Performance of urban green areas in ecosystem services proficiency: a case study in Porto, Portugal

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2018

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Nota Prévia

Na elaboração desta tese, e nos termos do número 2 do Artigo 4º do Regulamento Geral dos Terceiros Ciclos de Estudos da Universidade do Porto e do Artigo 31º do D.L. 74/2006, de 24 de Março, com a nova redação introduzida pelo D.L. 63/2016, de 13 de Setembro, foi efetuado o aproveitamento total de um conjunto coerente de trabalhos de investigação já publicados ou submetidos para publicação em revistas internacionais indexadas e com arbitragem científica, os quais integram a Secção II da presente tese. Tendo em conta que os referidos trabalhos foram realizados com a colaboração de outros autores, a candidata esclarece que em todos eles, foi a principal responsável pela sua conceção, bem como pela obtenção, análise e discussão de resultados, e ainda pela elaboração da sua forma publicada.

O trabalho foi realizado sob orientação do Doutor Mário Cunha, Professor Auxiliar do Departamento de Geociências, Ambiente e Ordenamento do Território da Faculdade de Ciências da Universidade do Porto e Investigador no Centro de Investigação em Ciências Geo-Espaciais da Universidade do Porto, e sob coorientação do Doutor Paulo Farinha Marques, Professor Associado do Departamento de Geociências, Ambiente e Ordenamento do Território da Faculdade de Ciências da Universidade do Porto e Investigador no Centro de Investigação em Biodiversidade e Recursos Genéticos (CIBIO-InBio). Os trabalhos foram maioritariamente realizados na Universidade do Porto e no CIBIO-InBio, que funcionaram como entidades de acolhimento, estando também abrangido um período de estadia de dois meses na Northern Research Station do USDA Forest Service, em Syracuse (EUA), sob a supervisão do Doutor David Nowak.

Este trabalho foi apoiado pela Fundacão para a Ciência e Tecnologia (FCT) através da bolsa de doutoramento SFRH/BD/91028/2012.

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To Gabriel, for a better future.

Acknowledgements

The work presented in this thesis is the result of four years of study and research activity conducted at the University of Porto (Faculty of Sciences) and at the Research Center of Biodiversity and Genetic Resources of the University of Porto, including a short term stay at the Northern Research Station of the USDA Forest Service as a visiting scholar.

This work would not have been possible without the funding provided by the Portuguese Foundation for Science and Technology (FCT) through an individual doctoral scholarship (ref. SFRH/BD/91028/2012), which supported most of the expenses related with the research activity during the last four years.

The long and hard path that led to this doctoral thesis could not have been completed without the critical contribution of many people who also made things easier and much more pleasant for me.

I wish to express my deepest appreciation for all the support provided by my supervisor, Professor Mário Cunha, who so willingly accepted to guide me along this journey in a disciplinary field that was not his own. I have greatly benefited from his solid knowledge, rigorous scientific scrutiny and truly permanent enthusiasm with this work, which kept me so motivated and inspired even when I was feeling less confident. I cannot thank him enough for his encouragement, respect and prompt assistance in all steps of the way, which I believe were determinant for accomplishing this immense task.

I would like to thank my co-supervisor, Professor Paulo Farinha Marques, for his encouragement and wisdom, as well as for stimulating me to widen my research perspectives. He was a constant reminder of the challenges that lay ahead the discipline of Landscape Architecture, and provided great assistance in helping me to find the direction for this work.

It was a true inspiration to meet David Nowak, one of the world leading researchers in the field of Urban Forestry, and project leader of i-Tree at USDA Forest Service. Dave had the patience to clarify all my (many) questions, and supplied relevant insights for this research. Besides having the privilege to benefit from his remarkable knowledge and intelligence, I was struck by his notable character and generosity. I had so many good moments with Dave and his family while we stayed together in Buffalo for Thanksgiving, and during many weekends in Syracuse. They certainly made the snowy winter away from home much more bearable.

I also would like to thank Dave's research team for kindly receiving me at the Northern Research Station, and particularly to Robert Hoehn, Alexis Ellis and Satoshi Hirabayashi for their key assistance in my research using i-Tree Eco.

João Gonçalves was an invaluable help in the statistical analysis of the data. Moreover, his out-of-the-box reasoning and sharp intellect greatly contributed to enrich this research.

My appreciation goes additionally to Isabel Branco for introducing me to Filipe Araújo, Porto's Councilman for Innovation and Environment. Filipe Araújo took great interest in this research and provided the support and resources to host David Nowak in Portugal, as well as to trigger the implementation of i-Tree in Portugal. From the City Council of Porto, my deepest gratitude goes also to Isabel Lufinha and Cristina Azurara. Their time, interest and willingness in helping this research and in organizing a seminar by Dave Nowak and I was truly invaluable.

Marta Pinto, from the Regional Centre of Expertise on Education for Sustainable Development of the Porto Metropolitan Area (CRE.Porto), was a crucial contact point to reach out to secondary schools in Porto and establish fruitfully partnerships to survey the population. I would like to thank her effort and time, and hope that new mutual collaborations may arise in the future.

My deep thanks goes also to the four teachers who took their time and energy to collaborate in this research with their students: Cândida Neves from the Secondary School Alexandre Herculano, Rosa Costa from EBS Rodrigues de Freitas, Sandra Lopes from EBS do Cerco, and Fátima Afonso, from Colégio D. Duarte.

Professor Cristina Queirós, of the Faculty of Psychology and Educational Sciences of the University of Porto, kindly accepted to provide guidance in developing a method to study the perceptions of city dwellers, and in analyzing the data obtained from questionnaires applied in Porto. Her knowledge, generosity and time were essential to accomplish the objectives of the study.

In the office, the friendship from my colleagues was comforting and much appreciated. Isabel Pôças was the longstanding companionship along the way, from which I have taken support and advice.

I also wish to thank my dear sister-in-law, Sandra Alves, for proofreading the final version of the thesis.

Besides all the people directly or indirectly related with this work, no one deserves more my deepest acknowledgement than my parents, who have been my biggest supporters for all my life, and have endured so many sacrifices to provide for me and my brothers. I deeply thank them for all their love and help. My mother was such a pillar of strength for me during this period, particularly when my son Gabriel was born almost two years ago. Even at distance, while taking care of my ill father, she managed to be present all the time. I cannot thank her enough.

Lastly, but foremost, I owe my profoundest thankfulness to my beloved husband, Paulo Alves. He encouraged me to enter this path and to pursue my own directions, while providing all the care, support and love I needed. Paulo gave priceless assistance for this research, using his unique expertise in Botany and Ecology but also reviewing texts, providing opinions, and extra help for field-data collection. Our lives have been challenged by the birth of our child and by so many other demanding changes, but he managed to have the immense patience, dedication and selflessness to be there for me and Gabriel. You both have been my lighthouse all the way, a home to strive for.

Abstract

This thesis focuses on the impact of benefits generated by urban green areas in the quality of life in cities. The concept of ecosystem services (ES), defined here as the benefits human populations derive from ecosystems, is adopted to identify and measure the environmental and socioeconomic outcomes of urban ecosystems. Green areas deliver many urban ecosystem services (UES), which are substantially influenced by the composition and configuration of vegetation. Therefore, design and management of green spaces may play a decisive role in promoting UES supply by acknowledging and taking advantage of vegetation attributes and structure. Yet, research on UES is a recent and evolving field, and many barriers still difficult the explicit incorporation of benefits into planning, design and management of green spaces.

The thesis aims to explore, test and validate methods to analyze and measure UES provided by urban vegetation, allowing to identify site-specific patterns and drivers of supply. The final objective of this work is to support a scientifically robust approach concerning vegetation use, in order to advance evidence-based design and planning of the urban green structure.

The research project consisted in a case study developed in Porto (Portugal), which is presented in full detail in three peer-reviewed articles exploring distinct aspects of urban vegetation and green spaces influencing UES supply.

In **Paper 1** a methodology is proposed to investigate associations between socioeconomic indicators and structural variables of the urban forest in Porto, and also which structural variables, if any, differ along a socioeconomic gradient. The research outcomes were subsequently related with UES supply across the city. A pattern of environmental inequity across Porto emerged from the results, in which wealthier areas revealed better access to UES provided by urban trees than more deprived parts of the city. In addition, the variables of urban trees with the highest impact in UES supply for Porto were isolated to help formulating specific orientations for urban planning, design and management of green spaces.

Paper 2 explores the influence of diverse types of urban green spaces in UES provision for Porto, building from the hypothesis that distinct types of stewardship and functions of urban green spaces affect differently their composition and configuration in terms of vegetation. Eight types of green spaces in Porto were identified and mapped according to a performance ranking of UES supply, and one potential disservice generated by urban vegetation was considered as well. The distribution of urban green types across a

socioeconomic gradient in Porto was also investigated, expanding the findings of **Paper 1** regarding environmental inequity, drivers of UES supply and orientations to support decision-making processes aiming to increase urban resilience.

Paper 3 focuses one particular type of green space in Porto, and explores the cultural dimension of urban ecosystems by investigating how perception affects UES management. The purpose was to investigate the influence of socioeconomic variables in the perception of benefits and losses / costs caused by street trees, identified in **Paper 2** as one of the most proficient types of green space delivering UES in Porto. Street trees are also easier to establish in densely built cities frequently lacking available area for new sizable green spaces. Our results evidenced that the perception of benefits and losses / costs generated by a specific green type is strongly affected by socioeconomic characteristics of beneficiaries, which need to be properly considered in planning and management initiatives in order to insure positive outcomes.

The three articles provide an integrated approach to the assessment of ecosystem services at the local scale, valuable to support the informed design, planning and management of urban green spaces. Additionally, this thesis includes an operationalization section targeting a practice-oriented audience. The operationalization section illustrates how the findings of this research can be synthetized and translated into clear and specific orientations to increase UES supply and urban resilience in our study area, and provides a more accessible communication interface to managers, designers and planners of green spaces working in Porto.

Keywords: urban ecosystem services, regulating ecosystem services, urban planning, urban vegetation, environmental equity, green space, social-ecological systems, sociocultural values, perception, i-Tree, evidence-based landscape architecture.

Resumo

Esta tese debruça-se sobre o impacto dos benefícios gerados pelas áreas verdes na qualidade de vida nas cidades. O conceito de serviços dos ecossistemas (SE), definido como os benefícios que os seres humanos obtêm dos ecossistemas, é aqui utilizado para identificar e medir os efeitos ambientais e socioeconómicos dos ecossistemas urbanos. As áreas verdes fornecem muitos serviços de ecossistemas urbanos (SEU), sendo estes substancialmente influenciados pela composição e estrutura da vegetação. Por conseguinte, o design e a gestão de espaços verdes podem desempenhar um papel decisivo no fornecimento de SEU, através do reconhecimento e utilização adequada da estrutura e atributos da vegetação. A investigação na área dos SEU encontra-se, contudo, num estado incipiente e em intenso desenvolvimento, persistindo muitas barreiras à incorporação explícita dos benefícios das áreas verdes no seu planeamento, design e gestão.

A tese pretende explorar, testar e validar métodos de análise e medição de SEU fornecidos pela vegetação urbana, de forma a permitir a identificação de padrões locais de provisão e fatores com influência nos mesmos. Este trabalho tem como objetivo final promover uma abordagem ao uso da vegetação nos espaços verdes suportada por evidências científicas, e estimular a sua aplicação no design e planeamento da estrutura verde urbana.

O projeto de investigação consistiu num caso de estudo desenvolvido no Porto, apresentado detalhadamente em três artigos científicos onde são explorados distintos aspetos da vegetação urbana e dos espaços verdes com influência no fornecimento de SEU.

No **Artigo 1** propõe-se uma metodologia para investigar associações entre indicadores socioeconómicos e variáveis estruturais da floresta urbana do Porto, bem como a eventual variação de determinadas variáveis estruturais ao longo de um gradiente socioeconómico. Os resultados do estudo foram subsequentemente relacionados com o fornecimento de SEU na cidade. Um padrão de desigualdade ambiental no Porto emergiu neste trabalho, no qual as áreas mais favorecidas revelaram melhor acesso a SEU fornecidos pelas árvores urbanas do que as zonas mais carenciadas da cidade. Neste estudo foram ainda isoladas as variáveis das árvores urbanas com maior impacto no fornecimento de SEU no Porto, de forma a permitir a formulação específica de orientações para o planeamento urbano, design e gestão de espaços verdes.

O **Artigo 2** explora a influência de diversos tipos de espaços verdes urbanos no fornecimento de SEU no Porto, partindo da hipótese de que diferentes tipos de gestão e funções dos espaços verdes afetam a composição e configuração da vegetação. Foram identificados e hierarquizados oito tipos de espaços verdes no Porto de acordo com o respetivo desempenho no fornecimento de SEU, considerando-se ainda um potencial desserviço gerado pela vegetação. A distribuição de tipos de espaço verde ao longo de um gradiente socioeconómico no Porto foi também analisada, tendo-se expandido as conclusões do **Artigo 1** em relação à desigualdade ambiental, fatores responsáveis pelo fornecimento de SEU e orientações de suporte à tomada de decisão e promoção da resiliência urbana.

O **Artigo 3** examina um tipo específico de espaço verde no Porto e explora a dimensão cultural dos ecossistemas urbanos, nomeadamente analisando como a perceção afeta a gestão de SEU. Este estudo debruçou-se especificamente sobre a influência de variáveis socioeconómicas na perceção de benefícios e perdas / custos gerados pelas árvores de arruamento, identificadas no **Artigo 2** como um dos tipos de espaço verde com melhor performance ao nível do fornecimento de SEU no Porto. As árvores de arruamento são também mais fáceis de instalar em cidades densamente construídas, frequentemente carenciadas em áreas disponíveis para a criação de novos espaços verdes com dimensão apreciável. Os resultados evidenciaram a intensa influência das características socioeconómicas dos beneficiários na perceção de benefícios e perdas / custos gerados por um tipo específico de espaço verde, devendo aquelas ser devidamente consideradas nas iniciativas de planeamento e gestão de modo a assegurar efeitos positivos.

Os três artigos expõem uma abordagem integrada à avaliação dos serviços de ecossistemas à escala local, com capacidade para informar e fundamentar o design, planeamento e gestão os espaços verdes urbanos.

Esta tese inclui ainda uma secção de operacionalização destinada a uma audiência orientada para a prática profissional. A secção de operacionalização ilustra de que forma os resultados deste projeto de investigação podem ser sintetizados e traduzidos em orientações claras e específicas para a promoção do fornecimento de SEU e da resiliência urbana na área de estudo, constituindo uma forma de comunicação mais acessível para os profissionais dos espaços verdes em exercício no Porto.

Palavras-chave: serviços de ecossistemas urbanos, serviços de regulação, planeamento urbano, vegetação urbana, equidade ambiental, espaço verde, sistemas social-ecológicos, valores socioculturais, perceção, i-Tree, arquitetura paisagista baseada na evidência.

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Glossary

Diameter at breast height [of trees]: diameter of the trunk of a standing tree usually measured at 1.30m above ground level (in the United States it is measured at 4.5 feet, or 1.37m above the soil, which is the standard measurement adopted in the i-Tree Eco field data protocol).

Ecosystem disservices: nuisances and losses that ecosystems cause to humans.

Ecosystem services: the benefits human populations derive from ecosystems.

Environmental equity: equitable sharing of environmental impacts and risks by a community.

Resilience: the magnitude of disturbance that can be tolerated before moving to a different region of state space controlled by a different set of processes.

Social-ecological system: system in which humans and nature are inextricably linked, such as cities.

Urban forest: network or system comprising all woodlands, groups of trees, and individual trees located in urban and peri-urban areas (definition of the Food and Agriculture Organization of the United Nations).

Abbreviations

DBH: diameter at breast height
EBLA: evidence-based landscape architecture
ES: ecosystem services
MEA: Millennium Ecosystem Assessment
TEEB: The Economics of Ecosystems and Biodiversity
UES: urban ecosystem services

Introduction

While cities become the living environment for the majority of the world population (United Nations, 2015), urban green areas are emerging as crucial to sustain human health and wellbeing for city dwellers due to the many benefits they can provide. Urban green areas constitute urban ecosystems in which biotic organisms interact with abiotic components but, unlike natural ecosystems, they are heavily influenced and shaped by the social, economic and cultural dimensions of human organizations.

Although urban areas rely greatly on the products and benefits provided by ecosystems external to cities, urban ecosystems can have a strong impact in the local environment because they deliver many critical benefits for humans, such as air and water quality regulation, water flow maintenance and flood protection, micro and regional climate regulation, recreation, aesthetic pleasure and cultural values (Bolund & Hunhammar, 1999; Gaston, Ávila-Jiménez, & Edmondson, 2013), just to name a few. Moreover, as many worldwide environmental problems are originated in urban areas (Grimm et al., 2008), urban ecosystems can also play a relevant role in mitigating the ecological footprint of cities.

Nevertheless, the importance of urban ecosystems has been almost disregarded until recently, and urban areas were barely considered in the Millennium Ecosystem Assessment, the first global initiative launched by the United Nations in 2001 to assess the consequences of worldwide ecosystem change to human wellbeing and health (Alfsen, Duval, & Elmqvist, 2011).

This thesis focuses on the impact of benefits generated by urban green areas in the quality of life in cities. The concept of ecosystem services (ES), defined here as the benefits human populations derive from ecosystems (MEA, 2005), provides the framework to explicitly identify and measure the environmental and socioeconomic outcomes of urban ecosystems.

Green areas deliver many urban ecosystem services (UES) which are greatly dependent of the composition and configuration of vegetation, their most dominant and defining element. Therefore, design and management of green spaces may play a decisive role in promoting UES supply by acknowledging and taking advantage of vegetation attributes and structure. Yet, research on UES is a recent and evolving field, and many barriers still difficult the explicit incorporation of benefits into planning, design and management of green spaces.

Urban areas form complex social-ecological systems, or systems in which humans and nature are inextricably linked; as Berkes, Colding, and Folke (2003) underline, the concept of social-ecological system emphasizes the humans-in-nature view. The resilience of cities, or the magnitude of disturbance that can be tolerated before moving to a different region of state space controlled by a different set of processes (Carpenter, Walker, Anderies, & Abel, 2001), depends on the capacity of urban ecosystems to function and deliver UES within specific governance systems and socioeconomic dynamics. This means that similar patterns of UES supply may result from very distinct drivers. Consequently, initiatives targeting desirable and sustainable changes in urban ecosystems need to be grounded in the deep understanding of both the socioeconomic and ecological influences shaping the local urban environment. However, information about these influences at the local or regional scale is seldom available for urban planners, managers and designers of green spaces in a suitable scale or format able to assist the decision-making process. Clear and understandable orientations stemming from scientific knowledge are required to support effective actions, but frequently there is a mismatch between research outputs and the specific needs for information of urban stakeholders.

This thesis aims to explore, test and validate methods to analyze and measure UES provided by urban vegetation, allowing to identify site-specific patterns and drivers of supply. Through the identification of the aspects of the urban vegetation affecting UES delivery as well as their drivers of change, it is possible to generate detailed information suitable for urban planning, design and management, and promote the effective integration of the ES framework into urban planning and design.

The final objective of the thesis is to support a scientifically robust approach concerning vegetation use, in order to advance evidence-based design and planning of the urban green structure.

Section I provides the conceptual background of the research by addressing the main concepts, context and pertinence of the theme, and introduces a case study developed in Porto. The case study is described in Section II, in which three peer-reviewed articles explore distinct aspects of urban vegetation and green spaces influencing UES supply.

In **Paper 1** a methodology is proposed to investigate associations between socioeconomic indicators and structural variables of the urban forest in Porto, and also which structural variables, if any, differ along a socioeconomic gradient. The research outcomes were subsequently related with UES supply across the city. A pattern of environmental inequity across Porto emerged from the results, in which wealthier areas revealed better access to UES provided by urban trees than more deprived parts of the city. In addition, the variables of urban trees with the highest impact in UES supply for Porto were isolated to help formulating specific orientations for urban planning, design and management of green spaces.

Paper 2 explores the influence of diverse types of urban green spaces in UES provision for Porto, building from the hypothesis that distinct types of stewardship and functions of urban green spaces affect differently their composition and configuration in terms of vegetation. Eight types of green spaces in Porto were identified and mapped according to a performance ranking of UES supply, and one potential disservice generated by urban vegetation was considered as well. The distribution of urban green types across a socioeconomic gradient in Porto was also investigated, expanding the findings of **Paper 1** regarding environmental inequity, drivers of UES supply and orientations to support decision-making processes aiming to increase urban resilience.

Paper 3 focuses on a particular type of green space in Porto, and explores the cultural dimension of urban ecosystems by investigating how perception affects UES management. The purpose was to investigate the influence of socioeconomic variables in the perception of benefits and losses / costs caused by street trees, identified in **Paper 2** as one of the most proficient types of green space delivering UES in Porto. Street trees are also easier to establish in densely built cities frequently lacking available area for new sizable green spaces. Our results evidenced that the perception of benefits and losses / costs generated by a specific green type is strongly affected by socioeconomic characteristics of beneficiaries, which need to be properly considered in planning and management initiatives in order to insure positive outcomes.

The three articles presented in Section II provide an integrated approach to the assessment of ecosystem services at the local scale, valuable to support the informed design, planning and management of urban green spaces (Fig. 1).

The purpose of **Section III** is to illustrate how the findings of this research can be synthetized and translated into clear and specific orientations to increase UES supply and urban resilience in our study area, and provides a more accessible communication interface to managers, designers and planners of green spaces working in Porto.

In the **Conclusion and Perspectives** section, we highlight the main contributions of the thesis for advancing UES research and its effective implementation to tackle urban challenges. We conclude suggesting directions for future research.

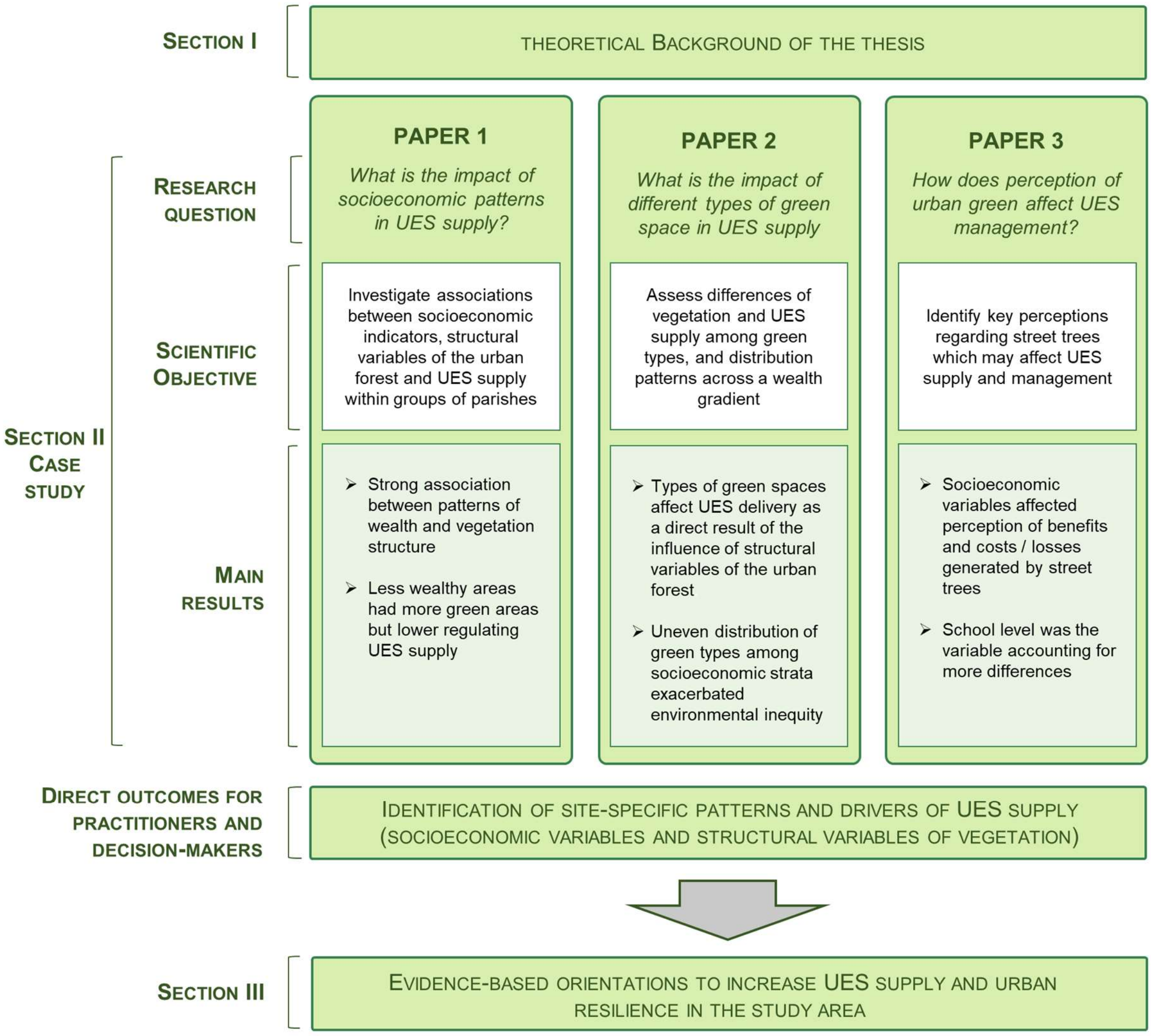

FIGURE 1 – Structure of the thesis. Section I provides the theoretical background and introduces the case study developed in Porto, Portugal, to generate scientific evidence addressing three research questions concerning UES supply of green spaces (Section II). Section III operationalizes the direct outcomes of the case study for practitioners and decision-makers, and illustrates how the gap between science and practice can gradually be diminished.

Section I

CONCEPTUAL FRAMEWORK

1| The ecosystem services approach

The concept of ecosystem services (ES) has emerged in the last decade as a new worldwide paradigm to communicate effectively the tight relationship between ecosystems and human wellbeing.

According to the most broadly used definition, ES "are the benefits people obtain from ecosystems". This definition was mainstreamed by the Millennium Ecosystem Assessment (MEA), a global initiative launched by the United Nations in 2001 to assess the consequences of ecosystem change across the planet for humans and establish the scientific basis for conservation and sustainable use of ecosystems.

The concept itself is imbued of an anthropocentric view that has been criticized by many authors, who argue against an instrumental or utilitarian view of nature regarded as something to be used by humans (Costanza et al., 2017). However, the argument made by ES advocates is that the concept does not entail a simplified view of nature, but rather recognizes the role and dependence of humans as part of the biosphere, fostering a perspective of complex interdependence amongst all other species and their supporting environment (Costanza et al., 2017). Hence, the ES concept encourages precisely the inverse of a perspective centered in "consuming" nature, which has led to a disastrous situation in global ecosystems and biodiversity (Cardinale et al., 2012).

Although the expression "ecosystem services" was first used by Ehrlich & Ehrlich in 1981, by the end of the 1960 decade and early 1970's numerous authors had already stressed the social value of Nature's functions, and from that time onward the human dependence of natural resources began to attract public attention for the cause of biodiversity conservation (Gomez-Baggethun & Ruiz-Perez, 2011; Haines-Young & Potschin, 2010; Hermann, Schleifer, & Wrbka, 2011). One of the most important milestones to universalize the ES concept was the explicit adoption of an ecosystem approach by the Convention on Biological Diversity, in 1992, which was defined as "*a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way*", aiming to balance the goals of safeguarding, utilization and fair sharing of the benefits delivered by genetic resources (Secretariat of the Convention on Biological Diversity, 2004).

