest proportion of trees was expected. It was also the case for Simpson's index, because GREEN substrata had generally more diversity than GREY substrata. DBH and tree condition are less dependent of tree quantity, and thus were not very affected by substratum type.

GAM analysis revealed that the variables with highest impact in the proficiency of the four regulation ES analyzed for Porto were tree DBH and tree biomass, surpassing by far tree density and the effect of the type of species (in terms of compactness of canopy). As in Porto about two quarters of the trees were found to have a low DBH (below 25.4 cm), these results suggest that it is very important for ES proficiency to allow trees to develop to full size. In addition, severely pruned trees are common in this city and TLA/TLB were low in many sampled specimens with high DBH, suggesting that tree density or high DBH only do not compensate low TLB for C net sequestration.

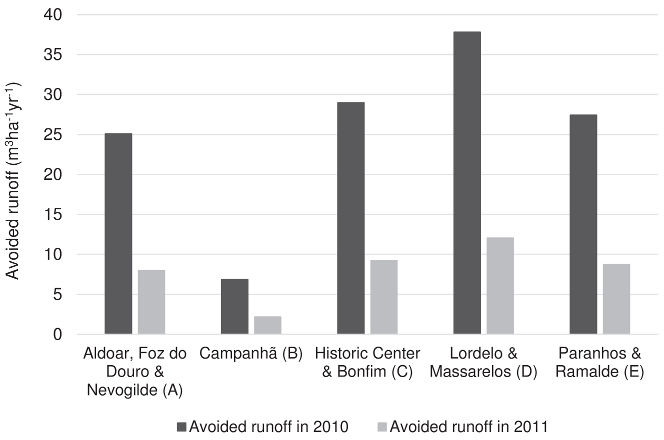

**Fig. 6.** Comparison of avoided runoff in 2010 and 2011 for trees and shrubs in GREEN strata, per parish group in Porto.

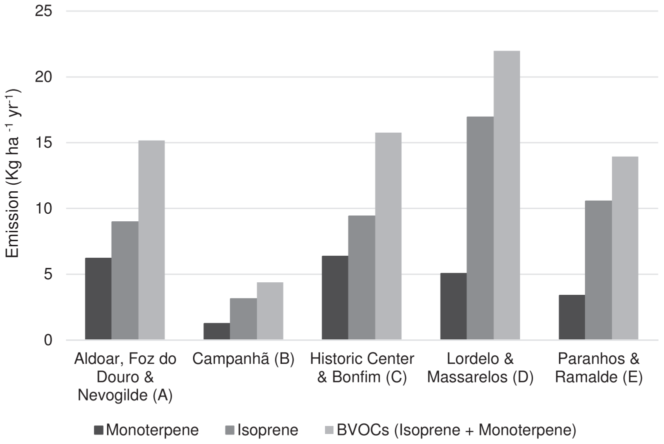

**Fig. 7.** Emissions of Biogenic Volatile Organic Compounds (BVOCs) for trees and shrubs in GREEN strata, per parish group in Porto.

Inadequate species selection and inappropriate planting location were probably the most relevant factors that prevented trees to grow to full extent. This had a clear impact in ES proficiency, as shown with energy efficiency results.

The civil parish of "*Campanhã*" (stratum "B") is usually considered by Porto's inhabitants and stakeholders as the greenest of Porto. This is due to its yet rural character, that survived the overwhelming urbanization of the city during the last century (Madureira et al., 2011). However, results from this research showed that "*B*" had by far the lowest tree density, highest rate of trees with low DBH, higher dominance effect of some species and lower ES proficiency in its green stratum, even though it had the highest proportion of green areas (46.80%; see Table 3).

Interestingly, the green stratum "*A*" had the second highest tree density and proportion of green areas in parish, but this was not accompanied by results in ES proficiency. The two parish groups with intermediate socioeconomic indicators (strata "C" and "E") had higher densities of stored C, net C sequestration, pollution removal and avoided runoff, especially "*C*". Stratum "*C*" is historically the oldest area of Porto, and this was reflected by DBH composition of trees, which showed the lowest proportion of trees with DBH < 12.7 cm. "*A*" is much more recent in terms of construction age (Table 1), and had the second highest proportion of trees with DBH < 25.4 cm (about 79%). These findings suggest that average building age is an important indicator of ES proficiency in Porto. However, stratum "*A*" had a considerable number of new green areas with very young trees in public spaces that are expected to develop in the coming years, and thus they