Another relevant contribution was the seminal article by Costanza et al. (1997) about the value of the global natural capital, which presented an estimate of the economic value of seventeen ES in sixteen biomes. The high monetary value determined by these authors (averaged in $33 trillion per year) had an enormous impact in the scientific community, as well as in the formulation of policies destined to the preservation of natural resources (Costanza et al., 2017; Hermann et al., 2011). In the next decade, the thorough and wide-ranging analysis of ES began its establishment through the work of Daily (1997), de Groot, Wilson, and Boumans (2002) and others (see Gomez-Baggethun & Ruiz-Perez, 2011 for a general overview concerning the emergence of the ES approach), setting the ground for the framework adopted by MEA.

According to the ES classification proposed by MEA, ecosystems deliver four groups of services: provisioning, regulating and cultural services include the direct contributions of ecosystems regarding human wellbeing, whereas supporting services are the foundation required to maintain all other types of services (Table 1; Millennium Ecosystem Assessment, 2003).

TABLE 1: Categories of Ecosystem Services (ES) according to the conceptual framework established in the Millennium Ecosystem Assessment (Millenium Ecosystem Assessment, 2003).

CATEGORY OF ES	DEFINITION	EXAMPLES
Provisioning	Products obtained from ecosystems	Food, fresh water, fuelwood, fiber, biochemical and pharmaceutical resources, genetic resources
Regulating	Benefits obtained from regulation of ecosystem processes	Climate regulation, disease regulation, hydrological cycle regulation, air and water purification
Cultural	Nonmaterial benefits obtained from ecosystems	Recreation, aesthetic pleasure, inspiration, education, sense of place, cultural heritage, spiritual and religious enrichment
Supporting	Services necessary for the production of all other ES	Soil formation, nutrient cycling, primary production

The ES framework adopted by MEA identifies the links between the four categories of ES and specific components of human wellbeing (Fig. 2), highlighting the intensity of those relationships and their potential for mediation through socioeconomic factors. The possibility to buy or create an alternative for a lost or damaged ES represents a high potential for mediation, which is, however, dependent of the type of ES, the ecosystems under consideration, and their beneficiaries. In developed countries, scientific knowledge and technology can be applied to replace or mitigate the loss of certain ES - artificial drainage and urban stormwater management systems are examples of this. However, the loss of productive capacity of soils for food provision in very poor communities might not be replaceable due to the lack of financial resources of the population to acquire fertilizers or eatable goods obtained from elsewhere.

In any case, the potential to mediate socioeconomically relationships between ES and human welfare is very limited in most ES, as illustrated in Fig. 2. Therefore, biodiversity conservation is fundamental to insure human security, health and wellbeing.

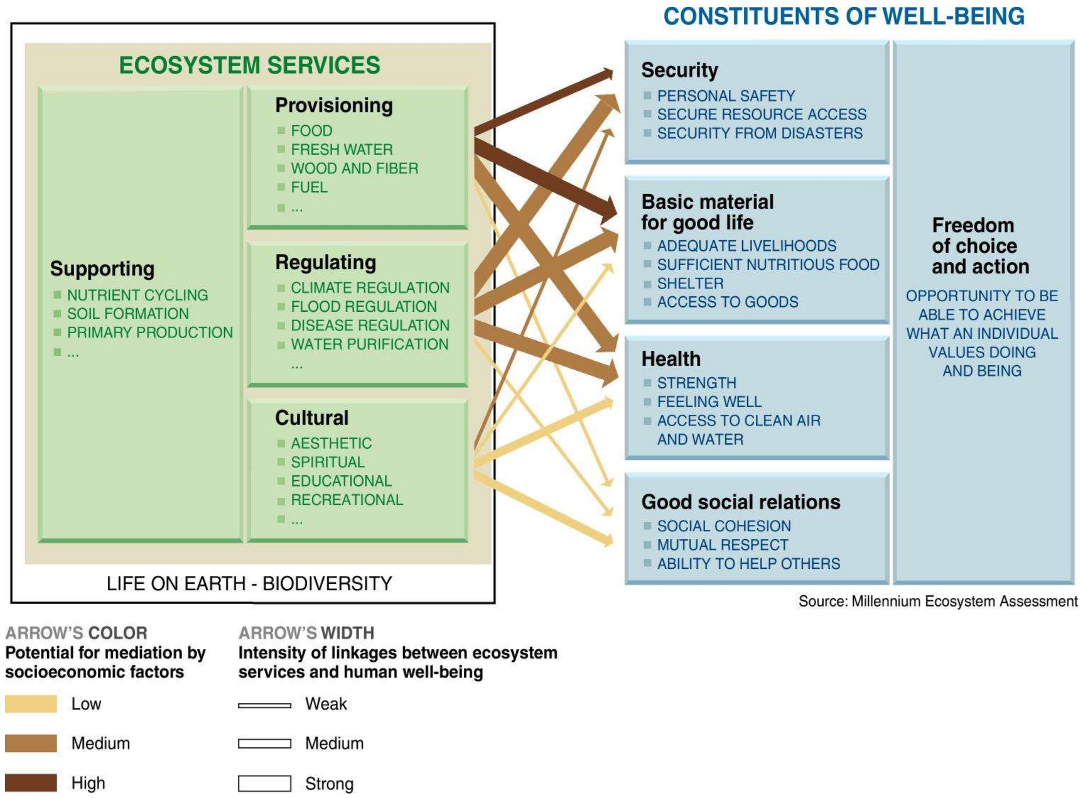

FIGURE 2 – Links between categories of ecosystem services and constituents of human wellbeing according to the conceptual framework established in the Millennium Ecosystem Assessment (image reproduced with the permission of Millennium Ecosystem Assessment).

By identifying and assessing fluxes of value to human societies resulting from the condition and availability of natural capital, the ES approach has helped the scientific community to promote biodiversity conservation. However, to sustain those fluxes of value in the present and future, it is necessary to better understand how ecosystems function and deliver ES, and how they react to change and driving forces of pressure.

Research is therefore evolving continuously to deliver methods to classify, quantify, map and value ES, and several global initiatives have emerged to better structure these efforts.

One of the worldwide initiatives most acknowledged was The Economics of Ecosystems & Biodiversity (TEEB), a global study launched in 2007 by the German Federal Ministry for the Environment and the European Commission (Sukhdev, Schröter-Schlaack, Nesshöver, Bishop, & Brink, 2010), focusing the economic benefits of biodiversity and the costs of its loss. TEEB fostered an approach based in first recognizing and demonstrating the direct and indirect economic value of ecosystems, followed by the identification of incentive instruments to incorporate the values of ecosystems into decision-making (such as payments for ecosystems); it delivered reports and guides for implementation at multiple scales and contexts, featuring several case studies at country and biome level. Recurring to the dominant discourse of political and economic perspectives based in monetary terms, TEEB aimed to align science, economy and policy expertise to deliver concrete action targeting biodiversity loss and its impacts. At the time, and in a context where traditional conservation approaches failed to slow down the pace of consumption of the natural capital (Guo, Zhang, & Li, 2010; Krausmann et al., 2009), especially because they were reluctant in embracing the economic and sociopolitical drivers behind ecosystem degradation, economic valuation was considered an innovative strategy to halt biodiversity loss (Gomez-Baggethun & Ruiz-Perez, 2011).

Due to the prevailing separation of economics and conservation policy domains, it was argued by many authors that using an economic valuation approach would help to take into account the benefits generated by ecosystems, which would otherwise not be considered in institutional, political and economic decision-making spheres (Daily et al., 2000; Peterson, Hall, Feldpausch-Parker, & Peterson, 2010). Proponents of the economic approach to environmental problems recognize the “market failure” for the mainly public goods and services delivered by ecosystems and biodiversity, for which no prices exist, but consider that this issue could be partially overcome through the development of proper valuation methods for externalities (effects of private exchanges in third-party interests, usually ignored by society unless declared illegal) or “shadow” prices (i.e, the marginal cost of ES production) (Richmond, Kaufmann, & Myneni, 2007; Ring, Hansjürgens, Elmqvist, Wittmer, & Sukhdev, 2010).

Economic valuation gave rise to the emergence of markets for ES based in the “polluter pays principle”, in which the negative externalities of ecosystem degradation are translated into a monetary cost to be covered by the economic agents causing them;

positive externalities are also considered under a “steward earns principle” fueled by payments for ecosystem services, in which beneficiaries pay the stewards of ES for maintaining and protecting them (Gomez-Baggethun & Ruiz-Perez, 2011). According to this view, prices or economic values can strongly encourage administrators, politicians, institutions and consumers to consider the true value of the natural capital in resource management, even if many challenges prevent the complete acknowledgement of this value in monetary terms (Ring et al., 2010).

Despite the well-intended purpose of the TEEB initiative to promote economic valuation as a way to highlight the contribution of ES to wellbeing, substantial criticism was raised due to the economic basis of the valuation approach. One of the main arguments of controversy concerned the suitability of an economic approach to address non-marketable goods and services, risking even to produce undesired results for biodiversity conservation due to the commodification of ES. ES commodification is intrinsically connected with ES monetary valuation, which underlies the sale and exchange through markets, as has occurred with services such as carbon sequestration and watershed regulation (Gomez-Baggethun & Ruiz-Perez, 2011). Problems arising from commodification of ES are the limits to what, from an ethical point of view, may be subject to sale, and the risk to use ES not as an eye-opening metaphor to reflect upon our relationship with Nature, but as a blinder of the social-ecological complexity of processes behind ES supply (Norgaard, 2010).

As noted by Chan, Satterfield, and Goldstein (2012), the economic perspective fails to address the cultural and moral dimensions of intangible value that risk to become hidden externalities in the process of ES valuation. In a global economy striving for economic growth at the cost of ecosystems located far from their beneficiaries, cultural practices and identity of local traditional communities living in those ecosystems may consequently become threatened by conflicting types of value.

Nevertheless, economic valuation has a relevant place within multi-criteria analysis by contributing with relevant information for cost-benefit assessments; these offer, however, only a partial perspective of the complex issues related with biodiversity conservation (Spangenberg & Settele, 2010).

Despite the criticism related with its economic foundation, TEEB was decisive to foster the actual incorporation of ecosystems and the services they provide into the realm of political and economic affairs, changing the previous dominant mindset in which humans and nature were seen as separate.

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) emerged in 2012 in the context of this new global mindset considering biodiversity conservation as a priority to sustain long-term human wellbeing. IPBES is an independent intergovernmental body currently comprising 126 member states, aiming to provide policymakers with the scientific knowledge concerning biodiversity, ecosystems and their services, including tools and methods for their protection and sustainable use (www.ipbes.net). As a science-policy platform, IPBES aims to review, synthetize and assess available scientific knowledge for policy support. Due to the involvement of governments, IPBES has a strongly political role to effectively support the use of scientific information in decision-making processes.

The concept of ES is still undergoing intense debate (Costanza et al., 2017), and different interpretations have been proposed to overcome difficulties in operationalizing it in distinct contexts. Some authors noted that the MEA was ambiguous in distinguishing between direct benefits of the ecosystems to humans, and the environmental mechanisms (or functions) by which those benefits are generated (Haines-Young & Potschin, 2010; Wallace, 2007). Clarifying what ES are and how they can be classified is an essential step towards establishing the mechanisms of ES flowing from biodiversity to humans, and understanding the impact of management and policies on biodiversity.

Several contributions have been made to consolidate a consensual definition and classification for ES (Boerema, Rebelo, Bodi, Esler, & Meire, 2017; Costanza, 2008; Daily, 1997; de Groot et al., 2002; Haines-Young & Potschin, 2010; Wallace, 2007). To address the issue of confounding services with ecological functions or structures, Haines-Young and Potschin (2010) proposed a service cascade model that helps to distinguish the final products of ecosystems from the underlying processes that originate them (Fig. 3). The authors highlight that the main purpose of this model is helping to grasp a better understanding of the complexity of relationships between nature and humans, rather than supporting an inflexible compartmentation of ecosystem elements that is highly unlikely in real contexts.

Although the service cascade model has been widely used in research and policy affairs worldwide, recently Costanza et al. (2017) questioned its use, arguing that it simultaneously oversimplifies the complex process of ES generation, while unnecessarily complicating a very straightforward definition (ES are by definition the benefits of ecosystems to humans, whether perceived or not by beneficiaries).

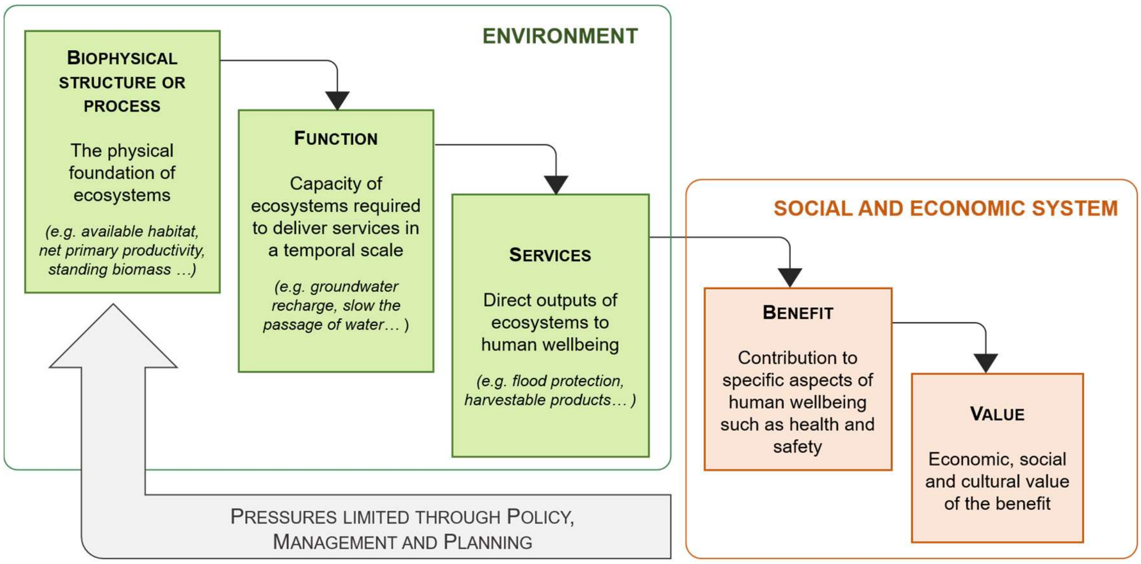

FIGURE 3 – The Ecosystem Service cascade model adapted from Haines-Young and Potschin (2010) and Potschin and Haines-Young (2016).

Adopting the service cascade model, the Common International Classification of Ecosystem Services (CICES) seeks to advance the standardization of ES classification, in order to enable the development of accounting methods and comparisons of assessments (www.cices.eu). CICES derived from the work of the European Environment Agency regarding environmental accounting, and was proposed to the United Nations in 2010 within the revision of the System of Environmental-Economic Accounting (Haines-Young & Potschin, 2011). In order to address challenges for ES analysis such as different scale and thematic resolution, CICES developed a hierarchical ES classification structure consisting of five levels, as illustrated in Fig. 4.

According to CICES, ES refer specifically to the final outputs or products of ecological systems to human wellbeing (meaning that they are directly used or consumed by people), which can be grouped in three top-level categories (or sections) of ES: provisioning, regulating and cultural services. The category of supporting services initially outlined in the MEA classification structure for ES was not covered in CICES, as its proponents considered these to be only indirectly used or consumed. Supporting services were considered to be within the scope of ecological processes, functions and properties of ecosystems that are required for the production of ES, and therefore more suitable to other forms of environmental accounting (Haines-Young & Potschin, 2011).

It is undeniable that biodiversity is affected by decisions concerning land use, resource allocation and economic development, whether or not decision-makers acknowledge this impact (Alberti, 2005; Cardinale et al., 2012). Therefore, sustaining the crucial benefits provided by ecosystems to human wellbeing and survival requires a better understanding of which and how ES are delivered by specific ecosystems, to what extent they are demanded by beneficiaries and subject to ecological thresholds and trade-offs, and what can compromise their delivery. Society's decisions should rely in an informed appraisal of the biophysical limits of the ecological processes, as well as of the temporal and spatial scales in which they take place. The ES framework should not replace other narratives which, despite not being based in stock-flow models, provide much needed knowledge about ecological systems (Norgaard, 2010), but rather complement them and effectively bridge the science and policy realms. Knowledge from social sciences is also essential to cast light on the sociocultural drivers of change in ecosystems, on what matters to humans, and in how the characteristics of beneficiaries and social context affect the use of ES (Chan, Guerry, et al., 2012).

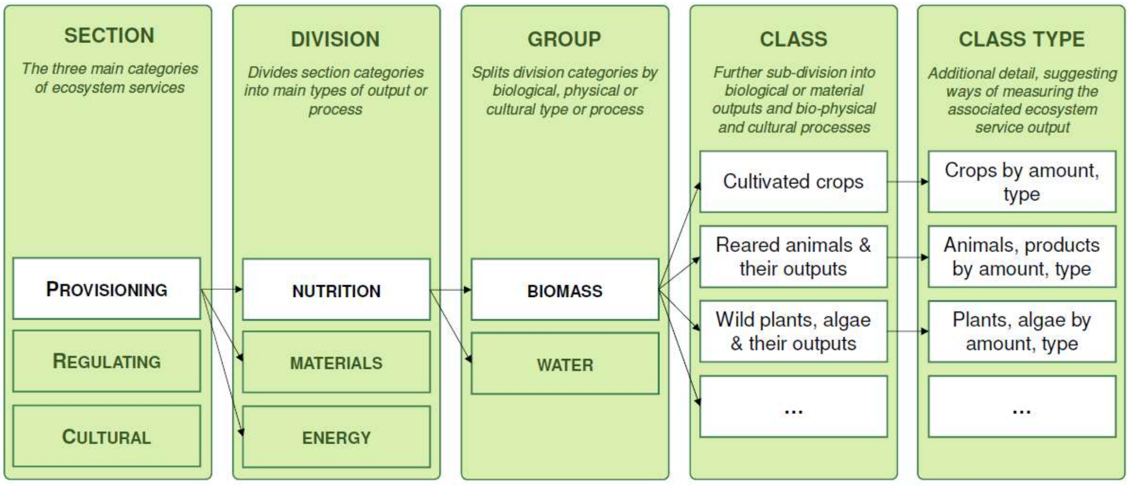

FIGURE 4 – Hierarchical classification of ecosystem services proposed by the Common International Classification of Ecosystem Services (CICES), adapted from Haines-Young and Potschin (2013).

Regardless of the pitfalls pointed to the ES discourse, such as serving as a complexity blinder of global ecological, economic and political problems (Norgaard, 2010), or its anthropocentric / instrumental tonic and potential contribution to the commodification of nature, amongst others (Schröter et al., 2014), both the scientific community and general society have broadly accepted it. For that reason, it has the potential to help assess and powerfully communicate the implications of distinct management strategies on biodiversity and human subsistence, thus setting the ground for a new paradigm in governance systems and institutions.

2| Urban ecosystem services (UES)

In just more than a century the urban world population has expanded from about 10% in 1900 to 54% in 2014, and is expected to surpass 66% in 2050 (Grimm et al., 2008; United Nations, 2015). In Europe, city dwellers already peaked 73% in 2014, and were estimated to reach 80% in 2050 (United Nations, 2015).

In light of this extraordinary growth, cities have rapidly sprawled by converting large portions of wild, agricultural and forestry land into urbanized areas with diffuse and ever-changing boundaries. Urban settings originate enormous demands for resources (e.g. energy, food, fiber, fuel…) provided by other ecosystems and generate large amounts of pollution, causing huge impacts in ecosystems and biodiversity at all scales, thus severely accelerating the pace of global environmental changes (Alberti, 2005; Grimm et al., 2008).

Compared to other types of landscapes, urban areas are unique in many aspects. They are shaped by the complex interaction of socioeconomic, institutional and biophysical systems, and constitute social-ecological systems that cannot be properly understood by studying separately the properties and processes of each system (Alberti, 2005). The intense and intertwined processes that shape cities cause highly patchy spatial patterns and persistent disturbance processes, as the human dominance pervades ecological processes by altering intentionally or non-intentionally natural occurrences such as fire regimes, vegetation ecological succession, species occurrence or biogeochemical cycles (Alberti, 2005; Alfsen et al., 2011; Grimm et al., 2008). The urban heat island effect, intensified stormwater runoff, decreased groundwater recharge, altered soil properties and changes in biodiversity patterns are just some of the particular phenomena of the urban environment that reflect the magnitude of human activities and the replacement of predominately permeable areas by built surfaces, thus potentiating the fragmentation and disruption of ecosystems (Alberti, 2005; Pauleit & Breuste, 2011).

Only a few decades ago researchers gained interest in understanding the specific dynamics and processes influencing the urban environment, as mounting evidence of human's actions in multiscale ecosystems began to emerge and ecologists recognized humans as components of ecosystems (McDonnell, 2011). Yet, cities were barely addressed by the MEA, even though in the last decades many findings have advanced the scientific understanding of the effect of urban patterns over ecosystem functions and properties (see Alberti, 2005, for a detailed review on this topic).

More recently, research started to focus the potential of urban areas to generate UES that may mitigate the negative consequences of urbanization (Bolund & Hunhammar, 1999; Gomez-Baggethun & Ruiz-Perez, 2011; Haase et al., 2014). Some crucial services generated by ecosystems are impossible to import to cities, and hence need to be generated locally (e.g. microclimate regulation, flood control, noise buffering, air filtration, recreation, aesthetic value, sense of place, …). Other services, such as food or water provision, greatly contribute to increase urban resilience to socioeconomic, political and environmental shifts (McPhearson, Andersson, Elmqvist, & Frantzeskaki, 2015). Urban ecosystems can play a determinant role in fostering the adaptation of urban areas to new conditions, by providing the necessary flexibility to cope with uncertainty and intensified environmental risks. In addition, due to the increased exposure of the human population to urban environments, the services delivered by ecosystems in cities hold the potential to affect the health and wellbeing of millions of people. Therefore, UES supply may have a strong impact in human wellbeing presently and in the future, as challenging issues such as climate change, fast population growth and social inclusion become more pressing. In view of this, the need of better understanding UES supply and demand has been acknowledged by many authors (e.g. Erik Andersson et al., 2014; Gomez-Baggethun & Barton, 2013; Haase et al., 2014; Kowarik, 2011).

Many studies have focused specifically in the impacts of urban ecosystems on human health, demonstrating for example the influence of green spaces in the physical and psychological health of city dwellers (Tzoulas et al., 2007), the decrease of asthma prevalence in children living in areas with more street trees (Lovasi, Quinn, Neckerman, Perzanowski, & Rundle, 2008), stress diminution in greener urban areas (Roe et al., 2013; Thompson et al., 2012), increased longevity (Takano, Nakamura, & Watanabe, 2002; Tanaka, Takano, Nakamura, & Takeuchi, 1996), reduced morbidity (Maas et al., 2009) and mortality (Gascon et al., 2016), and lower cardiometabolic risk (Paquet et al., 2013). Associations between mental health and green spaces were also found (Cohen-Cline, Turkheimer, & Duncan, 2015; Sturm & Cohen, 2014; White, Alcock, Wheeler, & Depledge, 2013), and self-reported health condition has also been positively related with green areas (de Vries, Verheij, Groenewegen, & Spreeuwenberg, 2003; Maas, Verheij, Groenewegen, de Vries, & Spreeuwenberg, 2006; Payne, Orsega-Smith, Roy, & Godbey, 2005).

The beneficial influence of urban green areas extends beyond individual aspects, by fostering social cohesion and reduction of socioeconomic health inequalities (Camps-Calvet, Langemeyer, Calvet-Mir, & Gómez-Baggethun, 2016; Maas et al., 2009; Mitchell & Popham, 2008). Urban green spaces in neighborhoods can strengthen social relationships and community ties, contributing to increase interactions among residents, safety feelings and children's play, and to reduce crime and incivilities (Kim & Kaplan, 2004; Kuo, 2003).

Most of the studies relating human health with green spaces have assessed only associations with quantitative measures of green (e.g. area, distance to green spaces), which may explain some inconclusive evidence supporting specific relationships (Lachowycz & Jones, 2013; van den Bosch & Ode Sang, 2017). Only a few studies explored the influence of green quality variables in health, but results suggested that quality plays a more significant role than quantity of green space available (e.g. de Vries, van Dillen, Groenewegen, & Spreeuwenberg, 2013; Francis, Wood, Knuiman, & Giles-Corti, 2012; van Dillen, de Vries, Groenewegen, & Spreeuwenberg, 2012).

Specific pathways or mediators linking health outcomes to green areas remain considerably inconclusive or lacking supporting evidence, though some significant relationships have already been found (de Vries et al., 2013; van den Bosch & Ode Sang, 2017). To our knowledge, research on this topic has seldom considered explicitly UES supply as a potential explanatory variable (but see Salmond et al., 2016; van den Bosch & Ode Sang, 2017).

As one of the main components of urban green areas, vegetation can strongly influence UES supply, and therefore human health and wellbeing. There is considerable evidence that vegetation can mitigate the urban heat island effect and regulate local microclimate (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Cao, Onishi, Chen, & Imura, 2010; Chang, Li, & Chang, 2007; Declet-Barreto, Brazel, Martin, Chow, & Harlan, 2013; Oliveira, Andrade, & Vaz, 2011), and some studies have explored the relationship between temperature and vegetation composition (Shashua-Bar, Potchter, Bitan, Boltansky, & Yaakov, 2010), configuration of urban green areas (Cao et al., 2010; Chang et al., 2007) and the urban landscape (Connors, Galletti, & Chow, 2013). Urban ecosystems can also reduce the ecological footprint of cities by storing large amounts of carbon as above ground biomass of trees (Jansson & Nohrstedt, 2001), thus contributing to reduce negative effects in global climate change caused by anthropogenic agents.

In addition, several authors have demonstrated the role of vegetation in filtering air pollutants, contributing to improve and regulate air quality (Cavanagh, Zawar-Reza, &

Wilson, 2009; McDonald et al., 2007; Nowak, Crane, & Stevens, 2006). There are indications that trees have greater filtering capacity than shrubs because of their larger leaf area and potential to increase turbulent mixing of the passing air (Beckett, Freer-Smith, & Taylor, 2000); among them, the conifers seem to have a greater filter capacity than deciduous trees (Beckett, Freer-Smith, & Taylor, 2000; Beckett et al., 2000; Freer-Smith, Beckett, & Taylor, 2005). Other tree variables that have been suggested to account for differences in terms of particulate matter deposition are species traits and morphological characteristics of leaves (Liu, Guan, & Peart, 2012; Sæbø et al., 2012).

Vegetation can also reduce environmental noise exposure (Bolund & Hunhammar, 1999; Klingberg, Broberg, Strandberg, Thorsson, & Pleijel, 2017; Ow & Ghosh, 2017), which is a growing concern in cities due to its negative impacts in human health (World Health Organization, 2011).

Furthermore, it has been demonstrated that vegetation structure is one of the most determinant variables affecting urban biodiversity and habitat quality (Beninde, Veith, & Hochkirch, 2015; Threlfall et al., 2016).

Vegetation is also the component of green spaces most susceptible to direct manipulation by humans in cities, whether by top-down management actions or bottom-up informal stewardship (Kendal, Williams, & Williams, 2012; Threlfall et al., 2016).

In light of all these considerations, it becomes clear that there is a need to acknowledge how the composition and structure of vegetation affect UES supply, in order to promote effective benefits for urban populations.

3| Ecosystem services as a basis for urban planning, management and design

By rendering an holistic, yet objective perspective over ecological, economic and social concerns, the ES framework provides the possibility to identify and bring to the decision-making level services and values often neglected, particularly those characterized by intangible and non-tradable character (notwithstanding their strong impact on the well-being of human beings). Once these values are explicitly recognized, along with the processes that generate and degrade them, it is possible to develop efforts that go beyond the simple conservation of valuable environmental resources. Given the large uptake of land caused by urbanization processes, and the consequent degradation of natural ecosystems, promoting UES supply likewise in man-made environments such as gardens, parks, and green roofs is necessary to sustain urban wellbeing and resilience. Design, management and planning of urban green areas should therefore encourage solutions that actively promote the production of beneficial services in cities (Steiner, 2016).

Although research on ecosystem services has expanded impressively in recent years, as underlined by an exponential number of scientific publications on the matter (Costanza & Kubiszewski, 2012), several challenges have prevented this growing body of knowledge to be fully implemented in decision-making processes, particularly in the urban realm (Haase et al., 2014; Kremer et al., 2016). One relevant barrier deepening the science-policy gap is the frequent mismatch between the questions researchers seek to answer, and the information needs of planners, designers and decision-makers (McDonnell & Hahs, 2013). This is especially patent in the number of studies addressing UES without focusing the thematic and spatial detail that would provide specific orientations for the design of green spaces. Even though planning at wider scales is essential to insure connectivity in green areas, and consequently to support biodiversity and UES supply, it remains largely unexplored to what extent the site-specific characteristics of green areas influence their performance, and the effective accomplishment of planning goals through designed spaces targeting ecological outcomes. Ecosystem management has been frequently conceived and addressed as a global, national or regional concern, but yet the local-scale decisions are causing fast and uncontrolled urban sprawling, fragmentation of ecosystems and subversion of higher-level intentions and goals (Brody, 2003). Therefore, policies concerning ecosystem management should consider the local scale as crucial for successful implementation.

Considering that vegetation largely dominates green spaces, and that its structure and composition may influence considerably UES supply, there is the need to better understand these effects and explicitly include them in the design, planning and management of green areas at the local-scale. Evidence-based use of vegetation may be a powerful way to accomplish simultaneously many gains: enhancement of UES supply, better communication of the advantages of nature-based solutions to politicians, stakeholders and institutions; and increase of transversal support from society to ecosystems and biodiversity.

Green areas deliver more than just ecological outcomes: they constitute the dominant interface of city dwellers with nature, generating many psychological and social benefits. Some studies have highlighted that different social groups and communities view nature differently. Fraser and Kenney (2000) analyzed differences in perceptions of the urban forest of four communities living in Canada (British, Chinese, Italian and Portuguese), and related the three different views of nature that emerged from the study to the cultural background of respondents, and to the landscape history of each country of origin associated with the communities. Buijs, Elands, and Langers (2009) explored differences in images of nature and landscape preferences among immigrants from Islamic countries and Dutch natives, and concluded that the former revealed low fondness for wild landscapes with no management, whereas the latter deeply appreciated this type of image of nature. Within similar cultural contexts, the extent to how a person benefits directly of green spaces is also influenced by other factors that affect accessibility and opportunity to use them, such as the availability of proximity gardens and parks, or owning resources to travel to further distances. A recent research strand has analyzed differences in provision of green spaces across cities, strongly suggesting environmental inequity towards more deprived communities or social groups (Escobedo, Clerici, Staudhammer, & Corzo, 2015; Escobedo et al., 2006; Heynen, Perkins, & Roy, 2006; Jenerette, Harlan, Stefanov, & Martin, 2011; Kabisch & Haase, 2014; Landry & Chakraborty, 2009; Pham, Apparicio, Séguin, Landry, & Gagnon, 2012). Furthermore, characteristics such as age, gender and education level influence individual values and the perception of nature, and produce different patterns of use of green areas. Perception of nature is particularly important because it is the key process by which humans experience ecological processes, engage with ecosystems, and base decisions upon altering the landscape (Gobster, Nassauer, Daniel, & Fry, 2007).

All these studies suggest that environmental equity and social inclusion require more than a balanced provision of green spaces across cities: planners, designers and managers need to take into account different cultural and social groups of beneficiaries when shaping specific aesthetics and functionality into built or managed environments, instead of following one-size-fits-all orientations. The ES framework provides a way to link explicitly cultural benefits to the ecosystems generating them, facilitating a structured approach to investigate these relationships and incorporating them in decision-making processes.

4| Ecosystem Services and Landscape Architecture

Before addressing the uptake of the ES discourse within the discipline of Landscape Architecture, it is necessary to discuss its current use of scientific knowledge to inform practice-oriented problems.

Although the focus of design-oriented disciplines leans very much towards practice, there has been increasing agreement that education, training and decision-making should be grounded in a solid knowledge base stemming from scientific research (Brown & Corry, 2011; Meijering, Tobi, van den Brink, Morris, & Bruns, 2015; van den Brink & Bruns, 2014). Drawing a parallelism with medicine, likewise a practice-oriented profession, Brown and Corry (2011) argue that the latter has succeeded to evolve, in about a century, from a practice based in beliefs to a scholarly profession strongly informed by scientific research, and because of that it has reached a highly recognized and powerful status. According to these authors, Landscape Architecture is still grasping its way towards an evidence-based discipline due to a general lack of factual information supporting decisions, and to the absence of a monitoring and reporting culture. The bleakly low amount of peer-reviewed research by landscape architects corroborates this reality (Brown & Corry, 2011; Gobster, Nassauer, & Nadenicek, 2010).

Evidence-based design and planning have become a priority in a context of overwhelmingly complex societal challenges that require broad social and institutional consensus (Brown & Corry, 2011). Calkins (2005) concluded, within the scope of a survey to landscape architects in the United States, that it is urgent to develop research supporting the economic and performance advantages of ecological design, which encompasses the "protection or restoration of ecological processes with the intent of minimizing the impact of the built intervention on the local and global environment". To generate such research, it is necessary to effectively bridge the researchers' and practitioners' concerns into a scientifically sound perspective, but yet objective enough to support decision-making processes. In spite of this, studies related with the practical aspects of designing or planning green spaces are still scarce (Calkins, 2005).

Brown and Corry (2011) define evidence-based landscape architecture (EBLA) as "*the deliberate and explicit use of scholarly evidence in making decisions about the use and shaping of land"* and further elaborate that it *"supports decisions but does not dictate* *them (…) and (…) uses knowledge – generally from methodically studied experiment or experience – as the principal information source for design*." This definition clearly separates the act of designing from the evidence that should support it, while implicitly recognizing that EBLA is only possible if a fundamental knowledge base of scientifically obtained evidence exists.

It is worthwhile to stress that the purpose of scientific research is here understood as the ability to generate new knowledge able to move forward a discipline. Hence, one should be careful to define as scientific research studies that simply generate information by collecting data and applying existing methods to solve pragmatic problems; such studies are essential to gain better insight on complex realities, and are often used to inform design and management, but do not configure themselves scientific research which is essential to foster innovative methodological approaches (Milburn, Brown, Mulley, & Hilts, 2003; van den Brink & Bruns, 2014). However, *research by design* is a valid and acknowledged method to generate scholarly knowledge (see Deming & Swaffield, 2011; van den Brink & Bruns, 2014). Nevertheless, *research for design* provides the evidence-based foundation that may subsequently be tested through *research by design* studies (van den Brink & Bruns, 2014).

Building a solid foundation of scientific research for design requires leadership from fields dealing directly with the physical environment and its manipulation, such as Landscape Architecture, in order to insure the convergence of knowledge of fundamental disciplines (Ecology, Hydrology, Geology, Sociology, Climatology…) into the issues that matter the most to designers, planners and practitioners. However, Milburn and Brown (2016) identified a mismatch between the top five areas of research demanded by practicing landscape architects (sustainable design, water management, construction, ecology, and plant materials), and the top five areas actually researched by academic professors in Landscape Architecture (history, theory, perception, education, and case studies).

These considerations about the role of evidence and scientific knowledge as a backbone of Landscape Architecture set the context to reflect upon the yet-to-explore opportunities that emerge, within this discipline, from the ES discourse. Assessing, mapping and valuing ES not only provide sound evidence to inform practice, but can also reveal the ecological and socioeconomic value arising (or being degraded) from specific landscape changes. Besides guiding informed decision-making processes, the ES framework can therefore help to strengthen the leading role of Landscape Architecture in society, aiming to produce healthy and resilient environments. Tackling the global landscape challenges that humanity is currently facing requires no less than solid evidence-based knowledge of the social-ecological reality upon which one is sought to act. Not embracing this necessity could put the landscape at the hands of well-intentioned but potentially harmful “doctors”, as Brown and Corry (2011) warn.

5| Modelling and quantification of ecosystem services in urban areas

As a recent research field, UES have been a consistent subject of academic publications only in the last decade. According to a review by Luederitz et al. (2015), case studies using or developing UES assessment methods, tools or frameworks totaled a mere 56 in 2012. Additionally, most of the 201 studies published between 1999 and 2012 identified by the authors did not actually examine the UES mentioned in them.

A proliferation of approaches to quantify and assess UES has emerged more recently, rendering it difficult to establish a central trend, although a broad dichotomy can be drawn between quantitative methods focused in economic versus non-economic valuation. Economic, or monetary, methods include hedonic pricing, travel costs, avoided costs, replacement costs and stated preference methods (see Gomez-Baggethun & Barton, 2013, for a detailed overview of these methods in the urban context), and are especially useful to inform cost-benefit analysis. However, these methods provide limited information for planning, managing and designing green spaces that support effective UES delivery. For example, information concerning citizens' willingness to pay for green spaces may support the establishment of new green areas, but does not inform about which type of structure should be adopted; even if specific green features emerge as more appealing, these may not correspond to desirable ecological outcomes.

Non-economic approaches include ecological and sociocultural valuation methods; in the first case, physical or non-physical environmental aspects valuable for human wellbeing are assessed using ecological indicators as proxies, while in the latter case the human perceptions of UES are taken into account (Haase et al., 2014).

Nevertheless, a combination of methods is often used. For example, quantification methods based in ecological indicators can estimate tangible amounts of UES that are subsequently converted into monetary units (e.g. Escobedo et al., 2008; Soares et al., 2011).

Quantitative modelling of UES has gained increased attention to provide reliable estimates of UES provision because it facilitates grasping highly complex social-ecological urban systems. Yet, as Haase et al. (2014) noted, even if new advances in methods and indicators to assess and analyze UES are rapidly emerging, their actual suitability to inform urban planning is still very limited or undemonstrated. This is especially the case for methods assessing the heterogeneity of UES supply across the urban fabric. Some studies have used modelling approaches to explore the relationships between urban spatial structure and UES supply: Alberti et al. (2007) analyzed the impact of urban development patterns in the ecological conditions of streams in the Puget Sound lowland region, even if not adopting explicitly the ES framework; Tratalos, Fuller, Warren, Davies, and Gaston (2007) investigated how environmental metrics, stormwater runoff, maximum temperature and carbon sequestration were related with the urban form and social status of residents in five cities in the United Kingdom; McDonald et al. (2007) estimated the potential of tree plantations to reduce PM_{10} concentrations across two UK conurbations. Yet, most studies seldom generate specific information that may assist the planning and design of green spaces, although they provide valuable information concerning UES supply and underlying drivers.

Many studies have explored the role of urban trees in UES supply, due to their potential to mitigate the degradation of environmental conditions in cities. According to Roy, Byrne, and Pickering (2012), the method mostly used to quantify UES delivered by urban trees was the application of mathematical derivations (about 79% of 115 reviewed studies), followed by the i-Tree modelling tool (14% of studies). i-Tree was adopted in this research to generate UES estimates, hence more details are provided below and in Appendix A.

i-Tree is a suite of free tools developed by the USDA Forest Service, of which i-Tree Eco is the most comprehensive and powerful one (www.itreetools.org). i-Tree Eco delivers detailed information about the structure of the urban forest, based in field data collected in the study area and local pollution and meteorological data, and provides estimates for several UES (details about underlying calculations are provided in Nowak et al., 2008). It has been extensively used across the world, usually to analyze aggregate values of urban forest structure and UES supply (e.g. Baró, Haase, Gómez-Baggethun, & Frantzeskaki, 2015; Hutchings, 2012) or explore differences across one type of strata (e.g. Escobedo et al., 2006; Yang, McBride, Zhou, & Sun, 2004). Therefore, the substantial amount of international case studies using i-Tree Eco facilitates comparisons across cities. However, to our knowledge the full potential of this modelling tool to assist evidence-based urban planning, management and design of green spaces has not yet been explored.

6| Thesis approach

Building from the conceptual framework and issues so far highlighted, this thesis aims to contribute to the knowledge base of evidence required to support successful planning and design of urban green spaces, focusing particularly in vegetation use. By successful planning and design, we refer here to the ability of delivering green areas with significant positive impact in both the ecological and social urban realms, and therefore suitable to scientific assessments demonstrating their value.

The current lack of a set of scientific guidelines that can inform planning, design and management of vegetation to enhance UES supply, and the difficulty to transfer findings from case studies carried out in distinct social-ecological contexts, complicate the task to develop evidence-based practice. The research methodology adopted in the thesis aims to overcome these obstacles by providing an approach to urban settings able to generate scientific knowledge regarding UES delivery by green spaces, with the thematic and spatial detail required for practitioners and decision-makers at the local scale. In our view, this approach exemplifies how the gap between science and practice can gradually be diminished, and the much needed body of evidence-based knowledge for planning and design can start to emerge.

From the point of view of urban planning and design, it stands out as more relevant to approach UES supply from a spatially explicit perspective, which we adopted in our research. Mapping UES and identifying the drivers behind their spatial heterogeneity may provide relevant insights to promote UES performance and the equitable distribution of resources across cities. Understanding asymmetries of UES supply within cities configures a decisive step to support planning of the urban green structure in relation to socioeconomic equity and vulnerability of populations to environmental risks. However, UES mapping alone may not be enough to capture the asymmetry of supply across the urban fabric. It is necessary to cast light on spatial features that are suitable to manipulation, in order to support action targeting desirable changes. Therefore, in this research both qualitative and quantitative methods were adopted to uncover not only hot and cold spots of provision, but also the variables generating specific outcomes, which could subsequently be addressed by decision-makers.

The research was developed in the city of Porto, the center of the second largest metropolitan area of Portugal. Due to the inexistence of scientific information regarding

UES provision by green spaces in this city, our methodological approach (Fig. 1) consisted in first identifying the patterns of UES delivery in the city in relation to the socioeconomic drivers shaping them, while explicitly isolating the structural characteristics of vegetation that better explain the current performance of green spaces in Porto (Paper 1). In Paper 2, we aimed to expand the findings of Paper 1 by exploring how the vegetation structure of different types of green spaces affects UES provision. i-Tree Eco v5 was applied in both papers, combined with generalized linear and additive models in Paper 1; in Paper 2, an innovative combination of two stratifications schemes was used to generate more detailed insights for urban planning, management and design of green spaces. Paper 1 and 2 deliver the first outline, to our knowledge, of social-ecological processes affecting UES delivery in Porto, and simultaneously deliver practical information about vegetation structure across the city, highlighting which aspects can be tackled through planning, design and management of green spaces.

However, the value of green spaces extends far beyond vegetation structure and its ecological impact. The experience of nature is deeply affected by people's individual and cultural background, and influences the perceived value in green spaces. Such perceived value determines directly the provision of cultural UES by green spaces, which can only exist in a context where beneficiaries assign cultural value to nature. In addition, human values influence behavior towards ecosystems and biodiversity, which accordingly render positive or negative consequences for UES delivery and human wellbeing.

Cultural values are critical to insure the acceptance of new greening initiatives by communities, but they are often disregarded in the design, planning and management of urban green spaces. The resulting mismatch over the expectations of the community can cause nuisances, disempowerment feelings, and ultimately the failure of green spaces.

Paper 3 addresses the impact of perception in UES management, exploring street trees of Porto as a cultural element in the city. Street trees emerged, in Paper 2, as the second type of green space with the best performance concerning UES provision, and the easiest to implement in a city with dense urban fabric such as Porto. Perception of benefits and losses / costs generated by street trees was assessed using data from a survey conducted in the streets of Porto and parametric statistical tests.

Section III illustrates how the evidence generated in this research can be operationalized into practice (Fig. 1), and was structured as a fairly autonomous document directed to practice-oriented readers.

The thesis seeks to approach the complexity of urban social-ecological systems in a scientifically sound methodological manner, and derive evidence to support design, planning and management of green spaces. Therefore, it proposes a new paradigm for Landscape Architecture, which we hope may help to materialize the immense possibilities of this discipline in the XXI century.

Section II

CASE STUDY

Paper 1

Graça, M. S., Gonçalves, J. F., Alves, P. J. M., Nowak, D. J., Hoehn, R., Ellis, A., Farinha-Marques, P., Cunha, M. (2017). Assessing mismatches in ecosystem services proficiency across the urban fabric of Porto (Portugal): The influence of structural and socioeconomic variables. *Ecosystem Services, 23,* 82-93.

Paper available online on December 5, 2016

Classification according to journal: research paper

Bibliometric indicators from the Journal Citation Report, Institute for Scientific Investigation:

- Journal impact factor 4.072

- Journal rank

Environmental studies: position 8/105; quartile Q1, JIF percentile 92.857

Ecosystem Services 23 (2017) 82–93

Contents lists available at ScienceDirect

Ecosystem Services

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

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

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ARTICLE INFO

Keywords:
Urban ecosystem services
Regulating ecosystem services
Urban planning
Urban vegetation
Socioeconomic inequity

ABSTRACT

Knowledge regarding Ecosystem Services (ES) delivery and the socio-ecological factors that influence their proficiency is essential to allow cities to adopt policies that lead to resource-efficient planning and greater resilience. As one of the matrix elements of urban ecological structure, vegetation may play a major role in promoting ES proficiency through planting design. This research addresses the heterogeneity of ES delivered by the urban vegetation of Porto, a Portuguese city. A methodology is proposed to investigate associations between socioeconomic indicators and structural variables of the urban forest, and also which structural variables of the urban forest, if any, differ along a socioeconomic gradient. Our results reveal 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 variables such as building age. This should be followed by the identification of structural variables of the urban forest that better explain the differences, in order to target these through planning and management goals. The conceptual framework adopted in this research can guide adaptation of our methodology to other cities, providing insights for planning and management suitable to site-specific conditions and directly usable by stakeholders.

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

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http://dx.doi.org/10.1016/j.ecoser.2016.11.015
Received 7 July 2016; Received in revised form 8 November 2016; Accepted 22 November 2016
Available online 05 December 2016

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 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.

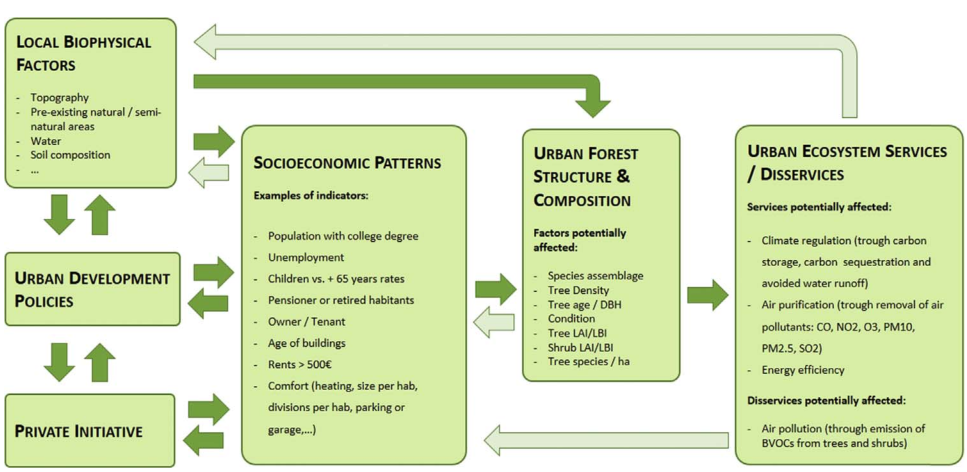

Fig. 1. Conceptual framework underlying the impact of socioeconomic patterns in shaping differently the urban forest structure across the urban fabric, thus affecting spatially ecosystem services proficiency. Dark green arrows highlight relationships predominantly direct, and light green stresses connections 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.)

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 socio-economic 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 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

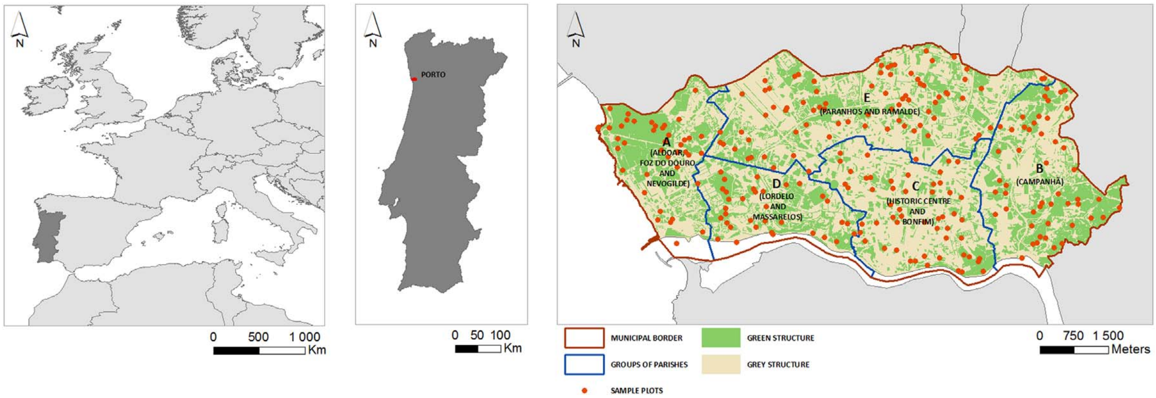

Fig. 2. Location of the study area (left and center) and pre-stratification scheme used in this investigation for sampling design (right). The green infrastructure was used to subdivide each parish group in two layers: GREEN refers to refers to the main green structure of the city (e.g. parks and gardens, 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.)

(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 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 $\Delta AICc < 2$ 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 $\Delta AICc > 10$ 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)).

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).

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 1 was 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

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[b]	21.0[a]	5,212,000[a]	65.2[1]	[a] Nowak et al. (2007); [b] DCPNY (n.d.)
Toronto	Canada	66,140[d]	26.6[c]	10,220,000[c]	160.4[c]	[c] Nowak et al. (2013); [d] PFR (n.d.)
Jersey City	USA	3,859[f]	11.5[e]	136,000[e]	35.3[1]	[e] Nowak et al. (2007); [f] CJC (n.d.)
Edinburgh	UK	11,468[g]	17.0[g]	638,000[g]	56.0[h]	[g] Hutchings et al. (2012) [h] Rumble et al. (2015)
Glasgow	UK	17,643[h]	15.0[h]	20,000,000[h]	112[h]	[h] Rumble et al. (2015)
Wrexham	UK	3,833[2i]	17.0[i]	364,000[i]	95[i]	[i] Rumble et al. (2014)
Torbay	UK	6,375[j]	11.8[j]	818,000[j]	105.0[h]	[h] Rumble et al. (2015); [j] Rogers et al. (2011)
Barcelona	Spain	10,121[k]	25.2[k]	1,419,823[k]	141[k]	[k] Chaparro and Terradas (2009)
Berlin	Germany	89,110[l]	42.7[l]	–	–	[l] Baró et al. (2015)
Rotterdam	Netherlands	27,740[l]	12.2[l]	–	–	[l] Baró et al. (2015)
Salzburg	Austria	6,570[l]	28.6[l]	–	–	[l] Baró et al. (2015)
Stockholm	Sweden	21,580[l]	37.5[l]	–	–	[l] 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.

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

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

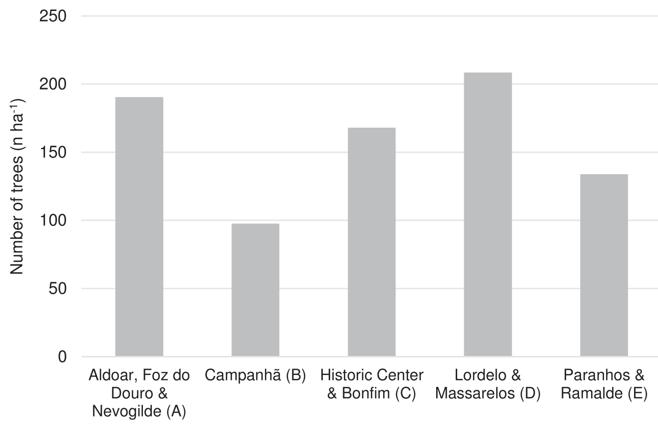

Fig. 3. Tree density in GREEN strata, according to parish groups in Porto.

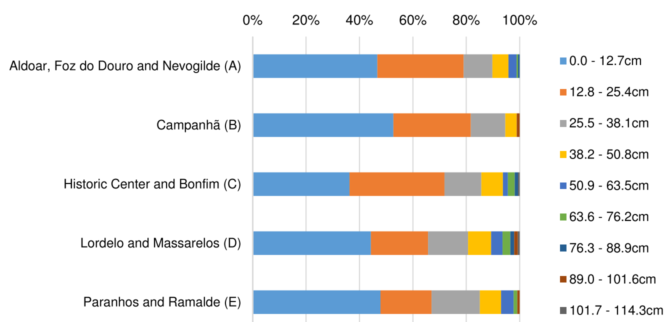

Fig. 4. Composition of tree population in GREEN strata according to Diameter at Breast Height (DBH) class, per parish group of Porto. The smallest trees (class 0.0–12.7 cm) account for the higher proportion of trees in all parish groups. (For interpretation of the references to color in this artwork,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

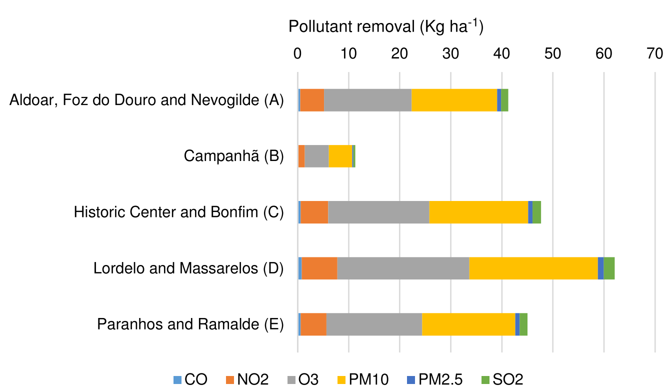

Fig. 5. Mean pollution removal for trees and shrubs in GREEN strata, per parish group in Porto (for 2011). (For interpretation of the references to color in this artwork, the reader is referred to the web version of the article).

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.

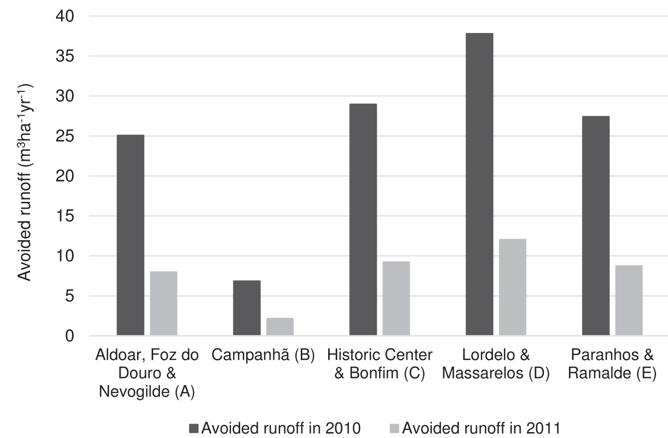

Fig. 6. Comparison of avoided runoff in 2010 and 2011 for trees and shrubs in GREEN strata, per parish group in Porto.