**Table 4**
Comparison of models used in GLM multimodel inference. Models with a subscript letter *i* include an interaction term with the categorical variable: "Type of substratum" which allows to separate the effect between the GREEN or GREY structure in each parish group. The column "Coef. sign" represents the coefficient signs as: positive ↗, and, negative ↙. For models with interactions terms with "Type of substratum" the first sign (on the left) is for green areas and the second (right side) is for the remaining areas.

| Response | Model | Explanatory (rates, except null) | Coef. sign | k | AICc | Δ AICc | AICc Wt | $R^2$ adjusted |
|---|---|---|---|---|---|---|---|---|
| *DBH* (cm) | $M_{A1}$ | Owner or co-owner | ↗ | 3 | −38.74 | 0.00 | 0.36 | 0.46 |
| | $M_{A4}$ | Built until 1945 | ↙ | 3 | −37.81 | 0.93 | 0.23 | 0.41 |
| | $M_{A2}$ | Pop with college degree | ↗ | 3 | −37.16 | 1.58 | 0.17 | 0.37 |
| | $M_0$ | Null model | ↗ | 2 | −36.84 | 1.91 | 0.14 | – |
| | $M_{A3}$ | Pop with 0–14 yrs | ↗ | 3 | −34.77 | 3.97 | 0.05 | 0.2 |
| | $M_{A1i}$ | Owner or co-owner: Type of substratum | ↗↗ | 4 | −32.98 | 5.76 | 0.02 | 0.47 |
| | $M_{A4i}$ | Built until 1945: Type of substratum | ↙↙ | 4 | −32.74 | 6.00 | 0.02 | 0.46 |
| | $M_{A2i}$ | Pop with college degree: Type of substratum | ↗↗ | 4 | −31.32 | 7.42 | 0.01 | 0.38 |
| | $M_{A3i}$ | Pop with 0–14 yrs: Type of substratum | ↗↗ | 4 | −29.02 | 9.72 | 0.00 | 0.22 |
| *Tree density* ($ha^{-1}$) | $M_{B2i}$ | Pop with college degree: Type of substratum | ↗↙ | 4 | 101.42 | 0.00 | 0.95 | 0.95 |
| | $M_{B1i}$ | Owner or co-owner: Type of substratum | ↗↗ | 4 | 107.65 | 6.23 | 0.04 | 0.90 |
| | $M_{B3i}$ | Pop with and +65 yrs: Type of substratum | ↙↙ | 4 | 112.12 | 10.70 | 0.00 | 0.85 |
| | $M_{B4i}$ | Building time between 1981 and 2011: Type of substratum | ↗↙ | 4 | 114.99 | 13.57 | 0.00 | 0.80 |
| | $M_0$ | Null model | ↗ | 2 | 120.65 | 19.22 | 0.00 | – |
| | $M_{B2}$ | Pop with college degree | ↗ | 3 | 124.48 | 23.06 | 0.00 | 0.04 |
| | $M_{B1}$ | Owner or co-owner | ↗ | 3 | 124.59 | 23.17 | 0.00 | 0.03 |
| | $M_{B4}$ | Building time between 1981 and 2011 | ↗ | 3 | 124.68 | 23.26 | 0.00 | 0.02 |
| | $M_{B3}$ | Pop with and +65 yrs | ↙ | 3 | 124.83 | 23.41 | 0.00 | 0.01 |
| *TLA* ($m^2\ ha^{-1}$) | $M_{D2i}$ | Pop with college degree: Type of substratum | ↗↗ | 4 | 201.42 | 0.00 | 0.93 | 0.89 |
| | $M_{D1i}$ | Owner or co-owner: Type of substratum | ↗↗ | 4 | 207.27 | 5.85 | 0.05 | 0.80 |
| | $M_{D3i}$ | Pop with and +65 yrs: Type of substratum | ↙↙ | 4 | 210.54 | 9.12 | 0.01 | 0.72 |
| | $M_0$ | Null model | ↗ | 2 | 213.14 | 11.72 | 0.00 | – |
| | $M_{D4i}$ | Building time between 1981 and 2011: Type of substratum | ↗↙ | 4 | 213.57 | 12.15 | 0.00 | 0.63 |
| | $M_{D2}$ | Pop with college degree | ↗ | 3 | 216.46 | 15.04 | 0.00 | 0.09 |
| | $M_{D1}$ | Owner or co-owner | ↗ | 3 | 216.95 | 15.53 | 0.00 | 0.05 |
| | $M_{D3}$ | Pop with and +65 yrs | ↙ | 3 | 217.34 | 15.93 | 0.00 | 0.01 |
| | $M_{D4}$ | Building time between 1981 and 2011 | ↗ | 3 | 217.38 | 15.96 | 0.00 | 0.00 |