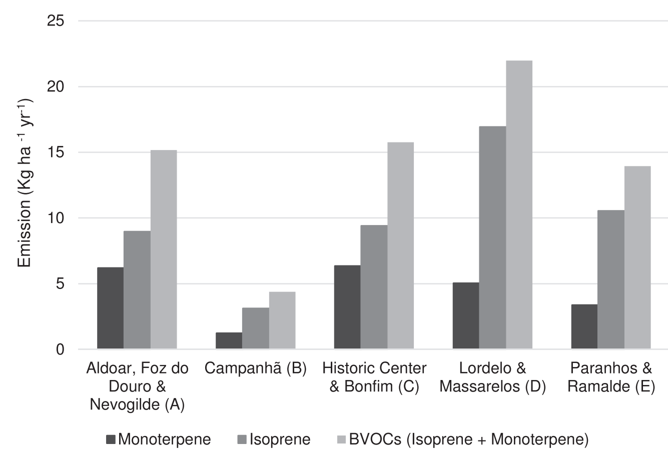

Fig. 7. Emissions of Biogenic Volatile Organic Compounds (BVOCs) for trees and shrubs in GREEN strata, per parish group in Porto.

This was the case for tree density, TLA, TLB and tree species per 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.

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

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}) (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	–

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 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 socio-economic 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.

Acknowledgement

We are grateful to Nuno Rodrigues, Daniela Cunha, Vasco Silva and Patrícia Monteiro for their assistance in the field work, and to Satoshi Hirabayashi and Daniel E. Crane, of the USDA Forest Service Northern Research Station, and Nuno Formigo, of the Faculty of Sciences of the University of Porto, for clarifications about calculation assumptions behind i-Tree Eco. We also thank the Institute of Earth Sciences (University of Porto) for providing precipitation data to run i-Tree Eco, and to the City Council of Porto for providing useful geographical information and data referring to existing tree surveys. 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.

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Paper 2

Graça, M., Gonçalves, J., Alves, P., Nowak, D., Hoehn, R., Farinha-Marques, P., Cunha, M. (2018). Assessing how green space types affect ecosystem services delivery in Porto, Portugal. *Landscape and Urban Planning*, *170*, 195-208.

Paper available online on November 20, 2017

Classification according to journal: research paper

Bibliometric indicators from the Journal Citation Report, Institute for Scientific Investigation

- Journal impact factor 4.563

- Journal rank

Environmental studies: position 6/105; quartile Q1, JIF percentile 94.762

Geography: position: 4/79; quartile Q1, JIF percentile 95.570

Urban Studies: 1/38; quartile Q1, JIF percentile 98.684

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
Available online 20 November 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*

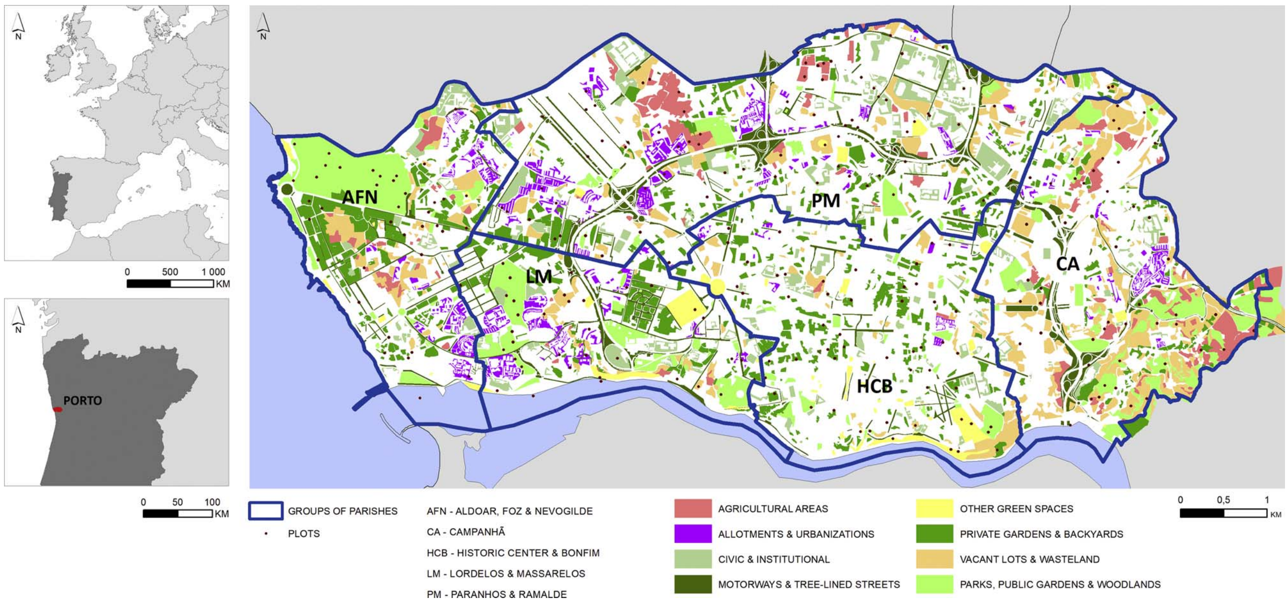

Fig. 1. Location of the city of Porto in the Northwest part of Portugal (left). Groups of parishes and typologies of urban green spaces (Appendix A) in Porto (right) used to, respectively, pre-stratify and post-stratify the 211 field plots used in this investigation (for interpretation of the references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

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.

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 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

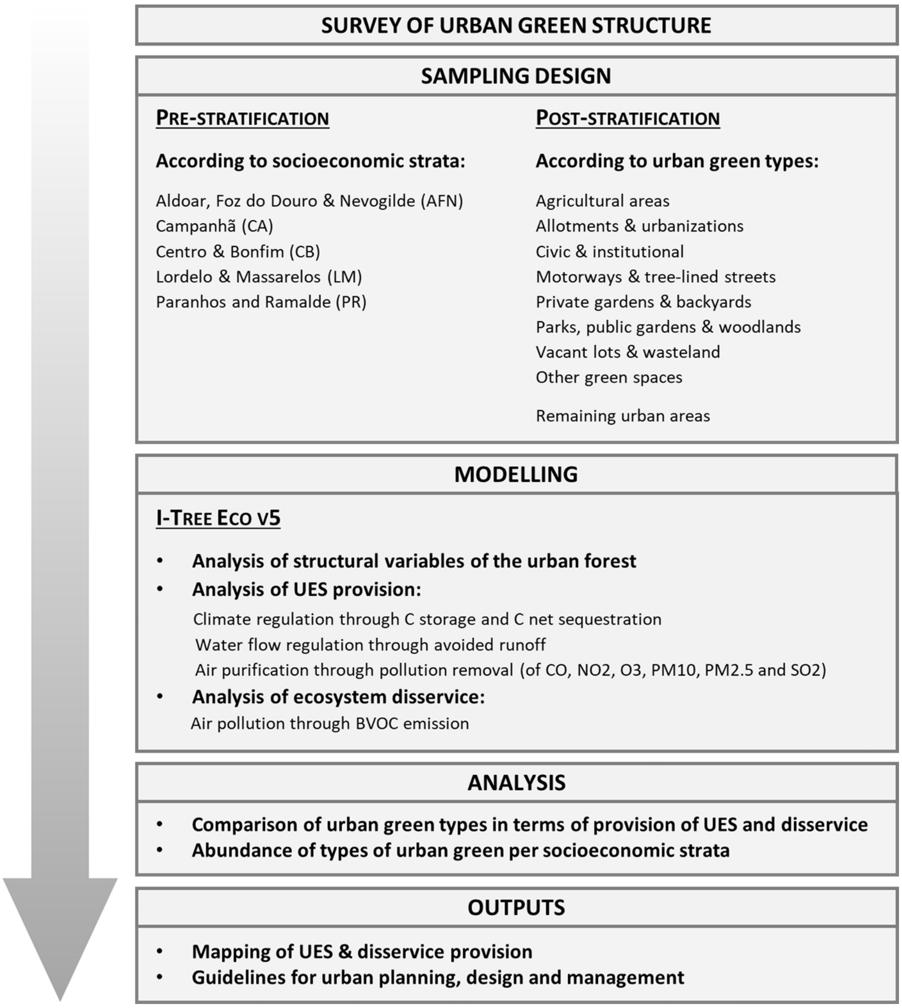

Fig. 2. Diagram of the methodology developed to investigate how different types of urban green spaces influence urban ecosystem services (UES) delivery across a socioeconomic gradient in Porto (Portugal).

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

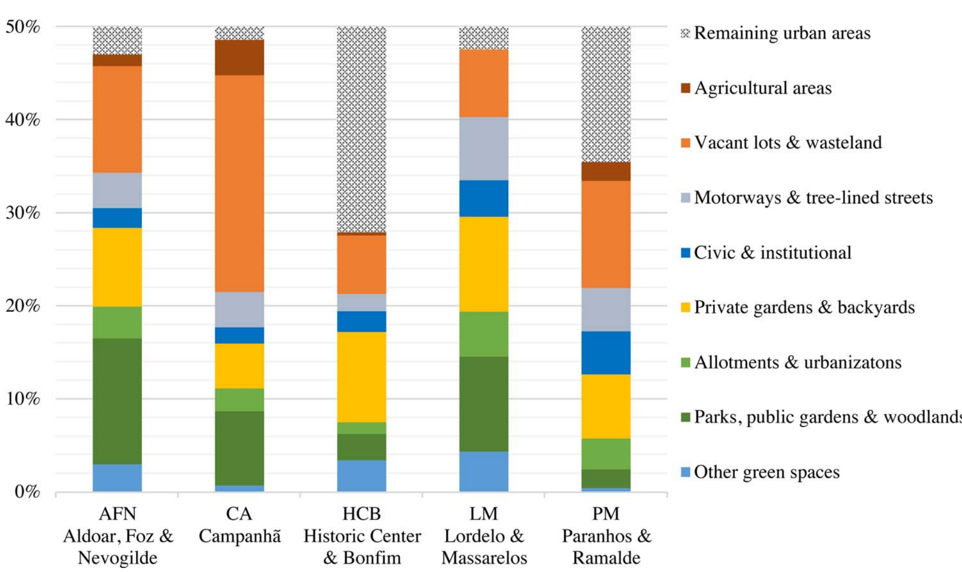

Fig. 3. Proportion of types of green spaces in total urban area per group of parishes in Porto. Graph bars illustrate only 50% of total area in each strata because the sum of green areas is below this percentage in all cases.

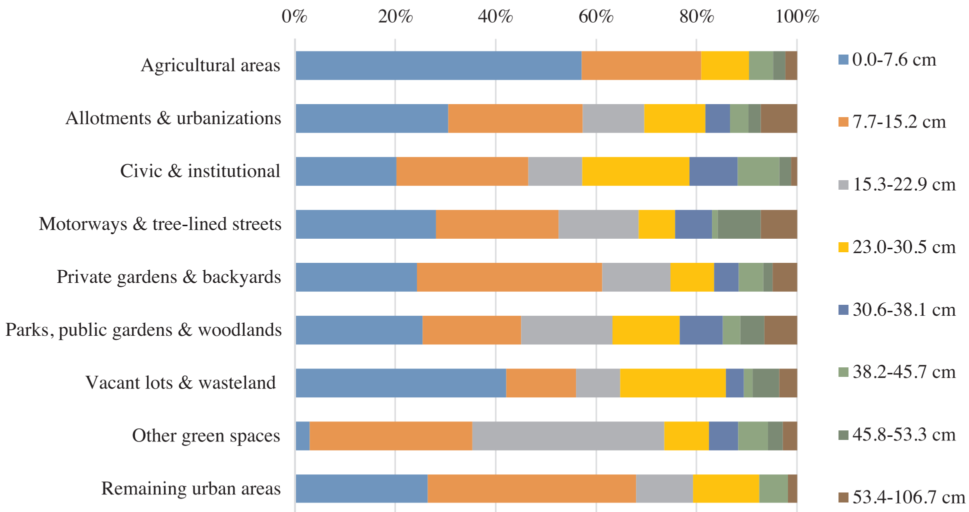

Fig. 4. Composition of tree population according to Diameter at Breast Height (DBH) class, per typology of urban green areas in Porto, estimated from sample means.

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

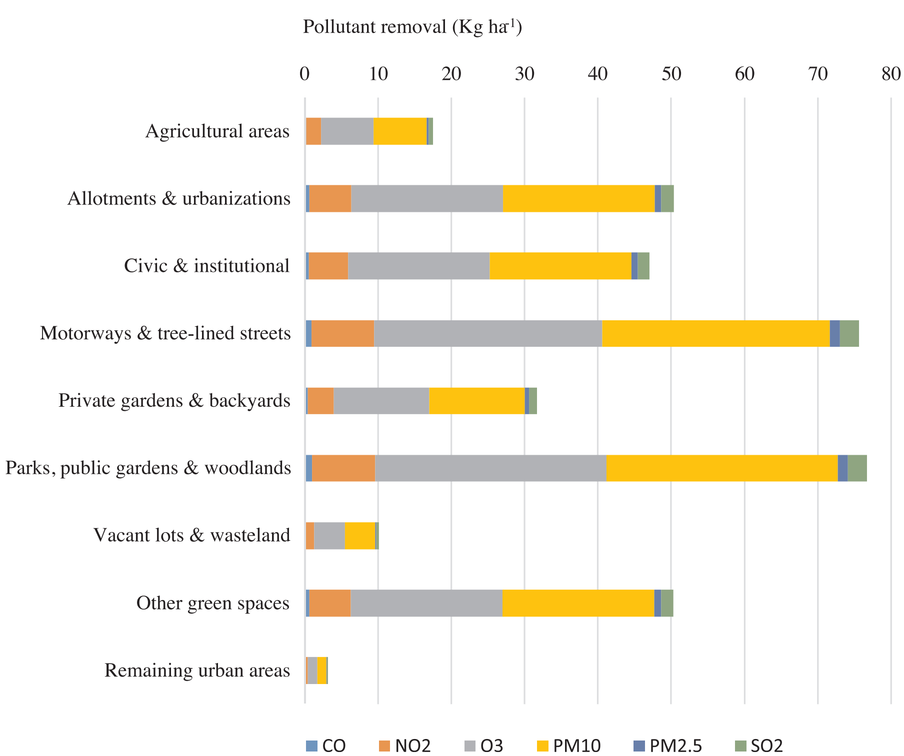

Fig. 5. Pollution removal per typology of urban green areas in Porto in 2011, estimated from sample means.

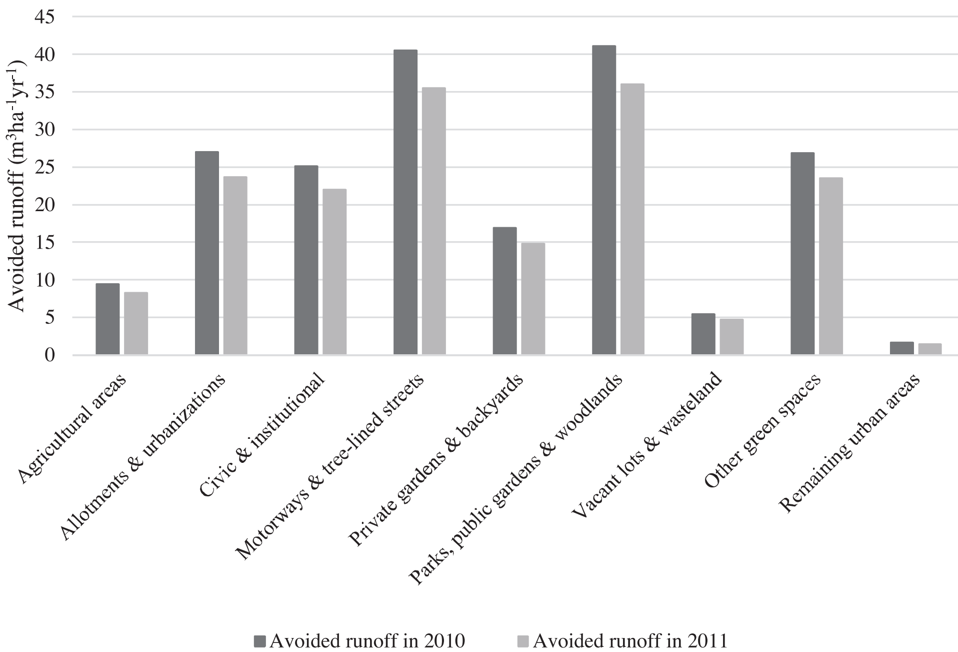

Fig. 6. Comparison of avoided runoff in 2010 and 2011 for trees in Porto, per typology of urban green areas (estimated from sample means).

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

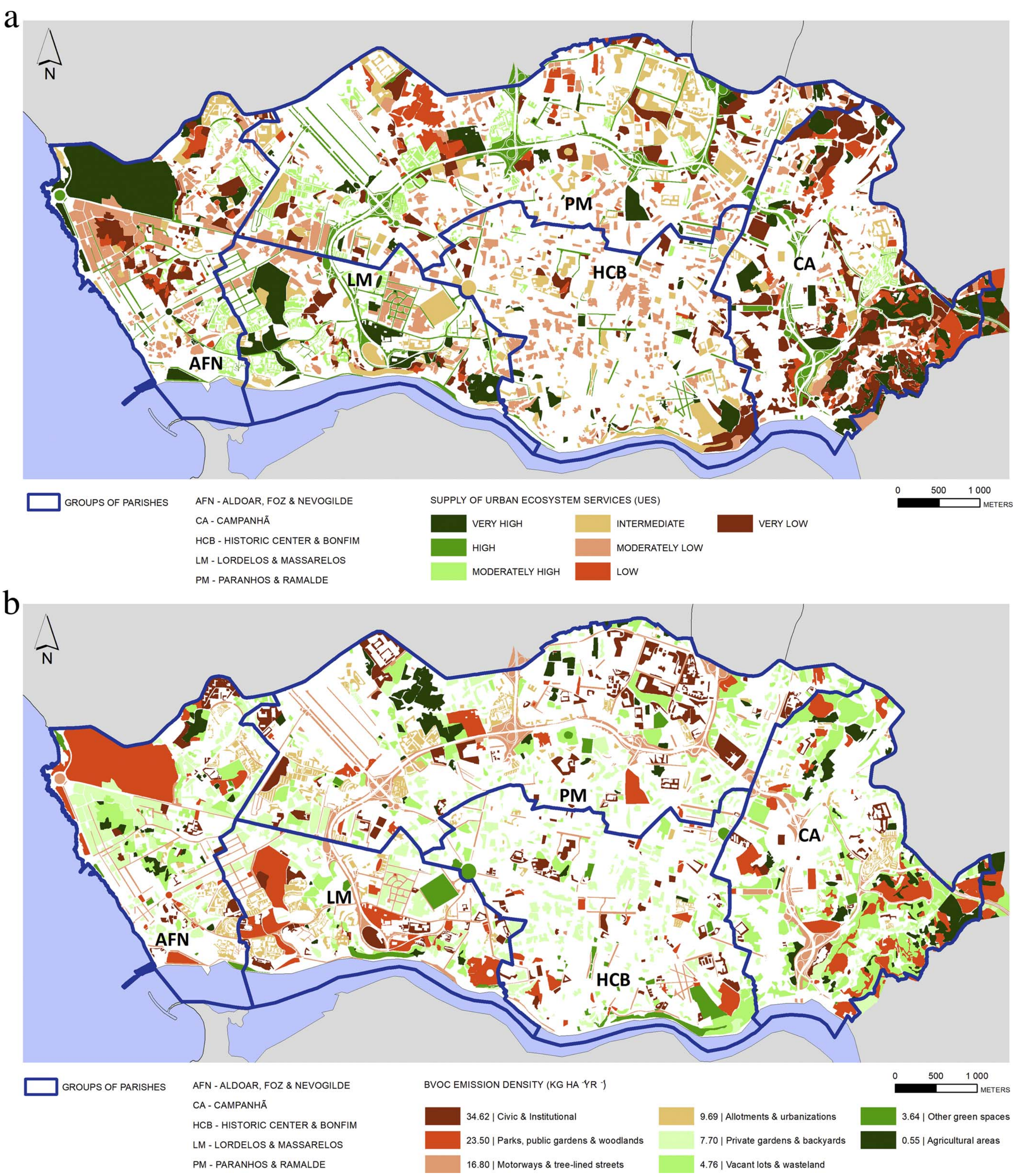

Fig. 7. (a) Performance of urban green areas per group of parishes of Porto, according to the average provision of four urban ecosystem services (UES): climate regulation through carbon storage and carbon sequestration; water flow regulation through avoided runoff; air purification through pollution 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 socio-economic 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

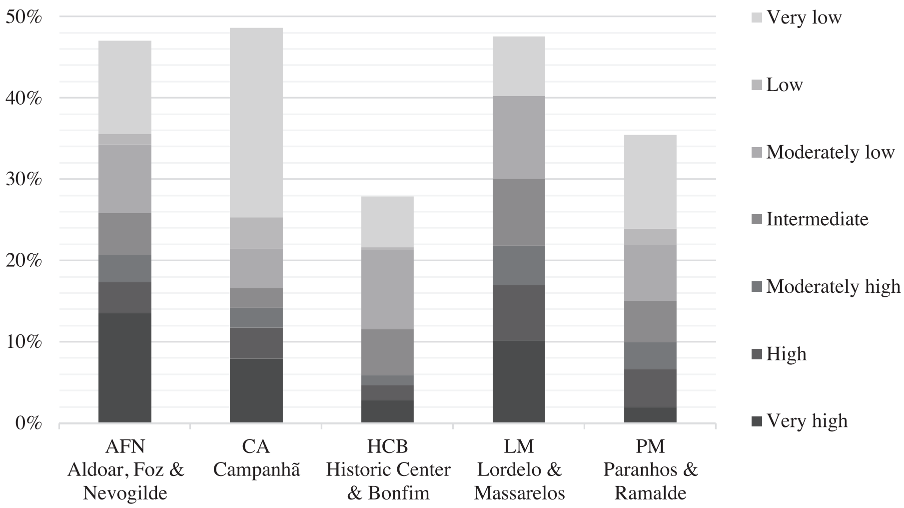

Fig. 8. Proportion of green spaces per group of parishes in Porto, according to the performance regarding delivery of regulating urban ecosystem services (UES). Ranking classes refer to the overall level of proficiency assigned to each type of green space: very high, high, moderately high, intermediate, 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 intrerception 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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Paper 3

Graça, M., Queirós, C., Farinha-Marques, P., Cunha, M. (2018). Street trees as cultural elements in the city: understanding how perception affects ecosystem services management in Porto, Portugal. *Urban Forestry & Urban Greening*, *30*, 194-205.

Paper available online on February 7, 2018

Classification according to journal: research paper

Bibliometric indicators from the Journal Citation Report, Institute for Scientific Investigation

- Journal impact factor 2.113

- Journal rank

Forestry: position 9/64; quartile Q1, JIF percentile 86.719

Urban Forestry & Urban Greening 30 (2018) 194–205

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

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

Street trees as cultural elements in the city: Understanding how perception affects ecosystem services management in Porto, Portugal

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ARTICLE INFO

Keywords:
Environmental justice
Preferences
Social-ecological systems
Sociocultural values
Urban planning
Urban greening

ABSTRACT

Processes shaping urban ecosystems reflect and influence the cultural context in which they emerge, bearing implications for ecosystem services (ES) planning and management. Investigating the perception of benefits and losses / costs delivered by a specific service providing unit (SPU) can generate objective orientations suitable for urban planning and management deeply embedded in the social-ecological systems where they occur, because the realization of ES into benefits and losses / costs is mediated by specific beneficiaries and reflects their characteristics, information and use of ecosystems. Street trees are a particularly relevant SPU in many densely built Southern-European cities due to the difficulty in implementing new sizeable green areas. In this study, a questionnaire was developed and applied in Porto to investigate how benefits (cultural, regulating and economic) and losses / costs caused by street trees are perceived by citizens and influenced by a set of socio-economic variables (N = 819 people aged 18 years or older), and parametric statistical tests were used to analyze the effect of gender, age and school level. Results evidenced that people in Porto valued more environmental benefits (particularly air quality improvement) than cultural ones. School level was the variable accounting for more differences, underlining a tendency in people with lower level of academic education to value less the benefits provided by street trees in Porto and attribute more importance to losses and damages, compared to people who attended university or had higher academic degree. Age also held considerable differences in mean responses, with older people showing more concern towards losses and costs, while gender influenced perception of cultural benefits, which were more important for women than for men. The findings of the research are discussed concerning implications for environmental justice, planning and management of urban ecosystems.

1. Introduction

Mainstreamed by the Millennium Ecosystem Assessment as the benefits human populations obtain from ecosystems (MEA, 2005), ecosystem services (ES) emerged as a metaphor to highlight public awareness on our dependence of nature, in order to foster biodiversity conservation (Gómez-Baggethun et al., 2010). However, the concept has been on the verge of stripping the human-nature relationship of the highly complex social-cultural drivers that define it (Chan et al., 2012). Ecosystems are not only shaped by humans according to diverse sets of cultural values, they also reflect and influence cultural systems in a bidirectional relational process. Hence, humans are not passive receptors of benefits and values generated by ecosystems, but rather active players in the interactive process that generates ES. It follows that processes shaping ecosystems cannot be properly understood without considering the cultural context in which they emerge, bearing implications for ES planning and management.

Cultural ecosystem services (CES) probably reflect more than any other type of ES the beliefs and practices behind landscape change, because they are imbued of the individual and collective experience upon which our relationship with nature is set. According to Fish et al. (2016), CES are the “ecosystems’ contribution to the non-material benefits (capabilities and experiences) that arise from human-ecosystem relationships”. CES generate many physical, emotional and

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https://doi.org/10.1016/j.ufug.2018.02.001
Received 21 August 2017; Received in revised form 10 December 2017; Accepted 5 February 2018
Available online 07 February 2018
1618-8667/

mental benefits (Fish et al., 2016; Russell et al., 2013), and their importance has been found to increase globally in developed countries, as dependence on provisioning and regulating ES decreases (Guo et al., 2010); in addition, they have a low potential for replacement, once degraded in the ecosystem (Plieninger et al., 2013).

Nevertheless, most CES are rarely accounted in an explicit manner in assessments and decision-making processes that shape the landscape (Chan et al., 2012; Plieninger et al., 2013), especially in urban settings, despite being considered by and large particularly important for the wellbeing of city dwellers, compared to other types of ES (Andersson et al., 2015b; La Rosa et al., 2016). Many challenges make it difficult to assess and value CES, although they have been increasingly considered a top priority for ES research to assist in tailoring urban planning and management of social-ecological systems (Kremer et al., 2016).

In light of the growing proportion of worldwide urban population, estimated to surpass 66% by 2050 (United Nations, 2014), urban ecosystems are becoming increasingly important for human wellbeing. They provide the interface through which most citizens primarily experience nature regularly, and potentially engage in a meaningful relationship that supports their welfare and happiness. In addition, previous research has shown the importance of informal stewardship in generating ecosystem services (Andersson et al., 2007), which is deeply influenced by local culture and knowledge systems. Therefore, understanding how citizens perceive and value urban ecosystems can generate insights about the cultural practices shaping them. Such knowledge might help to derive planning and management practices of urban ecosystems grounded in specific cultural contexts, which can potentially generate stronger values towards nature. This is particularly important, because a difference exists between potential and actual delivery of CES, the latter depending on the existence of beneficiaries recognizing value in ecosystems (Bagstad et al., 2014), which is not necessarily the case for a given urban setting (Kronenberg, 2015; Rae et al., 2016).

Fish et al. (2016) proposed a novel approach to understand CES as non-linear, relational *processes and entities* resulting from human-ecosystem interactions. According to these autors, CES are not unidirectional contributions of nature used or consumed by humans; instead, they are co-produced within culture-nature relationships, and are composed of two parts: the environmental places, or the geographical contexts of interaction between nature and people, and the cultural practices taking place in them. This idea is also conveyed by the Common International Classification of Ecosystem Services (CICES), in which "cultural services are primarily regarded as the physical settings, locations or situations that give rise to changes in the physical or mental states of people", thereby proposing a distinction between "settings that support interactions that are used for physical activities such as hiking and angling, and intellectual or mental interactions involving analytical, symbolic and representational activities" (Haines-Young and Potschin, 2013). By disentangling services from benefits, and identifying explicitly the components of CES, this conceptualization helps to bring down to earth the intangible elements in the social-cultural dimension of ES.

It is also crucial to establish direct relationships between specific cultural benefits and components of urban ecosystem that affect ES supply. According to Andersson et al. (2015a), the concept of Service Providing Units (SPU) can help to better understand the links between ES and the spatial structure and dynamics that sustain them, through the identification of "the smallest distinct physical unit that generates a particular ES and is addressable by planning and management". We suggest that investigating cultural benefits and losses/costs delivered by a specific urban SPU can provide objective orientations suitable for urban planning and management deeply embedded in the social-ecological systems where they occur, because the realization of ES into benefits and losses/costs is mediated by specific beneficiaries, and reflects their characteristics, perception, information and use of ecosystems (Fig. 1).

Street trees are a particularly relevant SPU in Southern-European cities because the usually dense urban matrix prevents the creation of new sizeable green areas. Street trees therefore constitute the most abundant and conspicuous public green element in these cities, and the most accessible form of nature to a significant share of the population. Moreover, urban trees provide many local ES (Roy et al., 2012) although scientific evidence identifying the specific environmental processes mediating street trees contribution to health outcomes is still scarce (Salmond et al., 2016). Nevertheless, many studies have related street trees with positive impacts in microclimate regulation (Gillner et al., 2015; Shashua-Bar et al., 2010; Vailshery et al., 2013), air quality regulation (Pugh et al., 2012; Vailshery et al., 2013) and stormwater regulation (Armson et al., 2013; Stovin et al., 2008). Research has also established links between urban street tree density and antidepressant rates (Taylor et al., 2015) and lower asthma prevalence in children (Lovasi et al., 2008), although some studies suggest that specific social processes, such as social cohesion, mediate the path between streetscape greenery and health outcomes (De Vries et al., 2013). Street trees therefore have the potential to enhance urban resilience and positively influence the quality of life in cities. However, the notion of benefit is highly subjective and should also be considered when developing strategies to support urban wellbeing: what is considered desirable by a particular social group can simultaneously be regarded as nuisance by another group, and some benefits stemming from ecological processes might not be perceived at all by local communities without proper formulation by responsible stakeholders, via participatory processes (Tadaki et al., 2015). Likewise, certain benefits generated by urban trees might be more demanded in contexts of environmental inequity

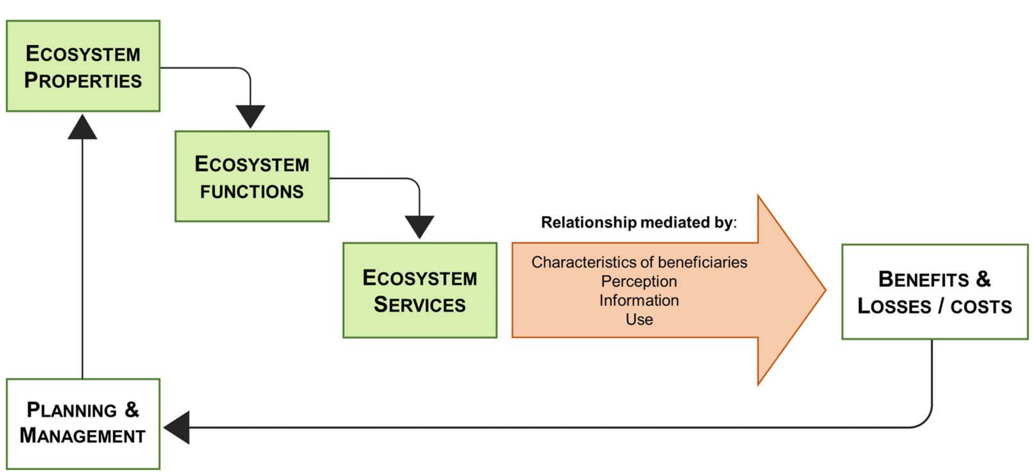

Fig. 1. Planning and management of social-ecological systems considering the role of beneficiaries in mediating the realization of benefits and losses/costs from ecosystem services.

(Landry and Chakraborty, 2009). For example, cooling and thermal comfort might be especially important for deprived social groups in urban areas prone to extreme heat events, who lack economic resources to mitigate exposure to heat stress (Jenerette et al., 2011; Pham et al., 2012). Socioeconomic factors and local environmental factors also influence attitudes and preferences of city dwellers towards urban trees (Avolio et al., 2015). Heynen et al. (2006) concluded that residents in poorer areas of Milwaukee were less fond of urban trees, and more aware of their disservices, implying that planting more trees in these communities would potentially augment their feeling of disempowerment. Schroeder et al. (2006) also observed that variables such as climate and proximity of trees to houses can affect attitudes of residents regarding street trees, and Fraser and Kenney (2000) found that cultural differences affected perception of the urban forest by four communities living in Canada. These findings suggest the need to customize locally decision-making frameworks based in ES, and bring together the cultural and scientific understanding in order to take into account both who are the beneficiaries of urban greening initiatives, and how they are actually benefited, to effectively generate positive outcomes for wellbeing.

Following this reasoning, an exploratory case study was developed in Porto, Portugal, to investigate the hypothesis that benefits and losses caused by street trees are perceived differently by citizens according to a set of socioeconomic variables: age, gender and school level. Results are discussed in light of existing scientific knowledge about ES supply by urban trees in Porto, and considering the implications for planning and management of urban ecosystems.

2. Methods

2.1. Study area

The research was developed in Porto (Fig. 2), the center of the second largest metropolitan area in Portugal. The city covers 41.4 km^2 and has a population of 237 591 residents (INE, 2011), but polarizes the daily commuting of the 17 municipalities of Porto Metropolitan Area (PMA), where 1 759 524 inhabitants live. Porto was the municipality of PMA with the greater negative variation in resident population between 2001 and 2011 (−6%; Faria et al., 2014), suffering from a double aging process due to the simultaneous increase of inhabitants over 65 years old (+27% of total population in 2015) and decrease of population ranging 0–14 years old (−12,3%; FFMS, 2017).

Porto has Mediterranean climate (Csb climate, according to Köppen-Geiger classification), with temperatures usually ranging between 5.0–16.8 °C in winter and 13.8–25.0 °C in summer (however they can reach 36 °C or higher) and precipitation averaging 1254 mm annually (IM, 2011). The city is fringed by the Atlantic Ocean in the west, and Douro River establishes the southern limit.

Abundant green areas and an immense rural belt surrounded the small urban core by the end of the 19th century. The interior of many blocks was green, there was a considerable number of public gardens and green areas totalized about 75% of the city, which decreased to a meager 30% by 2000 due to intense urbanization (Madureira et al., 2011). Nevertheless, Porto still holds outstanding value and the historic center was recognized as UNESCO World Heritage in 1996, attracting many tourists.

Nowadays, street trees are the green feature most accessible to the population in many parts of the densely built-up city. Furthermore, in a study comparing delivery of several regulating ES in Porto by eight types of green space, street trees were included in the second most proficient green type per unit area (Graça et al., 2018) hence constituting a major provider of local benefits.

Many studies also indicate Porto as an urban area particularly susceptible to the impacts of climate change and increased heat-wave risk (Lau et al., 2015; Monteiro et al., 2013; Rafael et al., 2016).

2.2. Survey design and implementation

A questionnaire was developed to assess how citizens perceive benefits and losses/costs caused by street trees in Porto, and what characteristics of the beneficiaries influence more strongly their opinion. Drawing from a literature review, potential cultural and economic benefits provided by street trees were listed, and possible losses/costs were likewise enumerated. Benfits related to provision services such as food or fiber supply were not included in this list, due to their residual importance in Porto.

To explore how information about urban ecosystems can affect perception regarding street trees, regulating ES were explicitly accounted for in our inventory. As regulating ES can provide multiple benefits simultaneously, one single benefit particularly relevant for urban planning and management was selected to represent each of six classes: i) air quality, ii) global climate regulation, iii) microclimate

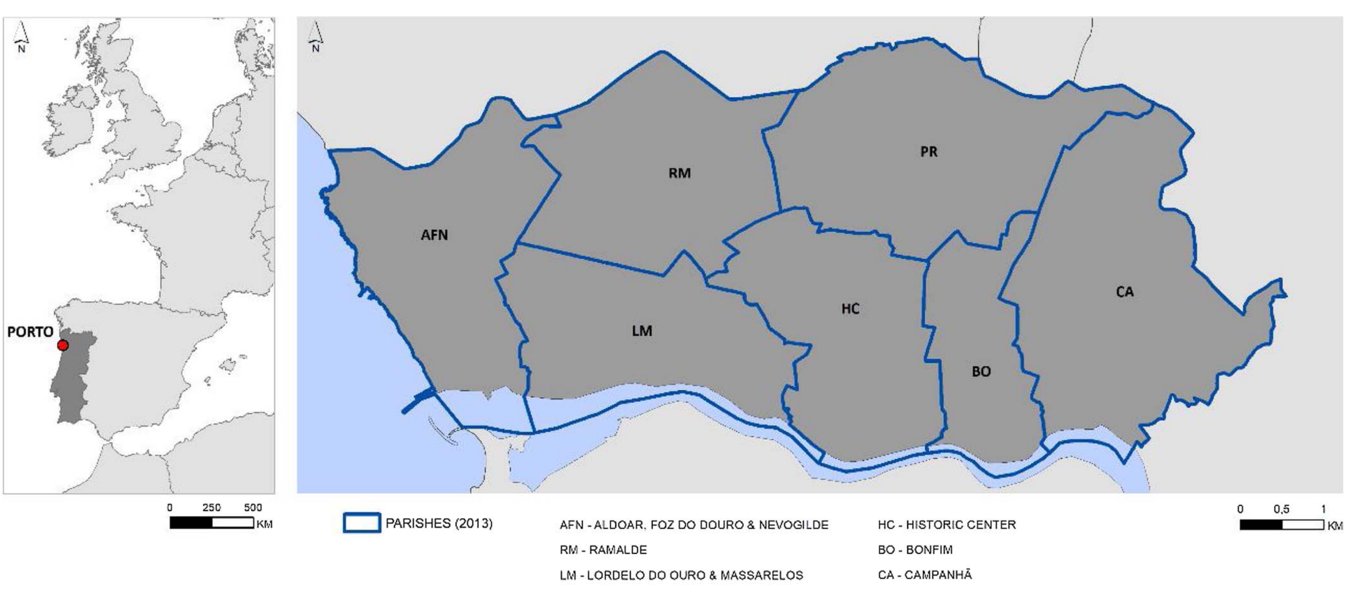

Fig. 2. Localization of the city of Porto, in Portugal (left), with the delimitation of the seven administrative parishes established since 2013 (right).

Table 1
Classes of potential benefits, losses/costs and ecosystem services generated by street trees.

Classes	Definition
Cultural benefits	
Inspiration	Stimulating new ideas, thoughts and/or creative expressions
Aesthetic pleasure	Beautifying streets, views and/or the city
Social cohesion	Promoting meetings with friends and neighbors
Leisure activities	Promoting recreation and tourism by providing pleasant places for walking, running, cycling, …
Sense of place	Fostering a sense of attachment to a place and/or to the city
Spiritual enrichment	Representing spiritual, religious, or personal special meanings
Education	Raising curiosity and knowledge about nature's cycles and biodiversity
Cultural heritage	Supporting local historical/cultural values and identity
Economic benefits	
Real-estate valorization	Increasing the monetary value of real-estate
Prosperous commerce/tourism	Fostering commercial/touristic activities which provide monetary revenues
Energy conservation	Increasing energetic efficiency of buildings, by reducing consumption of energy for cooling/heating
Losses & costs	
Goods and property damage	Damaging goods and structures such as cars, sidewalks, walls, …
Allergy risk	Increasing allergic reactions due to pollen release
Sunlight blocking	Providing unwanted shade, blocking sunlight
Visibility decrease	Reducing visibility to streets (from home)
Risk to individual integrity	Increasing risks for people's security due to tree or branch fall
Litter	Undesired accumulation of residues due to leaf and fruit fall
Insecurity feelings	Increasing fear of potential criminal activity in streets due to reduced visibility caused by trees
Unpleasant view	Unattractive views due to neglected maintenance or bad condition of trees
Maintenance costs	Public funds needed to support tree plantation and maintenance
Regulation & maintenance of ecosystems	Associated benefits
Air quality regulation	Improving air quality through removal of atmospheric pollutants
Climate regulation	Supporting global climate regulation through carbon sequestration/reduction of greenhouse gas concentrations
Microclimate regulation	Improving microclimatic comfort through regulation of local temperature and wind
Stormwater regulation	Preventing or mitigating floods by slowing down and intercepting rainwater before falling to the ground
Noise mediation	Buffering the noise of cars or specific activities
Habitat maintenance	Supporting lifecycle conditions for biodiversity in cities

These variables were selected and defined adapting lists from Bolund and Hunhammar (1999); Dobbs et al. (2011); Escobedo et al. (2011); Jim and Chen (2006); MEA (2005); Nowak and Dwyer (2007); Plieninger et al. (2013). Following the service cascade model proposed by Haines-Young and Potschin (2010), regulation and maintenance items were considered ecosystem services, to which benefits are associated; the list here presented for these services was built upon the Common International Ecosystem Service Classification (CICES).

regulation, iv) stormwater regulation; v) noise mediation and vi) habitat maintenance. Additionally, we followed the approach of CICES regarding supporting services (as defined by the Millennium Ecosystem Assessment), and considered that these are not final services or outputs directly consumed or used by beneficiaries (Haines-Young and Potschin, 2013), thereby not accounting them in this study. The resulting list (Table 1) was used to outline one single statement translating each variable into an easily comprehensible concept for the general population. A set of three additional statements was created to assess the general opinion of people about street trees in Porto, expressing their perceived trade-off between benefits and losses/costs.

The final set of 29 statements was organized in a questionnaire in Portuguese (Appendix A) consisting of three groups of questions. The first block consisted of seventeen questions in which interviewees were asked to rate the level of importance they attributed to a set of cultural, regulating and economic benefits provided by street trees according to a Likert-type scale with five possible responses (0 – not important, 1 – not very important, 2 – important, 3 – very important, 4 – no opinion). An open question was also included, to allow responses not included in the list of benefits developed by the research team. The second block included nine statements about potential losses/costs that interviewees should classify according to a five-class agreement scale (1 – strongly disagree, 2 – disagree, 3 – agree, 4 – strongly agree, 5 – no opinion). The same agreement scale was used in the last group of questions, in which the respondents were asked to evaluate the following three statements: "Trees bring more benefits than damages", "Bigger trees bring more benefits than smaller trees", and "The city of Porto needs more trees". The questionnaire also included fields to register the socioeconomic variables: age, gender and school level.

A test questionnaire was applied to a sample of ten convenience people of different ages, gender and school levels, unaware of the purposes and methods of this case study, to assess the duration of the interview (estimated around five minutes) and the clearness and meaning of the statements.

The final revised questionnaire was applied between February and May of 2017 in the streets of the city to a sample of 819 people aged 18 years or above, characterized in Table 2. The sample was representative of Porto's population regarding gender and age, although the age class 18–24 years old was overrepresented (15.6% in the sample versus 9% of the adult population in Porto) and people older than 64 years were underrepresented (19.8% versus 27.2% of the adult population). The proportion of people holding the 9th grade or below was smaller in the sample than in the real population (35.3% versus 51.6%), and consequently all other school levels were overrepresented.

The interviews were conducted mostly by students of the 11th and 12th grades of four secondary schools in Porto, and also by research staff. To recruit students, eighteen schools (public and private) with secondary school classes in Porto were invited directly or on behalf of the research team to participate in this project. Four schools accepted to take part in the project, and were subsequently contacted to schedule informative/training sessions for all participating classes in each school before carrying out the interviews. The purpose of the sessions was to familiarize students with the objectives of the study and the procedures to follow during the fieldwork. The distribution of teams was organized in order to target, as best as possible, the different zones of the city.

2.3. Statistical analysis

To study how citizens perceive benefits and losses/costs caused by street trees in Porto, the differences in mean response for each question

Table 2
Socioeconomic characterization of a sample of 819 people interviewed between February and May of 2017 in the streets of Porto (Portugal), to explore perception of benefits and losses/costs caused by street trees.

Socioeconomic variables	Classes	Percentage in sample	Percentage in Porto (INE, 2011)[a]
Gender	Men	46.2	45.5
	Women	53.8	54.5
School level	9th Grade or below	35.3	51.6
	High school (≤12th grade)	25.8	16.5
	University	28.2	24.7
	Master or higher degree	10.8	7.2
Age class (years old)	<18	–	14.8
	18–24	15.6	7.7
	25–44	31.6	25.6
	45–64	33.1	28.7
	+64	19.8	23.2
Municipality	Porto	73.0	–
	Other	27.0	–

[a] Percentages for school level in Porto refer only to the population aged 18 years or above.

(Appendix A), were assessed according to socioeconomic variables using one-way analysis of variance (ANOVA) for age and school level, and Student tests (*t*-test) for gender (variable with only two levels: men and women). Additionally, a single average response was calculated for each of the four dimensions of questions included in the questionnaire (cultural and economic benefits; regulation & maintenance ES; losses/costs caused by street trees; Table 1), by summing up the mean response for each individual question in a dimension, and then dividing the result for the total number of questions in that dimension. The objective was to assess if any of these dimensions held considerably more importance for respondents.

The main assumptions of normality and homogeneity of variance for the population samples were checked using respectively the Kolmogorov–Smirnov and Levene tests, which confirmed the non-normality of some variables. Nevertheless, parametric tests have been shown to yield robust results when analyzing data obtained with Likert-type scales, even though these are conceptually ordinal and may violate homogeneity of variance and normality assumptions (for a thorough discussion about the use of parametric tests to analyze data from Likert scales see Norman, 2010). In addition, we used a very large independent sample to insure that the distribution of response means approached a normal distribution, as established by the Central Limit Theorem of probability theory.

Results of ANOVA were expressed as F-ratio values (Fischer test) and the W-ratio value (Welch test) was used for cases without homogeneity of variance. Whenever differences resulted significant, individual means were compared using planned orthogonal contrasts ($p < 0.05$). Orthogonal contrasts are an essential aid in reducing the number of possible pairwise comparisons to the maximum number of independent hypotheses, and hence in ensuring the testability by comparing each level or class of each variable against the remaining, subsequently grouping together levels/classes that share similarities. All statistical analysis were run in IBM SPSS version 24.

3. Results

3.1. Aggregated dimensions of benefits and losses

Average responses according to the four dimensions of the questionnaire (cultural and economic benefits; regulation and maintenance ES; losses/costs caused by street trees) are presented in Table 3, and indicate that the people interviewed valued mostly the regulation & maintenance ES provided by street trees (mean: 2.40). Cultural benefits were also considered important (mean: 2.16), while economic benefits were the less appraised ones (mean: 1.89). The dimension concerning losses/costs was the one yielding the highest mean (2.60) among the four considered in our analysis, because a different numeric scale was associated with the possible responses to express agreement instead of degree of importance for each statement.

Results showed statistically significant differences of response according to gender only for the cultural benefits dimension, which was more important for women (mean: 2.22) than for men (mean: 2.08). Age also affected significantly responses, with older people (+64 years) consistently valuing more losses caused by street trees than other age classes, and the contrast analysis highlighted a dichotomy between people aged 18–44 years old and those above 44 years (Table 3). This suggests that differences of opinion are more pronounced when this threshold is crossed. The variable associated with the highest impact in mean responses was school level, which revealed significant differences for all the four dimensions considered in the questionnaire. People holding higher education level (university attendance or above) valued cultural benefits and regulation & maintenance ES considerably more than people holding lower school level, also showcasing a threshold between the first two classes and the two last. The contrast analysis showed that only people in the high school class had a significantly lower mean response concerning the economic benefits dimension, compared to all other classes. This might be due to the high variability in responses in this dimension (confirmed by the higher standard error of means), probably reflecting more individual differences than socioeconomic patterns. The losses/costs caused by street trees were significantly considered more important by people holding lower academic level than by people who attended or completed an university degree.

3.2. Individual benefits

Considering the sample as a whole, responses for individual items reflected the findings concerning the dimensions of benefits most and least valued (Table 4). All the regulation & maintenance ES ranked in the top positions of importance, with the exception of noise mediation (mean: 2.01). Nevertheless, two cultural benefits were also very highly accounted by respondents: aesthetic pleasure (mean: 2.46), and leisure activities (2.44). The benefit considered in average the least important of all was spiritual enrichment generated by street trees (mean: 1.50). Among economic benefits, the contribution of street trees to energy conservation in buildings was the most highly regarded (mean: 2.06). Promoting local commerce and tourism or increasing the monetary value of real-estate were considered among the least important benefits provided by street trees (mean: 1.71 and 1.90, respectively).

Gender played an important role in how benefits were perceived,

Table 3
Average perception of four dimensions of variables – cultural benefits, economic benefits, regulation & maintenance ecosystem services (ES), and losses/costs – generated by street trees in Porto (Portugal), according to socioeconomic variables. Results for 819 interviews.

Socioeconomic variables	Cultural benefits	Economic benefits	Regulation & maintenance ES	Losses & costs
Gender				
Men	2.08 (0.02)	1.89 (0.04)	2.36 (0.02)	2.58 (0.03)
Women	2.22 (0.02)	1.89 (0.04)	2.44 (0.02)	2.61 (0.03)
Student's t-test (Sig.)[1]	0.000	0.976	0.013	0.456
Age class (yrs)				
18–24	2.09 (0.04)	1.83 (0.06)	2.36 (0.04)	2.45 (0.04)[a]
25–44	2.20 (0.03)	1.91 (0.05)	2.46 (0.03)	2.52 (0.04)[a]
45–64	2.16 (0.03)	1.987 (0.04)	2.39 (0.03)	2.66 (0.03)[b]
+64	2.13 (0.04)	1.95 (0.06)	2.36 (0.04)	2.75 (0.04)[b]
ANOVA (Sig.)[2]	0.139	0.478	0.120	0.000
School level				
≤9th Grade	2.10 (0.03)[a]	1.94 (0.04)[a]	2.32 (0.03)[a]	2.76 (0.03)[a]
High school	2.10 (0.03)[a]	1.73 (0.05)[b]	2.33 (0.03)[a]	2.59 (0.03)[b]
University	2.22 (0.03)[b]	1.92 (0.05)[a]	2.53 (0.03)[b]	2.45 (0.03)[c]
≥Master degree	2.26 (0.05)[b]	2.02 (0.08)[a]	2.51 (0.05)[b]	2.42 (0.06)[c]
ANOVA (Sig.)[2]	0.001	0.003	0.000	0.000
Total sample	2.16 (0.02)	1.89 (0.03)	2.40 (0.02)	2.60 (0.02)

Response results are expressed as Mean (Standard Error) of response in a Likert-type importance scale for benefits and ES (0 – not important; 1 – not very important, 2 – important, 3 – very important), and an agreement scale for losses/costs (1 – strongly disagree, 2 – disagree, 3 – agree, 4 – strongly agree).
The superscript letters highlight differences between levels of one socioeconomic variable concerning mean responses; levels with similar responses for one dimension do not differ significantly according to orthogonal contrast analysis ($p < 0.05$).
[1] Significance of Student's *t* -test.
[2] Statistical significance of the F test (Fischer) or Welch test (for cases with unequal variances).

Table 4
Comparative analysis of potential benefits, ecosystem services (ES) and losses/costs generated by street trees in Porto (Portugal), for total sample and according to gender. Results for 819 interviews.

Benefits, ES and losses/costs		Gender		Student's *t*-test (Sig.)[1]
	Sample	Men	Women	
Cultural benefits				
Inspiration	2.07 (0.03)	1.96 (0.04)	2.15 (0.03)	0.000
Aesthetic pleasure	2.46 (0.02)	2.40 (0.03)	2.52 (0.03)	0.005
Social cohesion	2.22 (0.03)	2.17 (0.04)	2.26 (0.03)	0.063
Leisure activities	2.44 (0.02)	2.41 (0.03)	2.47 (0.03)	0.144
Sense of place	2.18 (0.03)	2.13 (0.04)	2.23 (0.03)	0.054
Spiritual enrichment	1.50 (0.04)	1.37 (0.05)	1.62 (0.05)	0.001
Education	2.21 (0.03)	2.11 (0.04)	2.29 (0.03)	0.000
Cultural heritage	2.10 (0.03)	2.03 (0.04)	2.16 (0.04)	0.016
Economic benefits				
Real-estate valorization	1.71 (0.04)	1.71 (0.05)	1.70 (0.05)	0.825
Prosperous commerce and/or tourism	1.90 (0.03)	1.88 (0.05)	1.91 (0.04)	0.659
Energy conservation	2.06 (0.03)	2.03 (0.05)	2.08 (0.05)	0.460
Regulation & maintenance ES				
Air quality regulation	2.71 (0.02)	2.69 (0.03)	2.73 (0.03)	0.268
Climate regulation	2.48 (0.02)	2.42 (0.04)	2.53 (0.03)	0.017
Microclimate regulation	2.45 (0.02)	2.40 (0.04)	2.49 (0.03)	0.059
Stormwater regulation	2.37 (0.03)	2.32 (0.04)	2.41 (0.04)	0.097
Noise mediation	2.01 (0.03)	1.95 (0.05)	2.06 (0.04)	0.092
Habitat maintenance	2.41 (0.02)	2.36 (0.04)	2.45 (0.03)	0.060
Losses & costs				
Goods and property damage	2.65 (0.03)	2.60 (0.04)	2.68 (0.04)	0.184
Allergy risk	2.95 (0.03)	2.89 (0.04)	3.00 (0.04)	0.071
Sunlight blocking	2.40 (0.03)	2.35 (0.05)	2.44 (0.04)	0.166
Visibility decrease	2.44 (0.03)	2.41 (0.04)	2.45 (0.04)	0.545
Risk to individual integrity	2.67 (0.03)	2.64 (0.04)	2.68 (0.04)	0.510
Litter	2.67 (0.03)	2.67 (0.04)	2.67 (0.04)	0.982
Insecurity feelings	2.35 (0.03)	2.34 (0.05)	2.36 (0.04)	0.764
Unpleasant view	2.65 (0.03)	2.65 (0.05)	2.65 (0.04)	0.921
Maintenance costs	2.54 (0.03)	2.56 (0.05)	2.52 (0.04)	0.535

Response results are expressed as Mean (Standard Error) of response in a Likert-type importance scale for benefits and ES (0 – not important; 1 – not very important, 2 – important, 3 – very important), and an agreement scale for losses/costs (1 – strongly disagree, 2 – disagree, 3 – agree, 4 – strongly agree).
[1] Statistical significance of Student's *t*-test.