| *TLB* ($Kg\ ha^{-1}$) | $M_{E2i}$ | Pop with college degree: Type of substratum | ↗↙ | 4 | 158.88 | 0.00 | 0.81 | 0.83 |
| | $M_{E1i}$ | Owner or co-owner: Type of substratum | ↗↙ | 4 | 163.28 | 4.40 | 0.09 | 0.74 |
| | $M_{E3i}$ | Pop with and +65 yrs: Type of substratum | ↗↙ | 4 | 164.24 | 5.36 | 0.06 | 0.71 |
| | $M_0$ | Null model | ↗ | 2 | 166.35 | 7.47 | 0.02 | – |
| | $M_{E4i}$ | Building time between 1981 and 2011: Type of substratum | ↗↙ | 4 | 167.82 | 8.94 | 0.01 | 0.59 |
| | $M_{E2}$ | Pop with college degree | ↗ | 3 | 169.96 | 11.08 | 0.00 | 0.06 |
| | $M_{E1}$ | Owner or co-owner | ↗ | 3 | 170.45 | 11.57 | 0.00 | 0.02 |
| | $M_{E3}$ | Pop with and +65 yrs | ↙ | 3 | 170.63 | 11.74 | 0.00 | 0.00 |
| | $M_{E4}$ | Building time between 1981 and 2011 | ↗ | 3 | 170.63 | 11.75 | 0.00 | 0.00 |
| *Tree species* ($ha^{-1}$) | $M_{F2i}$ | Pop with college degree: Type of substratum | ↗↗ | 4 | 86.67 | 0.00 | 0.60 | 0.79 |
| | $M_{F1i}$ | Owner or co-owner: Type of substratum | ↗↗ | 4 | 88.54 | 1.87 | 0.24 | 0.75 |
| | $M_{F31}$ | Pop with 0–14 yrs: Type of substratum | ↗↗ | 4 | 90.79 | 4.11 | 0.08 | 0.68 |
| | $M_0$ | Null model | ↗ | 2 | 91.94 | 5.27 | 0.04 | – |
| | $M_{F4i}$ | Building time between 1981 and 2011: Type of substratum | ↗↙ | 4 | 94.90 | 8.23 | 0.01 | 0.52 |
| | $M_{F2}$ | Pop with college degree | ↗ | 3 | 95.18 | 8.51 | 0.01 | 0.10 |
| | $M_{F1}$ | Owner or co-owner | ↗ | 3 | 95.26 | 8.59 | 0.01 | 0.09 |
| | $M_{F4}$ | Building time between 1981 and 2011 | ↗ | 3 | 95.76 | 9.09 | 0.01 | 0.05 |
| | $M_{F3}$ | Pop with 0–14 yrs | ↗ | 3 | 95.95 | 9.28 | 0.01 | 0.03 |
| *Simpson Index* | $M_{G4i}$ | Built until 1945: Type of substratum | ↙↙ | 4 | 5.07 | 0.00 | 0.72 | 0.77 |
| | $M_0$ | Null model | ↗ | 2 | 9.54 | 4.47 | 0.08 | 0.00 |
| | $M_{G4}$ | Built until 1945 | ↙ | 3 | 9.78 | 4.71 | 0.07 | 0.33 |
| | $M_{G3}$ | Pop with 0–14 yrs | ↗ | 3 | 10.30 | 5.24 | 0.05 | 0.30 |
| | $M_{G1}$ | Owner or co-owner | ↗ | 3 | 11.00 | 5.93 | 0.04 | 0.25 |
| | $M_{G3i}$ | Pop with 0–14 yrs: Type of substratum | ↗↗ | 4 | 12.49 | 7.42 | 0.02 | 0.52 |
| | $M_{G2}$ | Pop with college degree | ↗ | 3 | 12.90 | 7.83 | 0.01 | 0.09 |
| | $M_{G1i}$ | Owner or co-owner: Type of substratum | ↗↗ | 4 | 13.95 | 8.88 | 0.01 | 0.44 |
| | $M_{G2i}$ | Pop with college degree: Type of substratum | ↗↗ | 4 | 16.57 | 11.50 | 0.00 | 0.28 |
| *Tree condition* | $M_{C4}$ | Building time between 1981 and 2011 | ↗ | 3 | −33.37 | 0.00 | 0.50 | 0.49 |
| | $M_0$ | Null model | ↗ | 2 | −31.01 | 2.36 | 0.15 | 0.00 |
| | $M_{C4i}$ | Building time between 1981 and 2011: Type of substratum | ↗↗ | 4 | −30.79 | 2.57 | 0.14 | 0.63 |
| | $M_{C3}$ | Pop with 0–14 yrs | ↗ | 3 | −29.70 | 3.67 | 0.08 | 0.26 |
| | $M_{C1}$ | Owner or co-owner | ↗ | 3 | −28.74 | 4.63 | 0.05 | 0.18 |
| | $M_{C3i}$ | Pop with 0–14 yrs: Type of substratum | ↗↗ | 4 | −28.18 | 5.19 | 0.04 | 0.53 |
| | $M_{C2}$ | Pop with college degree | ↗ | 3 | −27.55 | 5.82 | 0.03 | 0.08 |
| | $M_{C1i}$ | Owner or co-owner: Type of substratum | ↗↗ | 4 | −25.71 | 7.66 | 0.01 | 0.39 |
| | $M_{C2i}$ | Pop with college degree: Type of substratum | ↗↗ | 4 | −23.42 | 9.95 | 0.00 | 0.24 |