Table 5
Comparative analysis of potential benefits, ecosystem services (ES) and losses/costs generated by street trees in Porto (Portugal) according to age classes. Results for 819 interviews.

Benefits, ES and losses/costs	Age classes (years old)				ANOVA (Sig.)[1]
	18–24	25–44	45–64	+64	
Cultural benefits					
Inspiration	1.94 (0.07)	2.13 (0.05)	2.07 (0.05)	2.07 (0.07)	0.133
Aesthetic pleasure	2.43 (0.06)	2.53 (0.04)	2.47 (0.04)	2.37 (0.06)	0.097
Social cohesion	2.13 (0.07)	2.29 (0.04)	2.23 (0.04)	2.15 (0.06)	0.141
Leisure activities	2.50 (0.06)	2.51 (0.04)	2.39 (0.04)	2.38 (0.05)	0.052
Sense of place	2.11 (0.06)	2.21 (0.05)	2.21 (0.04)	2.17 (0.05)	0.583
Spiritual enrichment	1.28 (0.08)[a]	1.53 (0.07)[b]	1.49 (0.06)[b]	1.65 (0.08)[b]	0.018
Education	2.18 (0.06)	2.25 (0.05)	2.20 (0.04)	2.19 (0.06)	0.795
Cultural heritage	2.00 (0.07)	2.12 (0.05)	2.15 (0.04)	2.05 (0.07)	0.249
Economic benefits					
Real-estate valorization	1.59 (0.09)	1.72 (0.06)	1.71 (0.06)	1.79 (0.08)	0.428
Prosperous commerce and/or tourism	1.88 (0.08)	1.86 (0.06)	1.88 (0.05)	2.01 (0.07)	0.391
Energy conservation	2.03 (0.08)	2.12 (0.06)	2.03 (0.06)	2.04 (0.08)	0.710
Regulation & maintenance ES					
Air quality regulation	2.66 (0.05)	2.76 (0.03)	2.71 (0.03)	2.65 (0.05)	0.146
Climate regulation	2.43 (0.06)[ac]	2.58 (0.04)[b]	2.42 (0.05)[ac]	2.45 (0.05)[bc]	0.027
Microclimate regulation	2.39 (0.06)	2.53 (0.04)	2.41 (0.04)	2.43 (0.05)	0.122
Stormwater regulation	2.38 (0.06)	2.43 (0.05)	2.34 (0.05)	2.29 (0.07)	0.333
Noise mediation	1.78 (0.09)[a]	2.03 (0.06)[b]	2.03 (0.06)[b]	2.12 (0.08)[b]	0.021
Habitat maintenance	2.42 (0.05)	2.45 (0.05)	2.42 (0.04)	2.30 (0.06)	0.149
Losses & costs					
Goods and property damage	2.63 (0.07)	2.57 (0.05)	2.73 (0.05)	2.66 (0.07)	0.132
Allergy risk	2.90 (0.07)	2.96 (0.05)	2.99 (0.05)	2.94 (0.07)	0.785
Sunlight blocking	2.25 (0.07)[a]	2.32 (0.05)[ab]	2.45 (0.05)[bc]	2.59 (0.07)[c]	0.001
Visibility decrease	2.26 (0.07)[a]	2.36 (0.05)[ab]	2.49 (0.05)[bc]	2.60 (0.07)[c]	0.002
Risk to individual integrity	2.43 (0.07)[a]	2.61 (0.05)[b]	2.67 (0.05)[b]	2.94 (0.06)[c]	0.000
Litter	2.56 (0.06)[a]	2.57 (0.05)[a]	2.76 (0.05)[b]	2.77 (0.07)[b]	0.003
Insecurity feelings	2.12 (0.06)[a]	2.24 (0.06)[a]	2.41 (0.05)[b]	2.64 (0.07)[c]	0.000
Unpleasant view	2.31 (0.08)[a]	2.51 (0.05)[b]	2.77 (0.05)[c]	2.97 (0.07)[d]	0.000
Maintenance costs	2.49 (0.07)	2.46 (0.05)	2.57 (0.05)	2.69 (0.08)	0.062

Response results are expressed as Mean (Standard Error) of response in a Likert-type importance scale for benefits and ES (0 – not important; 1 – not very important, 2 – important, 3 – very important), and an agreement scale for losses/costs (1 – strongly disagree, 2 – disagree, 3 – agree, 4 – strongly agree).
The superscript letters highlight differences between levels of one socioeconomic variable concerning mean responses; levels with similar responses for one dimension do not differ significantly according to orthogonal contrast analysis ($p < 0.05$).
[1] Statistical significance of the F test (Fischer) or Welch test (for the cases with unequal variances).

with significant differences being found in responses for five out of eight cultural benefits (inspiration, aesthetic pleasure, spiritual enrichment, education and cultural heritage), all of which were more important for women than for men. Women also considered the benefits associated with climate regulation as being more important than men did.

Age was the independent variable accounting for fewer differences in responses concerning benefits provided by street trees (Table 5). People aged 18–24 years valued significantly less spiritual enrichment and noise mediation than older people, and climate regulation was more highly regarded by those between 25 and 44 years old.

The academic education of respondents accounted for significant differences in twelve out of seventeen individual benefits, usually revealing that those who attended or completed a university degree valued more the benefits generated by street trees than those with lower school level (Table 6). Access to university emerged as a threshold affecting mean responses in all regulation & maintenance ES, and in three of the four cultural benefits showing significant differences (aesthetic pleasure, leisure activities and sense of place). The influence of street trees in promoting a prosperous commerce/tourism was also perceived differently among school level classes, and the contrast analysis revealed that people in the high school class rated this benefit as being less important than other classes.

3.3. Individual losses & costs

Allergy risk due to street trees was the issue more highly rated by respondents of the sample taken as a whole (mean: 2.95), as shown in Table 4. Insecurity feelings were the least important nuisance (mean: 2.35), although many people agreed that it was still a relevant problem (particularly people older than 64 years).

Age was behind a number of significant differences in average responses relative to damages caused by street trees. Older people consistently attributted higher importance to issues associated with personal safety (risk to individual integrity, insecurity feelings), accumulation of leaves and other residues (litter), deficient maintenance (unpleasant view), sunlight blocking and visibility decrease (Table 5).

Again, school level accounted for differences in all items except allergy risk, and also goods and property damage (Table 6), suggesting that people with higher academic education consider losses caused by street trees to be of less importance than those having lower schooling (especially people holding the 9th grade or below). One additional relevant finding is that people holding the 9th grade or below considered more negatively than all other school level classes the maintenance costs of street trees.

Considering gender, no significant differences were found regarding responses about losses and costs generated by street trees.

Table 6
Comparative analysis of potential benefits, ecosystem services (ES) and losses/costs generated by street trees in Porto (Portugal), according to school level classes. Results for 819 interviews.

Benefits, ES and losses/costs	School level classes				ANOVA (Sig.)[1]
	≤9th Grade	High school	University	≥Master degree	
Cultural benefits					
Inspiration	1.99 (0.05)	2.07 (0.05)	2.09 (0.05)	2.22 (0.09)	0.087
Aesthetic pleasure	2.30 (0.04)^{a}	2.44 (0.04)^{b}	2.59 (0.04)^{c}	2.70 (0.05)^{c}	0.000
Social cohesion	2.21 (0.04)	2.15 (0.05)	2.26 (0.05)	2.31 (0.07)	0.218
Leisure activities	2.34 (0.04)^{a}	2.39 (0.05)^{a}	2.57 (0.04)^{b}	2.58 (0.06)^{b}	0.000
Sense of place	2.11 (0.04)^{a}	2.14 (0.05)^{ab}	2.27 (0.05)^{b}	2.29 (0.08)^{b}	0.023
Spiritual enrichment	1.59 (0.06)^{a}	1.34 (0.07)^{b}	1.55 (0.07)^{a}	1.41 (0.11)^{ab}	0.046
Education	2.15 (0.04)	2.17 (0.05)	2.29 (0.05)	2.22 (0.07)	0.125
Cultural heritage	2.09 (0.05)	2.06 (0.06)	2.05 (0.05)	2.28 (0.08)	0.110
Economic benefits					
Real-estate valorization	1.74 (0.06)	1.60 (0.07)	1.66 (0.06)	1.88 (0.10)	0.126
Prosperous commerce and/or tourism	2.01 (0.05)^{a}	1.70 (0.07)^{b}	1.89 (0.06)^{a}	2.00 (0.10)^{a}	0.002
Energy conservation	2.06 (0.06)^{a}	1.88 (007)^{b}	2.20 (0.06)^{a}	2.14 (0.10)^{a}	0.005
Regulation & maintenance ES					
Air quality regulation	2.67 (0.03)^{a}	2.66 (0.04)^{a}	2.77 (0.03)^{b}	2.78 (0.05)^{ab}	0.035
Climate regulation	2.35 (0.05)^{a}	2.42 (0.05)^{a}	2.62 (0.04)^{b}	2.62 (0.06)^{b}	0.000
Microclimate regulation	2.30 (0.04)^{a}	2.40 (0.04)^{ac}	2.62 (0.04)^{b}	2.56 (0.07)^{bc}	0.000
Stormwater regulation	2.29 (0.05)^{a}	2.34 (0.06) ^{ab}	2.46 (0.05)^{b}	2.50 (0.07)^{b}	0.026
Noise mediation	2.00 (0.06)^{ab}	1.85 (0.07)^{a}	2.10 (0.06)^{b}	2.18 (0.09)^{b}	0.012
Habitat maintenance	2.33 (0.04)^{a}	2.31 (0.05)^{a}	2.57 (0.04)^{b}	2.47 (0.07)^{ab}	0.000
Losses & costs					
Goods and property damage	2.68 (0.05)	2.68 (0.05)	2.60 (0.05)	2.49 (0.08)	0.169
Allergy risk	3.03 (0.05)	2.92 (0.05)	2.93 (0.05)	2.84 (0.09)	0.206
Sunlight blocking	2.61 (0.05)^{a}	2.35 (0.06)^{b}	2.26 (0.05)^{b}	2.19 (0.09)^{b}	0.000
Visibility decrease	2.65 (0.05)^{a}	2.39 (0.06)^{b}	2.29 (0.05)^{b}	2.19 (0.09)^{b}	0.000
Risk to individual integrity	2.85 (0.05)^{a}	2.66 (0.05)^{b}	2.49 (0.05)^{c}	2.46 (0.09)^{bc}	0.000
Litter	2.86 (0.05)^{a}	2.59 (0.05)^{b}	2.52 (0.05)^{b}	2.56 (0.09)^{b}	0.000
Insecurity feelings	2.58 (0.06)^{a}	2.38 (0.06)^{b}	2.10 (0.05)^{c}	2.17 (0.10)^{bc}	0.000
Unpleasant view	2.82 (0.05)^{a}	2.75 (0.05)^{a}	2.41 (0.06)^{b}	2.44 (0.10)^{b}	0.001
Maintenance costs	2.71 (0.06)^{a}	2.52 (0.06)^{b}	2.36 (0.06)^{b}	2.41 (0.09)^{b}	0.000

Response results are expressed as Mean (Standard Error) of response in a Likert-type importance scale for benefits and ES (0 – not important; 1 – not very important, 2 – important, 3 – very important), and an agreement scale for losses/costs (1 – strongly disagree, 2 – disagree, 3 – agree, 4 – strongly agree).
The superscript letters highlight differences between levels of one socioeconomic variable concerning mean responses; levels with similar responses for one dimension do not differ significantly according to orthogonal contrast analysis ($p < 0.05$).
[1] Statistical significance of the F test (Fischer) or Welch test (for the cases with unequal variances).

3.4. Trade-offs among benefits and losses & costs

The first statement of the final set in the questionnaire referred to trade-offs among benefits and losses/costs caused by street trees, by asking respondents to evaluate the statement "Trees bring more benefits than damages". In average, people agreed or agreed a lot that trees bring more benefits than damages (mean = 3.50), as presented in Table 7. School level accounted for significant differences of opinion between people who attended university versus those who did not, showing a pattern where the former agree more than the latter with the statement. Still, about 4% (n = 33) of all respondents disagreed or strongly disagreed that trees bring more benefits than damages, of which only 4 people attended university or had a higher school level (data not shown). No significant differences were found for this statement considering age classes or gender (Table 7).

Most interviewed people also agreed that the city of Porto needs more trees (mean: 3.32), and the agreement intensity increased according to education level: those with higher education agreed significantly more with this statement (Table 7). Age also accounted for differences in mean response, with people between 25 and 44 years old agreeing more that Porto needs more trees than all the remaining age groups (mean: 3.41). Gender did not show statistically significant differences in responses (Table 7). Another important finding was that around 8% (n = 73) of the interviewees disagreed or strongly disagreed that Porto needs more trees, most of which completed the 9th grade or less (n = 39), or the 12th grade or less (n = 20) (data not shown).

The statement bearing less consensus in opinions was "Bigger trees bring more benefits than smaller trees" which accounted for about 35% (n = 217) of "disagree" or "strongly disagree" responses (data not shown). Surprisingly, younger interviewees (18–24 years old) and older people (above 64 years old) disagreed significantly more with the statement (mean: 2.58 and 2.71, respectively) than intermediate age classes (Table 7). No significant differences were found in response means according to school level or gender.

4. Discussion

This study revealed that people in Porto valued more environmental benefits (particularly air quality improvement) than cultural ones, not supporting the findings of Madureira et al. (2015). These authors analyzed, in four French and Portuguese urban areas including Porto, beliefs of residents concerning green space benefits, and found that cultural/social benefits were more valued than environmental ones in all cities, although "diminution of urban air pollution" was the second highest ranked individual benefit for Porto; however, "air temperature reduction" was in one of the lowest ranking positions for all cities. The disparities regarding our results might be due to a different formulation of individual benefits or to the fact that urban green spaces in general

Table 7
Agreement level for three statements relative to street trees in Porto (Portugal), according to socioeconomic variables. Results for 819 interviews.

Socioeconomic variables	Trees bring more benefits than damages	Bigger trees bring more benefits than smaller trees	The city of Porto needs more trees
Gender			
Men	3.50 (0.03)	2.85 (0.05)	3.29 (0.04)
Women	3.51 (0.03)	2.80 (0.04)	3.33 (0.03)
Student's t-test (Sig.)[1]	0.801	0.493	0.428
Age class (yrs)			
18–24	3.49 (0.05)	2.58 (0.07)[a]	3.22 (0.06)[ac]
25–44	3.55 (0.04)	2.89 (0.06)[bc]	3.41 (0.04)[b]
45–64	3.52 (0.04)	2.95 (0.05)c	3.31 (0.04)[bc]
+64	3.40 (0.06)	2.71 (0.08)[ab]	3.24 (0.07)[ac]
ANOVA (Sig.)[2]	0.177	0.000	0.038
School level			
≤ 9th Grade	3.34 (0.04)[a]	2.85 (0.06)	3.21 (0.05)[a]
High school	3.43 (0.04)[a]	2.79 (0.06)	3.28 (0.05)[ab]
University	3.67 (0.03)[b]	2.86 (0.06)	3.39 (0.04)[b]
≥Master degree	3.72 (0.05)[b]	2.79 (0.10)	3.57 (0.06)[c]
ANOVA (Sig.)[2]	0.000	0.833	0.000
Sample	3.50 (0.02)	2.82 (0.03)	3.32 (0.03)

Response results are expressed as Mean (Standard Error) of response in a Likert-type agreement scale (1 – strongly disagree, 2 – disagree, 3 – agree, 4 – strongly agree). The superscript letters highlight differences between levels of one socioeconomic variable concerning mean responses; levels with similar responses for one dimension do not differ significantly according to orthogonal contrast analysis ($p < 0.05$).

[1] Significance of Student's *t*-test.

[2] Statistical significance of the F test (Fischer) or Welch test (for the cases with unequal variances).

were considered in the study (while we restricted our analysis to street trees), but more probably to the composition of the sample used, which consisted mostly of respondents holding university degree or higher – about three quarters of the sample, far from the reality in Porto. Nevertheless, a study developed by Bertram and Rehdanz (2015) found that park visitors in four European cities considered the delivery of regulating ES in parks to be more important than the supply of cultural ES (with the exception of recreation), suggesting a potentially wider acknowledgment by city dwellers of the environmental impact of green spaces. Yet, other studies presented contrasting results (e.g. Casado-Arzuaga et al., 2013), indicating that more research is needed to better understand the role of the cultural context in perceiving and valuing different types of ES.

The results for Porto confirmed our initial hypothesis that benefits and losses/costs caused by street trees are perceived differently by citizens according to a set of socioeconomic variables. In our analysis, school level was the variable accounting for more differences in perception of benefits and losses/costs regarding street trees. We identified a tendency, in people with lower level of academic education, to value less the benefits provided by street trees in Porto and attribute more importance to losses and costs, compared to people who attended or completed a university degree. These results are in line with the findings from Avolio et al. (2015), who also found, in a survey of people living in five counties of southern California (in and surrounding the Los Angeles Metropolitan Area) that people with higher level of education attributed more importance to trees than people with less education. This is a noteworthy finding, given that the most deprived area of Porto (Campanhã), which represents about 14% of Porto's population, has a considerably larger proportion of residents holding the 9th grade or below (71% of residents aged 18 years or more; INE, 2011) and a much smaller share of people holding a college degree than all other parishes of Porto, as illustrated in Fig. 3. Furthermore, Graça et al. (2018) found that Porto displayed a considerable difference in terms of supply of regulating ES provided by the urban vegetation (climate and air quality regulation) across the city, and demonstrated environmental inequity towards access to the benefits provided by nature. These authors concluded that the eastern parish (Campanhã) was the greenest of the five city zones analyzed, but revealed the lowest proficiency of regulating ES supply in the whole municipality while the western area of Porto (parishes of Aldoar, Foz do Douro & Nevogilde, and Lordelo & Massarelos) revealed the best performance in ES delivery, reflecting a socioeconomic asymmetry between the deprived eastern side of the city and the wealthy parishes at west.

Of the socioeconomic indicators analyzed by Graça et al. (2017), the most striking was the much lower access to college education by those living in Campanhã, compared to the rest of the inhabitants of Porto (Fig. 3).

Although these findings suggest that the priority area in Porto to enhance environmental equity and ES supply by urban vegetation should be Campanhã, our results suggest that caution should be taken to insure that establishing more green areas and trees in the parish effectively promotes wellbeing in the community. This might be a concern because top-down institutional initiatives to improve tree

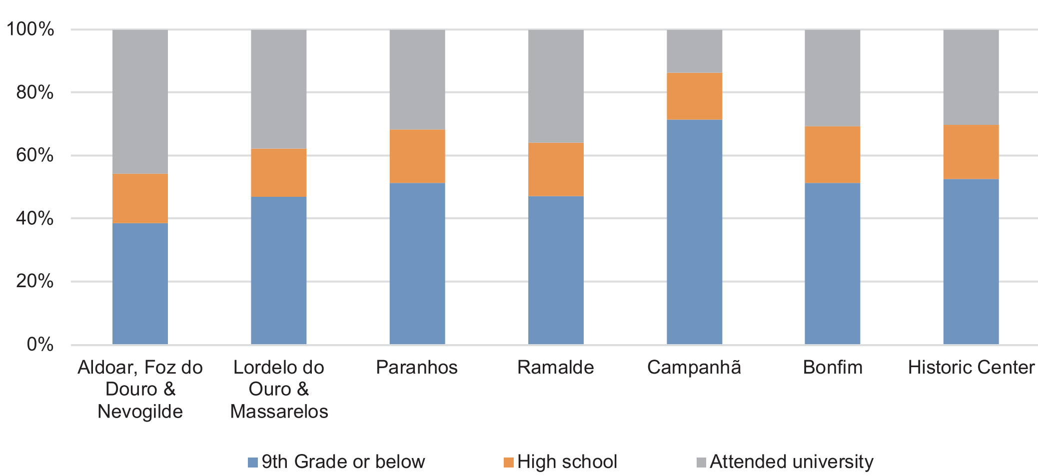

Fig. 3. School level of residents aged 18 years old or above, living in Porto in 2011, per parish of residence according to the administrative reorganization of parishes established in 2013 (INE, 2011).

density and condition in the parish risk to be considered as promoting more nuisances than wellbeing (Heynen et al., 2006).

Age was also an important variable explaining different perceptions regarding street trees, with older people showing more concern towards losses and costs. In a case study in southwest England, Flannigan (2005) noted, likewise, that increased age negatively influenced opinions about street trees. People aged 65 years or above constitute about 23% of Porto's population (20% in our sample), hence acknowledging and addressing negative aspects of street trees in urban planning and management is of crucial importance.

The differences accounted for gender can be explained by a stronger environmental attitude and behavior in women than men (Zelezny et al., 2000).

Information access can likewise influence intensely how benefits and losses/costs caused by trees are perceived, especially reflected in our results regarding the statement "Bigger trees bring more benefits than smaller trees", with which more than one third of the interviewed people disagreed or strongly disagreed. Research has shown that the size of trees impacts delivery of regulating ES (Nowak and Dwyer, 2007; Pretzsch et al., 2015), and the benefits associated with these services were in general considered the most important ones for respondents in our case study. Therefore, it was expected that people with higher education level would be more aware of the impact of tree size in generating benefits for wellbeing. Surprisingly, no significant differences were found for mean response across school level classes. These results suggest that there is a considerable margin to raise awareness among Porto's citizens about the increased value of bigger trees. If people become more aware of the advantages of larger specimens, they may change their attitude and behavior concerning nature and consider more positively trade-offs between benefits and losses/costs caused by trees, increasing public support for their protection (Jones et al., 2013).

Some authors suggest that environmental factors can also have an important role in shaping attitudes and preferences regarding trees. For example, Avolio et al. (2015) found that local climatic and environmental factors affected preferences for tree attributes as much as socioeconomic variables, and Schroeder et al. (2006) suggested that a cooler climate, together with the closer proximity of street trees to houses, might explain the preference for smaller trees in two communities of the United Kingdom, compared to one community located in the United States. Given the climate in Porto, shade could probably be regarded as an important asset for residents. However, the proximity of street trees to houses in Porto can probably explain the high level of general agreement with losses/costs and why so many interviewed people disagreed that bigger trees provide more benefits than smaller trees. Porto is a city with a dense urban fabric, where street trees are planted frequently very close to building facades, potentially creating many direct nuisances to residents.

Allergy risk was the most highlighted negative aspect of street trees, which is consistent with the association established by Ribeiro and Abreu (2014) between monthly hospital admissions and tree pollen in Porto, particularly of the genera *Acer, Platanus, Populus* and *Quercus*, which are very common in streets. Although more studies are needed to establish thresholds of allergenic pollen concentrations with impact in human health, caution should be taken regarding the choice of tree species when designing green spaces in urban settings (Cariñanos and Casares-Porcel, 2011).

Our results also underline climate and microclimate regulation as two of the most valued ES provided by street trees in Porto, and a general support for more trees in the city. Given the role that planting street tree species with high cooling potential in densely built areas might have in mitigating heat-wave risk (Gillner et al., 2015), this could be a positive strategy to enhance Porto's resilience to climate change. Nevertheless, street trees might also increase exposure to air pollution by trapping pollutants in narrow street canyons (Vos et al., 2013), although some studies suggest that vegetation type and design can have a significant impact in how air quality is affected (Gromke and Ruck, 2007; Janhäll, 2015).

The results do not allow to understand how the low importance attributed by respondents to direct economic benefits of street trees affects real-estate value in Porto, which has been found to increase with their presence in other geographical settings (Pandit et al., 2013). It is possible that local cultural and urbanistic characteristics affect real-estate valuation by street trees, but more research should be developed to answer these questions.

It has been demonstrated that opinions of urban residents about green spaces can vary across geographical contexts, although some consensual values emerge (Madureira et al., 2015). However, more studies are needed to confirm this consensus and to better understand the role of socioeconomic and cultural variables. Moreover, it is possible that specific types of green space are valued differently (e.g. urban parks might be more relevant for recreation and leisure than street trees, and private gardens might hold particular importance for provision of food).

Based in our findings, we strongly recommend implementing participatory approaches (see Lynam et al., 2007 for a comprehensive overview of methods) to provide more information to citizens about the benefits generated by urban trees, and work with the community to foster inclusive and democratic solutions. Co-management of the urban tree-resource can also lead to more legitimacy of measures, compliance from the community, justice, equity and empowerment (Berkes, 2009).

5. Conclusions

This exploratory study provided evidence that perception of benefits and losses/costs generated by a specific SPU is strongly influenced by the socioeconomic characteristics of urban societies, which might be a source of conflicts if not properly acknowledged in planning and management initiatives. Our results also underline that actions targeting environmental equity might have adverse effects, if the specific values and views of the community are overlooked. Furthermore, people may not be aware of the impact of specific factors, such as tree size, in ecological outcomes crucial for urban wellbeing. Therefore, appropriate communication strategies can be decisive to influence positively tree acknowledgement and support by urban citizens.

Our results encourage planning and management of street trees within a multicriteria decision-making framework, in which the specific location of trees, species type, future development and management must be considered in light of local problems and needs, in order to obtain the best compromise towards a desirable outcome for both stakeholders and beneficiaries. Consequently, integrating scientific knowledge and community opinions could provide a strong evidence-based strategy for implementing a successful urban green infrastructure.

Acknowledgments

This research was partially funded by the Portuguese Agency for Science and Technology (FCT) through PhD grant of M. Graça [ref. SFRH/BD/91028/2012] 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. The authors would like to express their sincere thanks to Cândida Neves (Esc. Sec. Alexandre Herculano), Fátima Afonso (Col. D. Duarte), Rosa Costa (Esc. Básica e Sec. Rodrigues de Freitas) and Sandra Lopes (Esc. Básica e Sec. do Cerco) for participating with their students in the data collection for this research.

Appendix A. Questionnaire applied between February and May of 2017 to a sample of 819 people aged 18 years old or above, in the streets of Porto (Portugal)

Note: translated to English from the original Portuguese version used to collect the data.

Please indicate your degree of importance for each of the following benefits provided by street trees:	**Not important**	**Slightly important**	**Important**	**Very important**	**No opinion**
Stimulating new ideas, thoughts and/or creative expressions					
Beautifying streets, views and/or the city					
Promoting meetings with friends and neighbors					
Promoting recreation and tourism by providing pleasant places for walking, running, cycling, …					
Fostering a sense of attachment to a place and/or to the city					
Representing spiritual, religious, or personal special meanings					
Raising curiosity and knowledge about nature's cycles and biodiversity					
Supporting local historical and cultural values and identity					
Improving air quality through removal of atmospheric pollutants					
Supporting global climate regulation through carbon sequestration / reduction of greenhouse gas concentrations					
Improving microclimatic comfort through regulation of local temperature and wind					
Preventing or mitigating floods by slowing down and intercepting rainwater before falling to the ground					
Buffering the noise of cars or specific activities					
Supporting lifecycle conditions for biodiversity in cities					
Increasing the monetary value of real-estate					
Fostering commercial / touristic activities which provide monetary revenues					
Increasing energetic efficiency of buildings, by reducing consumption of energy for cooling / heating					

Other important benefits: ______________________________

Please indicate your level of agreement concerning the following damages caused by street trees:	**Strongly disagree**	**Disagree**	**Agree**	**Strongly agree**	**No opinion**
Damaging goods and structures such as cars, sidewalks, walls, …					
Increasing allergic reactions due to pollen release					
Providing unwanted shade, blocking sunlight					
Reducing visibility to streets (from home)					
Increasing risks for people's security due to tree or branch fall					
Undesired accumulation of residues due to leaf and fruit fall					
Increasing fear of potential criminal activity in streets due to reduced visibility caused by trees					
Unattractive views due to neglected maintenance or bad condition of trees					
Public funds needed to support tree plantation and maintenance					

Other important damages: ______________________________

Please indicate your level of agreement with the following statements:	**Strongly disagree**	**Disagree**	**Agree**	**Strongly agree**	**No opinion**
Trees bring more benefits than damages					
Bigger trees bring more benefits than smaller trees					
The city of Porto needs more trees					

Age: __________ Gender: ☐ Female ☐ Male

School level: ☐ 9th Grade or below ☐ High school (≤12th grade) ☐ Attended or completed university ☐ Master or higher degree

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Section III

OPERATIONALIZATION

1| Towards a more resilient city

Sustainability has been considered for a long time the basilar stone of the desirable development of cities, and hence has become the focus of international initiatives across the world (e.g. International Council of Local Environmental Initiatives - ICLEI, European Sustainable Cities Platform). What is, therefore, sustainable urban development?