**Table 5**
Comparison of models used in GAM multimodel inference.

| Response | Model | Explanatory | k | AICc | Δ AICc | AIC Wt | $R^2$ adjusted |
|---|---|---|---|---|---|---|---|
| *Stored C* (Kg $ha^{-1}$) | MA3 | Tree DBH | 12.58 | 811.04 | 0.00 | 1.00 | 0.72 |
| | MA5 | Tree Leaf Biomass | 2.00 | 857.13 | 46.09 | 0.00 | 0.63 |
| | MA2 | Tree Density | 2.69 | 1057.43 | 246.39 | 0.00 | 0.27 |
| | MA4 | Tree Condition | 7.64 | 1099.63 | 288.59 | 0.00 | 0.16 |
| | MA1 | Shading Factor | 2.00 | 1130.89 | 319.85 | 0.00 | 0.03 |
| | M0 | Null Model | 1.00 | 1136.91 | 325.87 | 0.00 | – |
| *C Net Sequestration* (Kg $yr^{-1}$ $ha^{-1}$) | MB5 | Tree Leaf Biomass | 2.21 | 735.26 | 0.00 | 0.98 | 0.46 |
| | MB3 | Tree DBH | 10.71 | 743.55 | 8.29 | 0.02 | 0.47 |
| | MB2 | Tree Density | 2.87 | 748.98 | 13.71 | 0.00 | 0.44 |
| | MB4 | Tree Condition | 7.83 | 853.43 | 118.17 | 0.00 | 0.17 |
| | MB1 | Shading Factor | 2.55 | 882.79 | 147.52 | 0.00 | 0.04 |
| | M0 | Null Model | 1.00 | 892.39 | 157.12 | 0.00 | – |
| *Tree Leaf Area* ($m^2$ $ha^{-1}$)<br>(proxy for pollution removal and avoided runoff) | MC3 | Tree DBH | 8.63 | 820.54 | 0.00 | 1.00 | 0.51 |
| | MC2 | Tree Density | 2.92 | 926.56 | 106.02 | 0.00 | 0.25 |
| | MC4 | Tree Condition | 4.76 | 961.97 | 141.43 | 0.00 | 0.15 |
| | MC1 | Shading Factor | 3.15 | 997.17 | 176.63 | 0.00 | 0.01 |
| | M0 | Null Model | 1.00 | 998.54 | 178.00 | 0.00 | – |

will probably surpass in ES proficiency the parishes with intermediate or low socioeconomic indicators. It should be noted that possible leakage effects of ES provision among parish groups do not compensate the socioecological inequity evidenced by this research, as benefits such as avoided runoff, microclimate impact and energy efficiency are enjoyed essentially by dwellers in the near surroundings of the green areas providing these ES.

Higher values of Simpson's index in GREEN substrata with greater proportion of recent construction (“A” and “E”) also reinforce the influence of average building age in the urban forest. Results suggest that socioeconomic patterns in Porto are associated with species diversity of the urban forest. This is more visible in “*C*”, where a high prevalence of vacant areas and abandoned houses with private gardens/backyards is contributing to the expansion of the alien invasive *Acacia melanoxylon* (Table 3). In stratum “*B*” there was a lower prevalence of this species. However, the existence of many vacant areas is also giving rise to the rapid expansion of *Buddleja davidii*, an exotic ornamental shrub species very common in private gardens and not yet declared invasive in Portugal by the national legislation, but already listed in Spain. Although invasive species provide regulating ES, their negative impact in local biodiversity is an important trade-off that should also be considered when assessing their role for ES overall proficiency. Both GREEN substrata “B” and “C” recorded the two lowest Simpson index values, which reveals the dominance effect of some species and lower diversity compared with the other parish groups. Tree species density was also considerably lower in “*B*” than in the rest of the city, thus affecting resilience of the urban forest in this area of the city, by increasing vulnerability to plagues and diseases.

Results from this investigation are in line with findings of previous research concluding that less wealthy areas are more exposed to ES inequity (Escobedo et al., 2015; Jenerette et al., 2011; Landry and Chakraborty, 2009; Romero et al., 2012). However, there is also evidence of higher ES delivery in lower-income areas, compared to wealthier zones of cities such as Paris (Cohen et al., 2012) and Santiago do Chile (Escobedo and Nowak, 2009). This apparent contradiction might be explained by the impact of local factors such as planning trends (Cohen et al., 2012) or heterogeneity of pollution concentrations due to anthropogenic and biophysical factors, as was found in Santiago do Chile, where Escobedo and Nowak (2009) observed that pollution removal of PM10 was highest in low socioeconomic areas even though these had the lowest vegetative cover. As trees take a long time to grow, shifting socioeconomic patterns can also be reflected by a lag effect between the plantation of trees by a certain socioeconomic group, and fruition of their benefits by a different socioeconomic group.

Our results further indicate that building age is also a powerful variable to explain deviances from a linear relationship between ES proficiency and socioeconomic wealth, confirming previous findings (Grove et al., 2006; Hope et al., 2003). This means that the maturity of trees and green spaces in older urban areas can have a stronger impact in ES proficiency than higher densities of trees observed in wealthier parts of the city. However, recently constructed areas revealed more diversity in the urban forest, and if trees can fully develop in these areas a more direct association between ES proficiency and socioeconomic patterns is expected.

All these considerations strongly suggest that before setting planning and management goals, it is crucial to understand local patterns of ES, and their relationships with socioeconomic patterns, which can be affected by other variables such as building age. This understanding should be followed by the identification of structural variables of the urban forest that better explain the differences, in order to target these variables through planning and management goals. The conceptual framework adopted in this research (Fig. 1) can guide adaptation of our methodology to other cities, and provide insights for planning and management suitable to site-specific conditions and directly usable by stakeholders.

Some limitations and caveats should be acknowledged. i-Tree Eco uses measured hourly pollutant concentration which is assumed to be consistent throughout the city (i.e., concentration does not vary at the local scale). Also deposition velocities per unit of canopy cover is dependent upon an average leaf area index for the city, thus pollution removal is proportional to leaf area with no differentiation among individual species differences that may affect deposition velocities (Sæbø et al., 2012).

## 5. Conclusion

Planning and management goals for Porto can draw upon this research, such as targeting planting trees in the areas where ES proficiency needs reinforcement to mitigate inequity in ES delivery. Similarly, more attention could be given to the proper establishment of trees to allow for the full development of mature tree canopies and size, since results suggest that higher DBH (and consequently higher TLB in living trees) is a major factor impacting ES proficiency. Also, planting trees near buildings could be focused upon if energy efficiency benefits are to be attained. Porto's urban forest resilience can be improved with diversification of tree species used in new plantations, particularly in the most deprived parish, and better control of invasive vegetation in the city center and “*Campanhã*” (stratum “B”). BVOC emissions might be mitigated using low-emitting species in new plantations. These findings can contribute to sustain the foundation for a municipal strategy for trees, ES proficiency and equity, as well as to change the current national legislative model.

The variation in ES/socioeconomic relationships found among other cities in previous research suggests that site-specific factors have major impact in ES proficiency across the urban fabric. Planning and management goals should evolve from a paradigm more grounded in a set of indicators able to capture the dynamics of local social-ecological systems. This can be accomplished by determining local patterns and direction of ES/socioeconomic relationships, followed by identification of structural variables of the urban forest that better explain the differences. The proposed conceptual framework (Fig. 1) and methodology can be used in other cities, and results directly applied by local stakeholders to assess and establish monitoring benchmarks in ES proficiency across the city and to compare before/after scenarios for interventions. Mismatches between the local scale and planning/management goals at larger scales could be better understood and addressed, specifically the social-ecological dynamics that prevent some goals to be attained. Examples include the impact of private owner preferences regarding species and location choice for trees, frequent land use changes that impede trees from achieving larger sizes, proliferation of invasive species in vacant areas, and low ES proficiency even when green area is abundant and tree density is reasonable.

Future research is needed to address proficiency for ES, and contribute to develop a framework where trade-offs between negative impacts (e.g., invasive alien and high BVOC emission impacts) and positive effects of trees are considered to adequately inform the planning and design process.

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