According to the definition of ICLEI, the leading international network of local governments and cities, "*sustainable cities work towards an environmentally, socially, and economically healthy and resilient habitat for existing populations, without compromising the ability of future generations to experience the same*" (ICLEI, n.d.).

There seems to be wide consensus around the idea that sustainable development addresses simultaneously the dimensions of social equity, economy and environment (Ahern, 2013; Andersson, 2006). However, cities are not self-sufficient, as they strongly depend on the provision of goods and benefits from outside the urban borderline. Therefore, urban sustainable development cannot be isolated from its social, economic and ecological impact outside cities.

Ecosystem services (ES) provided by green spaces play a crucial role in supporting urban wellbeing, as discussed in Section 1, because many of these benefits need to be generated locally to be effective. The local supply of ecosystem services may also reduce the necessity to rely on distant ecosystems to support the needs of urban populations, therefore increasing the self-sufficiency of cities. This is a critical aspect, because while sustainability encompasses the integration of economic, social equity and environmental dimensions in a given spatial context, resilience is the key to sustain this integration across temporal scales (Ahern, 2013).

By resilience, we refer here to "*the capacity of a system to regenerate and adapt in the face of changing conditions and disturbance, while retaining essentially the same function, structure, identity, and feedbacks*" (Erixon, Borgström, & Andersson, 2013). In the urban context, resilience refers to the ability of a city to absorb changes and disturbance over time without compromising its ability to function, deliver ES and support human wellbeing. Examples of change and disturbance that affect cities are pollution, flooding, natural disasters, economic and political crisis, population migrations, climate change …, which may be accompanied by a shortage of goods and services (e.g. food, water) delivered within the urban boundaries, or from elsewhere. Such disruptive events or processes are inherent to complex dynamic systems as cities, and many times they are not completely known or understood. This means that planning for future urban development based in present-day state often involves coping with a high level of uncertainty regarding future scenarios. Resilient cities are able to better accommodate uncertainty, because they rely on strategic planning and design based in first understanding urban patterns and drivers, and secondly in acting proactively to enhance desirable results (e.g. increasing within-city food and water supply, creating and connecting permeable areas, enhancing tree cover in strategic areas, promoting multifunctionality in urban green spaces …).

Interconnected socioeconomic and environmental processes affect the urban form and urban patterns over time due to their temporal and spatial dynamics. Consequently, the success of green spaces will depend not only on their initial design, but also on their adequate alignment with the changing environmental context (e.g. adaptation to increasing drought periods, to pollution, to pests and diseases, ability to deliver critical local ES …) and socioeconomic conditions (acceptance and use by a diverse range of beneficiaries, enhancement of social equity and cohesion, provision of cultural ES, cost-effective management …). Following this reasoning, design of new green spaces should move from a paradigm based in a static view of *shape* to a paradigm based in *processes* continuously carving green structure, thus determining relevance and efficacy in the lens of sustainable and resilient urban development.

The supply of urban ecosystem services (UES) is not homogeneous across distinct green areas, due to their differences in terms of properties and functions. These differences result in an uneven supply of critical UES across the urban matrix, potentially lacking in some parts of the city or inaccessible to a number of citizens. Strategic planning of green spaces at the urban level needs to acknowledge and understand the causes behind patterns of UES supply, in order to direct future development towards desirable scenarios.

All these considerations render obvious that there is no such thing as fixed rules for planning and designing in a dynamic context. Rather, a systemic approach to a given urban context should be pursued to inform evidence-based action. Fig. 5 proposes a stepwise process-based methodological framework to inform and guide planning, management and design of green spaces towards sustainable and resilient urban development.

In light of the proposed framework, this thesis delivered site-specific information to inform action in Porto (step 1). The present section seeks to demonstrate how the knowledge generated from the research developed in Papers 1, 2 and 3 can be used to develop the subsequent steps of the framework.

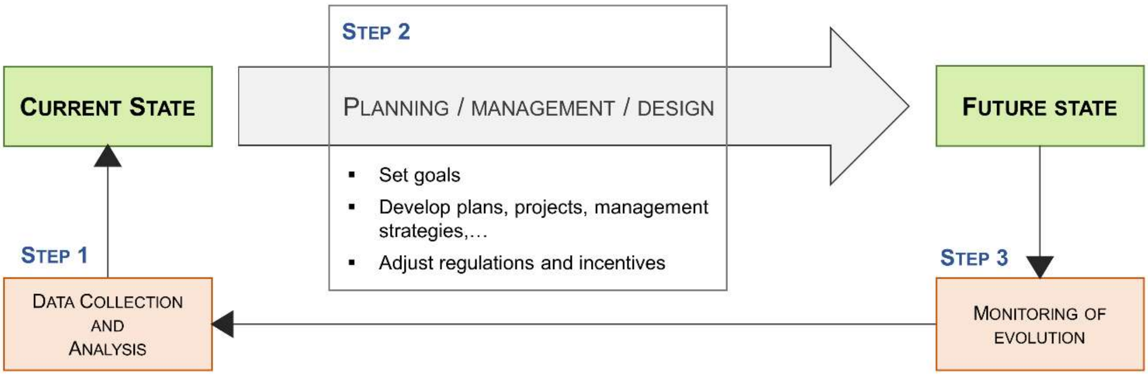

FIGURE 5 – Stepwise methodological approach to develop evidence-based planning / management / design of urban green spaces. The data collection and analysis provide the foundation of knowledge about urban patterns of UES supply and drivers of change (step 1), which will determine the directions for planning / management and design of green spaces (step 2) in order to guide urban development towards a desired future state. Monitoring the evolution of the future state (step 3) will generate new data and assessments (step 1), closing the cycle and allowing necessary adjustments in step 2.

2| Structure of section

This section was organized as a relatively independent document from the rest of the thesis, targeting a practice-oriented audience. Therefore, the language and structure in the document were adapted to facilitate understanding of the main results of the research, which were structured in a way to deliver objective and detailed information about:

- The specific characteristics of the urban forest that are currently affecting UES provision in Porto, and that can be manipulated by planners, designers and managers of green spaces;
- The main patterns of UES provision across the city, highlighting hotspots and coldspots;
- Main socioeconomic and cultural drivers that affect UES supply across the city.

The information generated along the research process allowed to identify a set of relevant urban issues in the study area, which are here presented and translated into desirable goals for urban planning, design and management of green spaces. A list of recommendations and orientations is subsequently suggested, addressing individually each of the proposed goals.

Following this underlying thread, Chapters 3 and 4 describe briefly the study area and methods used, and introduce the case study. Chapter 5 presents the global results of the research concerning the urban forest of Porto, addressing both its structure and ecological benefits. The heterogeneity of UES supply is the subject of Chapter 6, focusing on the relationship with socioeconomic patterns, and also with different types of green spaces. Chapter 7 is dedicated to explore the citizens' perception of benefits and losses / costs generated by street trees in Porto, addressing its pertinence for UES management. Lastly, Chapter 8 summarizes the main challenges for Porto identified in this research, and suggests a list of recommendations for planning, management and design of green spaces.

Although this section was organized to deliver as much practical information as possible for Porto, it is necessary to underline that the main purpose here is mainly illustrative, not prescriptive. Additionally, as i-Tree Eco delivered large amounts of data, only the main findings were selected and synthetized in this section.

The research was predominantly explorative in its methods and findings, because of the lack of information concerning UES supply in Porto. Nevertheless, the systemic approach here advocated can and should be used at finer scales to address the specific issues that emerged as relevant from our analysis, or other issues considered pertinent by decision-makers (e.g. tree planting in specific street canyons of Porto to improve air quality, selection of new planting areas to reduce flooding …).

3| Study area

This research was developed within the municipal boundaries of Porto, the center of the second largest Portuguese metropolitan area.

The city is situated in the northwest of Portugal, bordered by the Atlantic Ocean at west and Douro River at south. Covering only 41.42 Km^2, Porto is nevertheless the epicenter of a metropolitan area composed by 17 municipalities adding up to about 1,759,524 inhabitants (INE, 2014). The municipality is presently structured in 7 parishes. For the purpose of this study the parishes were clustered in 5 groups with similar socioeconomic and urbanistic characteristics, in order to simplify the data collection and analysis of information. Therefore, the parishes of Paranhos and Ramalde were converted in one single class, as well as the parishes of Historic Center and Bonfim (Fig. 6).

FIGURE 6 – Municipal border of Porto and groups of parishes analyzed in terms of supply of urban ecosystem services and urban forest structure. The main green structure in the city (green in the map) was used to subdivide each group of parishes in two substrata: GREEN and GREY.

Due to its geographic positioning, Porto benefits from a Mediterranean type climate. Temperatures are usually mild all year long, and the abundant precipitation occurs mainly between October to March (IM, 2011).

Plant species brought for gardening purposes from all corners of the planet have found here suitable conditions to thrive, resulting in an exquisite local flora. Yet, although species richness is nowadays considerably diverse, since the 19^{th} century the city went from about 75% of its area being green to some mere 30%. Nevertheless, some of the existing green areas have high sociocultural and ecological value.

In terms of planning, the city does not have currently any institutional plan or instrument specifically developed to target green spaces, nor a global strategy for Porto's green infrastructure. To our knowledge, there is no up-to-date survey of urban green trees under public domain, rendering the management of the urban forest more difficult.

Furthermore, there is no available information concerning the performance of Porto's green spaces in terms of delivery of ecosystem services.

4| Methods

This study delivered information about the composition and structure of the urban forest, estimates of UES supply across the city, and perception of citizens concerning street trees.

To obtain information concerning the urban forest and estimates of ES supply, field data was collected between May and September 2014 from a sample of circular 255 plots of 404.7 m^2 each, distributed across all city and including both public and private areas.

The largest proportion of urban vegetation can be found in the main green structure of Porto, where the supply of UES is expected to be higher. Therefore, in this study about 70% of the samples was assigned to the green structure of the city (GREEN in Fig. 6) to generate more detailed information about vegetation structure and UES delivery. The remaining areas (GREY) were also assessed, nevertheless, to generate estimates statistically valid for the whole city of Porto.

i-Tree Eco v5, a modelling tool developed by the USDA Forest Service (www.itreetools.org) was used to analyze the field data and generate UES estimates (see Appendix A for an overview of the i-Tree Eco model and field measurements). Generalized linear models (GLM) and generalized additive models (GAM) were used to cross ecological information and socioeconomic data relative to Porto's inhabitants, in order to cast light on specific drivers of UES supply in the study area.

To analyze patterns of citizen's perception of the benefits and losses / costs generated by street trees, 819 people aged 18 years or older were interviewed in the streets of Porto, between February and May 2017, using a questionnaire developed specifically for this study (Appendix B).

5| The urban forest in Porto

5.1| Urban forest structure

The urban forest of Porto has an estimated 281.000 trees and a tree cover of 10.6%.

Porto has one of the lowest tree cover values among the urban areas where i-Tree Eco was applied, far below other European cities such as Barcelona (25.2%), Berlin (42.7%) or Salzburg (28.6) (see Graça et al., 2017, for a comparison between Porto and other cities).

Small specimens mainly compose the urban forest in Porto. Around 49% of all trees have an estimated diameter at breast height (DBH) equal or smaller than 12.7 cm, and around 27% are between 12.8 cm and 25.4 cm (Fig. 7).

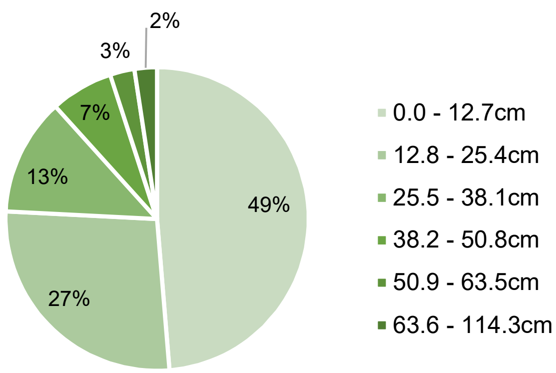

FIGURE 7 – Composition of tree population in Porto according to diameter at breast height (DBH) class. The smallest trees (class 0.0–12.7 cm) account for the highest proportion of all trees.

Nevertheless, the density of trees per hectare is similar to Edinburgh (56.0 trees/ha) and New York (65.2 trees/ha), which indicates that in these cities the higher

Main findings

- Porto has about 281.000 trees
- Tree cover is 10.6% of the city area
- Average tree density is 68.8 trees per hectare
- Most common species: *Quercus robur* (English oak – 5.3%), *Populus nigra* (black poplar – 4.2%) and *Quercus suber* (cork oak – 3.9%)
- A total of 143 species was inventoried (Appendix C)
- About 76% of all trees have diameter at breast height below 25.4 cm
- The species contributing more for total leaf area (10.6%) in the city is *Platanus x acerifolia* (3.1% of total tree population in the city), followed by *Acer negundo* (6.8% of all tree leaf area; 2.4% of the tree population)

tree cover is mainly due to the proportion of larger specimens. In Porto, although some of the most abundant species correspond to large-size adult trees, most specimens in the city are fairly small. The urban forest is predominantly constituted by undersized specimens, despite trees being planted in the city for centuries, which suggests an ongoing management or cultural practice in the city that prevents most trees to grow to full size. Some possible reasons that might explain the lack of larger specimens are frequent land-use changes causing tree cutting, cultural preference for smaller trees or severe pruning.

Porto's urban forest is substantially diversified. The most abundant tree species, *Quercus robur* (English oak) only accounts for 5.3% of the total tree population (Table 2), contrasting with findings form other cities where i-Tree Eco was applied. In Edinburgh, for example, the ten most common trees accounted for 65 % of the total tree population (Hutchings, 2012), and in New York the corresponding value was about 61.6 %, while in Porto it is about 35%. Tree species diversity is very important because it can minimize the impact of a species-specific pest or disease over the whole urban forest. For that reason, tree diversity could increase the resilience of the urban forest.

TABLE 2 – List of the ten most abundant tree species found in Porto.

Species name	Number of trees (estimated)	Percentage of the urban forest
Quercus robur	15035	5.3
Populus nigra	11687	4.2
Quercus suber	11085	3.9
Cornus sp.	10858	3.9
Cupressus sempervirens 'Stricta'	9765	3.5
Acacia melanoxylon	9126	3.2
Cupressocyparis leylandii	9095	3.2
Populus nigra 'Italica'*	8822	3.1
Platanus x acerifolia	8731	3.1
Camellia japonica	7372	2.6

*Although the Lombardy poplar (*Populus nigra* 'Italica') is actually a variety of the black polar (*Populus nigra*) for this study it was decided to distinguish between specimens due to their distinct tree shapes.

Although some species are less abundant in Porto, their importance may be very high in terms of UES supply. This is the case of *Platanus x acerifolia* (London planetree), which is currently the species in Porto's urban forest providing the largest amount of percent leaf area (10.64% of all the leaf area in the city), even if its population is relatively small (3,10 % of all trees) (Table 3). Leaf area is a relevant indicator of UES supply by distinct species, because many benefits generated by vegetation are directly dependent on the amount of leaves in the crown (e.g. air pollution removal, avoided runoff, microclimate regulation …).

TABLE 3 – List of the most important tree species found in Porto, sorted in descending order according to their contribution for the total leaf area of the urban forest.

Species	Percent Population	Percent Leaf Area
Platanus x acerifolia	3.10	10.64
Acer negundo	2.43	6.78
Pinus pinaster	1.92	4.32
Cedrus libani	0.48	3.56
Quercus robur	5.34	3.51
Celtis australis	0.49	3.06
Liquidambar styraciflua	0.89	3.04
Quercus suber	3.94	2.91
Populus nigra	4.15	2.79
Picea abies	1.01	2.60
Tilia platyphyllos	0.60	2.28

Regardless of the species, it is important to stress that larger trees (usually corresponding to higher DBH classes) provide much more leaf area than smaller individuals do, as illustrated in Fig. 8. The DBH classes explained about 97% of leaf area variance over Porto's green areas.

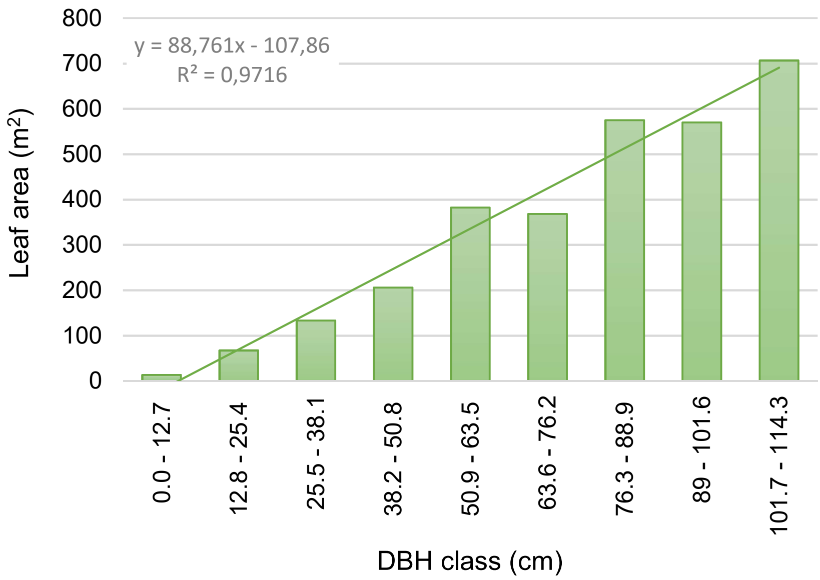

FIGURE 8 – Average contribution of leaf area by individual trees in Porto, according to diameter at breast height (DBH) classes. Specimens in the highest DBH class (101.7-114.3 cm) provide about fifty times more leaf area than specimens in the lowest DBH class (0.0-12.7 cm).

5.2 | Ecosystem services

5.2.1 | Air pollution removal

Trees can mitigate urban air pollution by removing directly atmospheric pollutants, but also by reducing air temperature and energy consumption in buildings, consequently decreasing air pollutant emissions from power plants.

i-Tree Eco v5 provided estimates of the air pollution removal by Porto's urban forest for the following pollutants: ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter less than 10 microns (PM_{10}) and 2.5 microns ($PM_{2.5}$), and sulfur dioxide (SO_2).

Of the estimated 64 tons yearly removed by trees in Porto, O_3 and PM_{10} accounted for the largest contribution (Fig. 9).

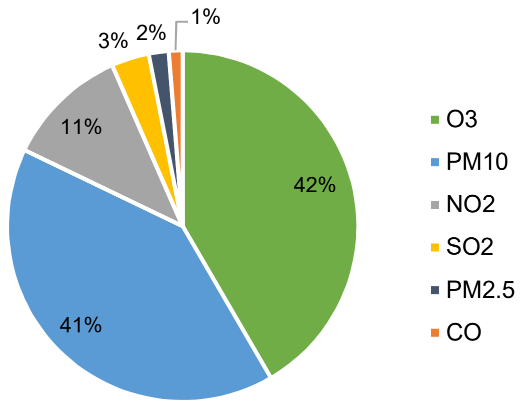

FIGURE 9 – Yearly air pollution removal generated by Porto's urban forest, in percentage of the following air pollutants: ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter less than 10 microns (PM_{10}) and 2.5 microns ($PM_{2.5}$), and sulfur dioxide (SO_2). Estimates obtained using the modelling tool i-Tree Eco v5, based in vegetation data from 2014 and pollution data from 2011.

In a nutshell

- Pollution removal (O_3, CO, NO_2, PM_{10}, $PM_{2.5}$, SO_2): 64 tons per year[a]
- Carbon storage[b]: 33 100 tons
- Carbon sequestration[c]: 1 500 tons per year
- Oxygen production: 3 450 tons per year
- Avoided runoff[d]: 38 800 m^3 per year
- Energy savings: negative results

[a] Results based in hourly pollution concentrations for 2011;

[b] Carbon storage: the amount of carbon bound up in the aboveground and belowground parts of woody vegetation;

[c] Carbon sequestration: the removal of carbon dioxide from the air by plants;

PM_x and O_3 are particularly associated to severe health hazards, and presently considered among the most problematic air pollutants in Europe (Guerreiro, 2017). Moreover, according to data from the European Environmental Agency, 9919 premature deaths were due to $PM_{2.5}$, NO_2 and O_3 exposure in Portugal during 2014 (Guerreiro, 2017).

Figure 10 illustrates the magnitude of air pollution removal by trees in Porto, converting the yearly amounts of pollutants into avoided emissions of cars.

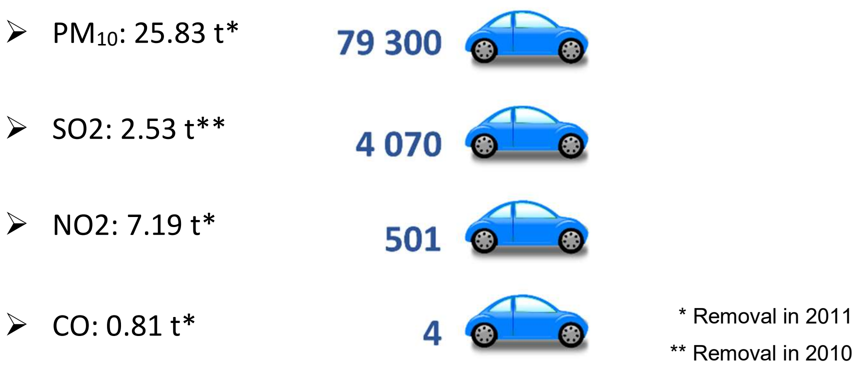

FIGURE 10 – Conversion of yearly air pollution removal generated by Porto's urban forest, according to pollutant type (at left), into avoided annual emissions by cars (at right). Pollutants considered: particulate matter less than 10 microns (PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO). Annual car emissions provided by i-Tree Eco v5, based in averages from USA for 2002.

5.2.2 I Carbon storage and sequestration

Urban forests can help to mitigate the impact of global climate change, by storing carbon as biomass of woody vegetation (carbon storage), and removing carbon dioxide from the atmosphere during photosynthesis (carbon sequestration).

Trees in Porto currently store 33141.2 t of carbon in trunks and branches, and sequester annually about 1292.6 t of net carbon.

Fig. 11 expresses the importance of Porto's urban forest in terms of annual avoided emissions by cars.

- Carbon storage: 33 141.2 t **21 900**
- Carbon sequestration: 1 292.6 t **1 000**

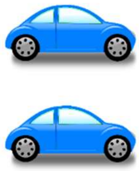

FIGURE 11 – Conversion of total carbon stored presently and yearly carbon net sequestration by the urban forest in Porto, into avoided annual emissions by cars. Annual car emissions provided by i-Tree Eco v5, based in averages from USA for 2002.

5.2.3 I Avoided runoff

Surface runoff is a major issue in urban areas, as it may cause flooding and contamination of the water flowing into streams, rivers, wetlands and oceans. This problem arises from the rainwater that reaches the ground and does not infiltrate into soil, and is severely magnified in urban settings covered by large amounts of impermeable areas.

Urban trees may play a significant role in mitigating surface runoff, by intercepting rainwater and preventing or delaying it to reach the ground.

Avoided runoff by trees in Porto was 38 811.1 m^3 in 2010, and 12 365.19 m^3 in 2011. The difference in these values is due to the higher occurrence of precipitation in 2010 than in 2011. This example illustrates how the magnitude of the benefits generated by the urban forest is dependent not only on the characteristics of trees, but also on other variables such as precipitation levels and pollution concentrations, which may change across time and throughout the urban fabric.

Figure 12 shows the impact of Porto's urban forest in terms of avoided runoff, for 2010 and 2011.

- 2010: 38 811.10 m^3 **15,5**
- 2011: 12 365.19 m^3 **4,9**

FIGURE 12 – Conversion of total yearly-avoided runoff by the urban forest in Porto into number of Olympic swimming pools (considering a pool size of 50 m x 25 m and 2 m depth, totaling a water volume 2500 m^3).

5.2.4 | Energy savings

i-Tree Eco v5 provides estimates for energy savings in residential buildings, based in USA data (construction types and vintages, energy use per type of fuel, climate …). Therefore, this module of the modelling tool is not suitable for international use.

However, in this study it was possible to adapt the model as much as possible to Porto, with the assistance of the i-Tree developing team in the Northern Research Station of the USDA Forest Service (details of the model adjustments for Porto are provided in Graça et al., 2017).

In Porto, only 13 trees (out of 863 sampled specimens in this study) were considered to have the minimum required height and distance to residential buildings (respectively 5.5 m and 18.3 m) to have impact in terms of energy savings. Due to the small number of sampled trees meeting the requirements for energy calculations, it was not possible to develop a statistically reliable citywide assessment of the impact of Porto's urban forest in this dimension. Nevertheless, it is worthwhile to note that the net impact of the 13 sampled trees in energy savings was negative, due to their inappropriate positioning relative to construction. The lack of more trees meeting the required specifications also suggests that in Porto people tend to avoid larger trees near housing.

5.3 | Disservices

5.3.1 | Emission of biogenic volatile organic compounds (BVOC)

Trees emit biogenic volatile organic compounds (BVOC) that can negatively affect air quality, by causing ozone (O_3) formation. In urban areas, BVOC emission is particularly relevant due to their reactivity to other atmospheric compounds generated by anthropogenic sources, particularly nitrogen oxides (NO_x). Some species emit more BVOC than others, especially when exposed to higher temperatures. The urban heat-island effect, combined with increased pollution levels, may therefore intensify degradation of air quality due to BVOC emission and ozone formation, especially in Mediterranean areas. In addition, it is known that BVOC emission by trees is stimulated by environmental conditions generating stress (high temperature, oxidative stress, herbivory or pathogen attack …), to which urban trees are particularly exposed (Calfapietra et al., 2013).

Consequently, planting low emitting species in urban areas prone to increased ozone formation may contribute to sustain air quality, especially in light of climate change.

The urban forest of Porto is presently constituted by many high BVOC-emitter species, of which oak species generate the maximum emission rates by Kg of leaf biomass (Table 4; Appendix D).

TABLE 4 – List of the top BVOC-emitting tree species found in Porto, sorted by descending order of BVOC emission of genus per Kg of leaf biomass. Isoprene and monoterpene emissions refer to totals for each species, taking into account its total leaf area in Porto's urban forest; total BVOC refers to the sum of isoprene and monoterpene emissions per species.

Species name	Isoprene (Kg)	Monoterpene (Kg)	Total BVOC (Kg)	BVOC emission (Kg/ Kg leaf biomass)
Quercus robur	3364.57	59.53	3424.10	0.067
Quercus rubra	1700.49	30.09	1730.58	0.067
Quercus palustris	1294.73	22.91	1317.64	0.067
Eucalyptus globulus	173.95	48.28	222.23	0.042
Liquidambar styraciflua	864.92	212.31	1077.23	0.036
Casuarina equisetifolia	353.56	3.27	356.83	0.033
Populus x canadensis	1237.19	10.27	1247.46	0.028
Populus nigra	1230.15	10.21	1240.36	0.028
Populus nigra 'Italica'	262.48	2.18	264.66	0.028
Populus alba	107.02	0.89	107.91	0.028
Populus simonii	67.31	0.56	67.87	0.028
Salix x sepulcralis	132.27	11.24	143.51	0.024
Salix cinerea	60.74	5.16	65.90	0.024
Salix sp.	56.34	4.79	61.13	0.024
Salix atrocinerea	31.25	2.66	33.91	0.024

BVOC: biogenic volatile organic compounds

6| How does UES supply vary across Porto?

In this study, UES supply provided by green spaces was compared across five different socioeconomic areas in Porto, and also across eight different types of green areas.

These two comparisons are addressed as independent topics in the following pages, to facilitate understanding of distinct drivers of UES supply in Porto.

6.1 | UES heterogeneity across socioeconomic spatial patterns[1]

Five spatial areas were analyzed in the first comparison to assess UES heterogeneity across Porto, corresponding to groups of parishes, or socioeconomic strata (Fig. 6). Each of these five strata represents an area with similar socioeconomic and urbanistic characteristics.

6.1.1 | Brief characterization of socioeconomic strata

Four socioeconomic indicators of the 2011 national census database were selected to differentiate the five parish-based strata analyzed in this study (see Graça et

[1] All the results briefly mentioned and discussed here are presented in full detail in Graça et al. (2017).

In a nutshell

- Strong association found between patterns of wealth and structure of the urban forest
- The less wealthy area of Porto presented the poorest results for structural variables of the urban forest and UES performance, although it was the greenest amongst the five groups of parishes analyzed
- Differences in types of urban green spaces affected UES supply
- UES performances across socioeconomic strata were affected by their relative proportion of types of green spaces
- Tree diameter and leaf biomass surpassed the impact of tree density and type of species in UES supply for Porto

al., 2017, for more details about the selection of indicators, and values per strata). Each of the selected indicators (population with college degree; population age; time of construction of buildings; building owners vs. tenant percentages) provided information concerning four different socioeconomic dimensions.

The western and southwestern strata, *Aldoar, Foz & Nevogilde* and *Lordelo & Massarelos*, presented the largest percentage of population with college degree, younger inhabitants (age ≤14 years) and more recent construction. Additionally, the occupants of more than half of the dwellings in these areas were their owners. *Campanhã*, the eastern stratum, had the lowest proportion of population with college degree and dwellings owned by their occupants, and exhibited a low share of recent construction (even though available space for new construction is abundant in this part of the city). Building from these findings, *Campanhã* was considered the most deprived area in Porto, while *Aldoar, Foz do Douro & Nevogilde* and *Lordelo & Massarelos* emerged as the wealthiest strata; *Paranhos & Ramalde* and *Historic Center & Bonfim* were considered as intermediate concerning wealth status.

6.1.2 I Differences across the urban forest

The five strata analyzed yelded considerable differences in terms of size, structure and composition of the urban forest. Concerning the total amount of green spaces per strata, Campanhã presented the largest proportion (46.8%), followed by the wealtier strata *Aldoar, Foz do Douro & Nevogilde* (45.8%) and *Lordelo & Massarelos* (43.6%).

However, *Aldoar, Foz do Douro & Nevogilde* and *Lordelo & Massarelos* presented the highest tree densities, and the latter had the highest share of trees with DBH equal or larger than 38.2 cm. It is not surprising, therefore, that *Lordelo & Massarelos* exhibited the highest values of tree leaf area and tree leaf biomass amongst all strata.

On the opposite side, *Campanhã* presented by far the lowest densities of trees, leaf area and leaf biomass among all strata, and the highest dominance effect by some species (indicating lower biodiversity) in the city. Additionally, this stratum had the largest share of smaller trees (52.7 % of trees with DBH ≤12.7 cm, and 81.7% of trees with DBH≤25.4 cm).

Historic Center & Bonfim presented the lowest proportion of small trees with DBH equal or less than 12.7 cm (corresponding to just 36,3% of all trees in this strata), which, together with a relatively abundant tree density (third best value amongst all strata) helps to explain its second ranking position in terms of tree leaf area and leaf biomass densities.

It is somewhat surprising that one of the two wealthiest parishes, *Aldoar, Foz do Douro & Nevogilde,* did not present better results in terms of tree leaf area and leaf biomass densities, given that it had the second highest tree density. This is probably due to the more recent construction age of this area of Porto, in which many new green spaces were established in recent decades. As trees in these areas develop, they are expected to provide the highest densities of tree leaf area and tree leaf biomass in the city.

Paranhos & Ramalde presented intermediate results for all structural variables of the urban forest (density of trees, leaf area and leaf biomass; composition in terms of tree DBH).

The composition of the urban forest was also substantially dissimilar across the five strata. *Campanhã* exhibited the lowest species richness (number of species), composed mainly by autochthonous species and others with agricultural value, while the two wealthiest strata (*Aldoar, Foz do Douro & Nevogilde* and *Lordelo & Massarelos*) presented a dominance of ornamental (exotic) species characteristic of gardens and parks. In *Historic Center & Bonfim*, the top abundant tree was *Acacia melanoxylon*, considered one of the most aggressive invasive species in Portugal (the national legislation actually prohibits its use and commercialization in the country). In *Paranhos and Ramalde,* the most abundant trees pertained to a mixture of both autochthonous and ornamental species.

6.1.3 I Impact of socioeconomic patterns in UES supply

The research developed in Graça et al. (2017) allowed to establish a statistical association between the structural variables of the urban forest and the socioeconomic indicators used to characterize the five groups of parishes analyzed in Porto. According to this study, the wealthiest strata emerged as having the best results in terms of structural variables of the urban forest (although *Aldoar, Foz do Douro & Nevogilde* is expected to achieve Porto's highest densities in tree leaf area and leaf biomass only in a few years, given the youth of most specimens found in this strata). As the structure of the urban forest directly affects UES supply, it is not surprising that the overall UES delivery by green spaces in each of the five strata reflected these differences.

The wealthy stratum of *Lordelo & Bonfim* presented the best results for climate regulation (considering stored C, net sequestered C and avoided runoff) and air purification through pollution removal. The green areas of *Campanhã* presented the poorest performance amongst all strata for both climate regulation and air pollution removal (Fig. 13).

Historic Center & Bonfim presented the second best performance in UES delivery (Fig. 13), although it was the least green of all five socioeconomic strata analyzed. The good performance was due to the size of trees in this stratum (which had the lowest proportion of small trees across Porto) combined with the third highest tree density in the city. These two structural variables of the urban forest originated the second highest densities of tree leaf area and biomass amongst all five parish groups, consequently affecting positively the overall UES supply.

Nevertheless, as already mentioned, *Aldoar, Foz do Douro & Nevogilde* will very likely become the stratum with the best UES performance in Porto in the forthcoming years, as the trees planted in new green areas develop (because it has more green areas and the second highest tree density in the city).

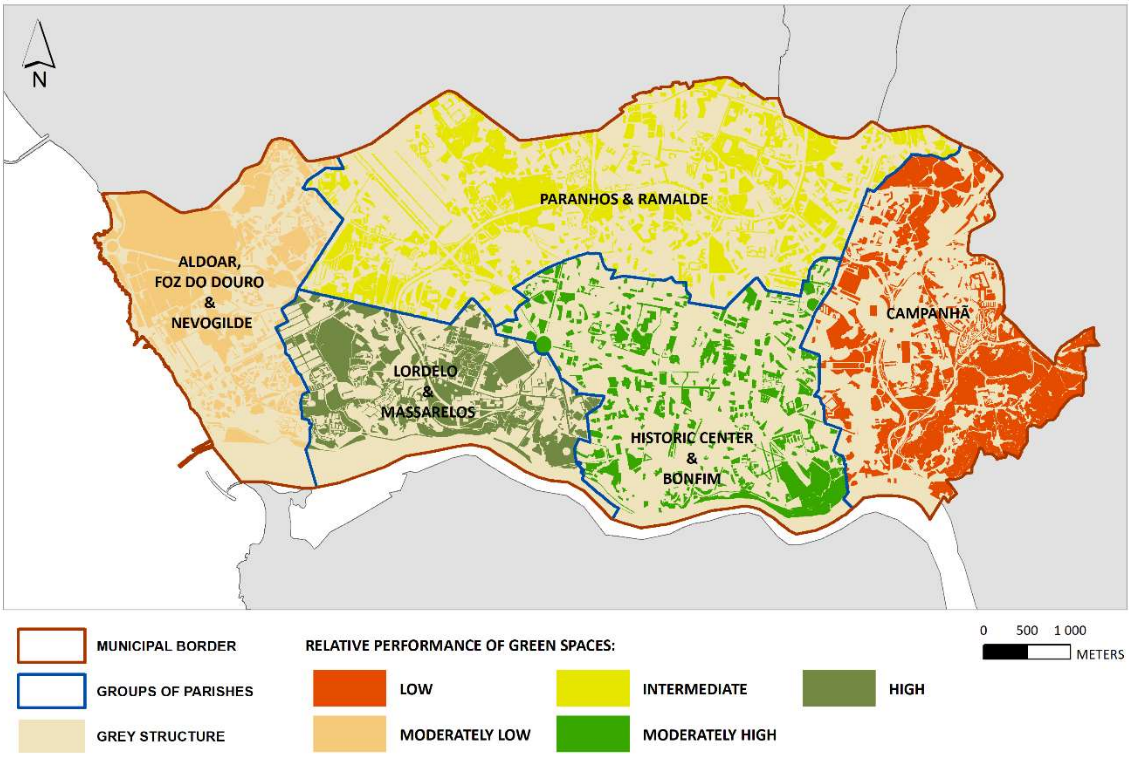

FIGURE 13 – Performance of urban green areas per group of parishes of Porto, according to the average provision of regulating urban ecosystem services: climate regulation through carbon storage and carbon sequestration; water flow regulation through avoided runoff; air purification through pollution removal. The performance is measured in a relative scale of comparison amongst the five groups of parishes (in which “high” refers to the best result amongst all five strata).

Graça et al. (2017) identified tree DBH and leaf biomass density as the structural variables of the urban forest that have the highest impact in Porto's UES supply, surpassing by far the effect of tree density and species type. These are precisely two of the variables for which *Campanhã* presented the worst results amongst all the five strata analyzed.

The results of the research for *Campanhã* clearly demonstrate that more green spaces do not equal better quality of the urban forest, nor higher performance in terms of UES delivery. In addition, the research also revealed that the wealthier areas in Porto benefit of a considerably better supply of UES, compared with the most deprived stratum. These findings highlight a pattern of environmental inequity across Porto, because the most deprived areas are potentially more exposed to environmental risks such as heatwaves, flooding and air pollution. Many studies have established positive relationships between such environmental risks and negative health outcomes (increased morbidity and mortality), which are particularly serious in more vulnerable populations lacking economic resources to alleviate these hazards (via home heating or cooling, for example, or appropriate health care).

6.2 I UES heterogeneity across types of green spaces[2]

Trees composing Porto's urban forest are distributed across many types of green spaces, both in private and public land, which encompass distinct regulations and stewardship regimes. These diverse conditions originate differences in vegetation composition and structure (for example, private owners may tend to choose plant species based in their personal preferences, institutional managers will take into consideration maintenance operations and costs …), which affect directly UES supply. Therefore, it is important to understand which types of green space have the best and worst performances, and why, in order to support better planning, management and design of green spaces.

6.2.1 I Brief characterization of green spaces

Eight different types of green spaces were analyzed and compared in a second study to assess UES heterogeneity across Porto. The green types represent the main eight

[2] All the results briefly mentioned and discussed here are presented in full detail in Graça et al. (2018a).

categories of green spaces found in Porto, adapted from an original survey by Farinha-Marques et al. (2011): *Agricultural areas, Allotments & urbanizations, Civic & institutional, Motorways & tree-lined streets, Private gardens & backyards, Parks, public gardens & woodlands, Vacant lots & wasteland* and *Other green spaces.*

In this study, 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 Graça et al., 2018a, for a description of the criteria used to select and classify each of the eight green types).

Green spaces in Porto corresponded to about 40% of the total urban area, of which *Vacant lots & wastelands* occupied the largest proportion (12.1% of total urban area). *Private gardens & backyards* presented the second higher amount of green spaces (7.8%), followed by *Parks, public gardens & woodlands* (6.3%). The other classes of green spaces covered a total urban area ranging from 1.6% to 4.1% each.

6.2.2 I Differences in the urban forest across types of green spaces

The structure of the urban forest varied considerably across the eight green types. Although there was not a clear ranking in terms of average structural indicators, two green classes emerged as presenting the best overall results: *Parks, public gardens & woodlands*, followed by *Motorways & tree-lined streets.* Both classes presented the highest densities of tree leaf area and biomass, and the largest proportion of trees with DBH equal or greater than 30.6 cm amongst all green types; additionally, both had a relatively high value for Simpson index, indicating diversity of species (Table 5).

The green class that emerged in this study as having the poorest results in structural variables was *Vacant lots & wasteland*, followed by *Agricultural areas*.

The composition of species was dissimilar amongst the green types. Autochthonous species predominated in *Parks, public gardens & woodlands* and non-native species in *Private gardens & backyards, Motorways & tree-lined streets, Allotments & urbanizations* and *Other green spaces.* One surprising result was the occurrence of the invasive *Acacia melanoxylon* as the most abundant species for *Civic & institutional. Vacant lots & wastelands* was dominated by a mixture of autochthonous and spontaneous species.

TABLE 5 – Summary of results for the urban forest structure in the city of Porto (Portugal), per type of green space (adapted from Graça et al., 2018a).

Type	Total estimated area of city (%)	Tree density (n ha^{-1})	Simpson Index*	Tree Leaf Area (m^2 ha^{-1})	Tree Leaf Biomass (Kg ha^{-1})
Agricultural areas	1.6	131.7	0.80	5,426.1	417.0
Allotments & urbanizations	2.9	190.7	0.85	15,420.1	1,265.1
Civic & institutional	3.1	201.0	0.80	14,352.5	1,529.6
Motorways & tree-lined streets	4.1	130.4	0.96	23,104.4	1,541.7
Private gardens & backyards	7.8	133.8	0.97	9,660.4	1,212.5
Parks, public gardens & woodlands	6.3	250.4	0.94	23,439.4	2,164.4
Vacant lots & wasteland	12.1	50.6	0.66	3,105.8	334.9
Other green spaces	2.1	153.2	0.69	15,344.9	1,539.5
City Total		64.0		4,857.6	453.1

* Simpson index informs about species dominance effects. Results in the table were calculated using the complement of Simpson's index, in which greater values denote higher diversity (see calculation details in Graça et al., 2018a).

6.2.3 I Impact of green types in UES supply

UES supply for each type of green space reflected the respective characteristics of the urban forest. Therefore, *Parks, public gardens & woodlands* presented the best results for carbon storage and sequestration, avoided runoff and pollution removal. The second best overall performance corresponded to *Motorways & tree-lined streets* (although in terms of carbon net sequestration this stratum was surpassed by *Allotments & urbanizations*).

The poorest total performance was found in *Vacant lots & wasteland*, followed by *Agricultural areas* and *Private gardens & backyards* (Fig. 14).

6.2.4 I BVOC emission across types of green spaces

The highest density in BVOC emissions, potentially increasing air pollution, was estimated for *Civic & Institutional*, followed by *Parks, public gardens & woodlands* (Fig. 15). The lowest BVOC densities were found in *Agricultural areas*.

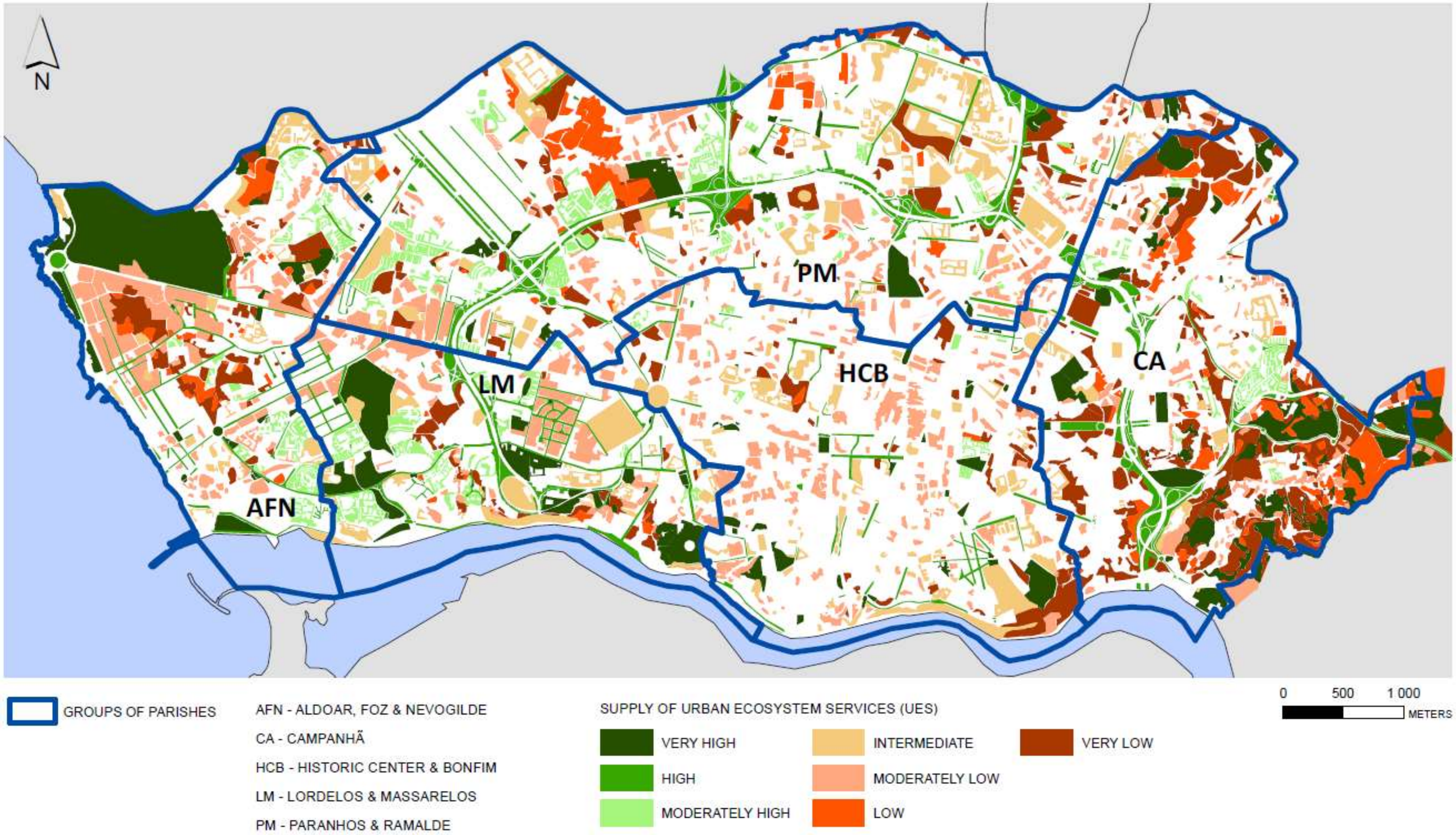

FIGURE 14 - Relative performance of urban green areas per group of parishes of Porto, according to the average provision of regulating urban ecosystem services (UES): climate regulation through carbon storage and carbon sequestration; water flow regulation through avoided runoff; air purification through pollution removal (source: Graça et al., 2018a).

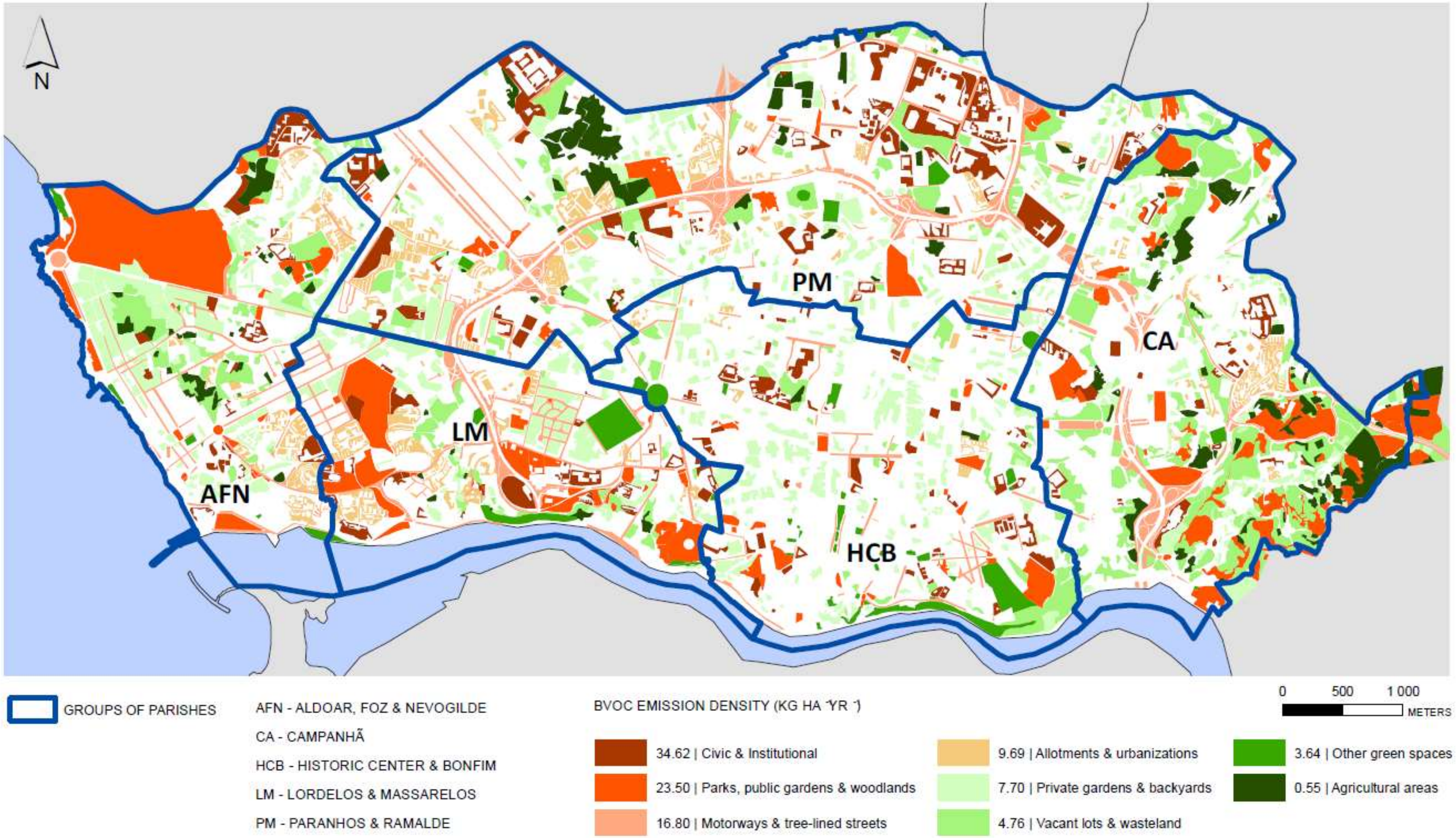

FIGURE 15 - Supply of urban ecosystem disservices: average density of biogenic volatile organic compounds (BVOC) by vegetation in urban green areas of Porto, according to groups of parishes (source: Graça et al., 2018a).

6.3 I Combined effects of types of green spaces and socioeconomic patterns in UES supply across Porto

UES supply varied amongst the socioeconomic strata as a result of the uneven distribution of types of green spaces across the city. The wealthier strata, *Lordelo & Massarelos* and *Aldoar, Foz do Douro & Nevogilde* were covered by the largest share of green types generating the highest densities of UES (especially *Parks, public gardens & woodlands*), while the deprived stratum *Campanhã* was dominated by green spaces yielding the poorest UES performance (about 50% of the green spaces in this parish were covered by *Vacant lots & wastelands*) (Fig. 16).

These findings help to better understand the origin of the differences in the urban forest across the socioeconomic strata, which reflect distinct functions of green spaces, diverse regulations frameworks and management regimes.

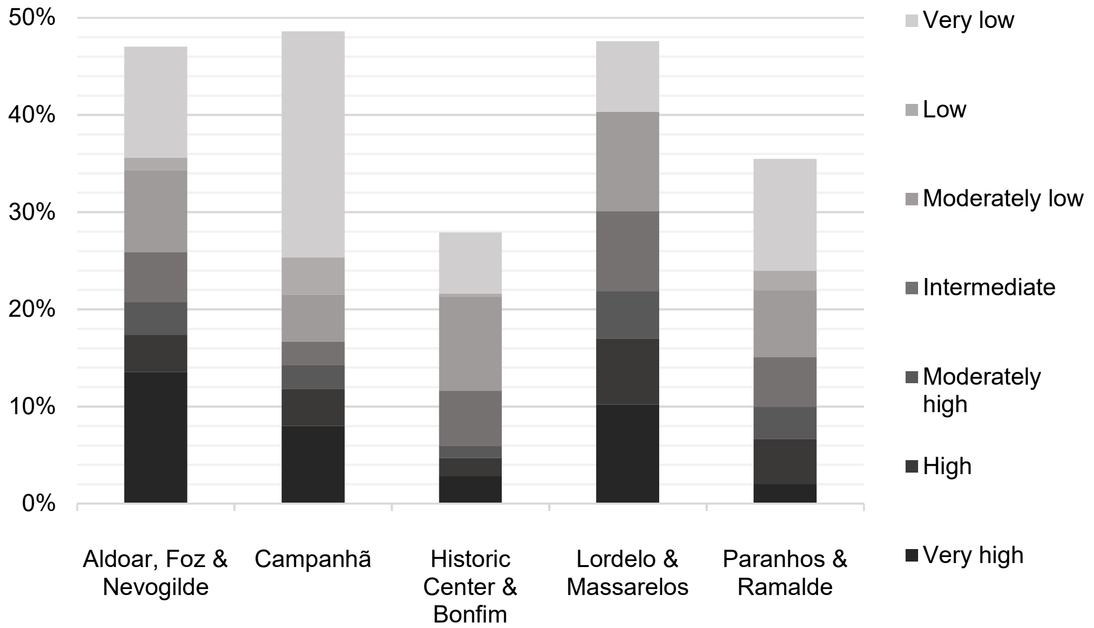

FIGURE 16 - Proportion of green spaces per group of parishes in Porto, according to the performance in delivering regulating urban ecosystem services. Ranking classes refer to the overall level of proficiency assigned to each type of green space: very high, high, moderately high, intermediate, moderately low, low, very low (Graça et al., 2018a).

7| Perception of street trees: influence on UES supply[3]

Densely built urban areas like Porto pose challenging obstacles to the creation of new sizable green spaces. Street trees are one of the easiest ways to increase urban greening, precisely because they do not require large portions of continuous land. Moreover, according to the findings of this research concerning supply of regulating UES by different types of green spaces, *Motorways & tree-lined streets* ranked the second best position in terms of overall performance.

City dwellers play a crucial role in determining UES supply across cities, because their use of the urban forest and relationship with nature are a main driver shaping urban ecosystems. People's preferences and behavior affect their choices in terms of what, where and how they plant, and even if they prefer not to have trees at all. In public areas, trees may be cherished and nurtured to full development, or may suffer damages and increased stress if potential beneficiaries do not appreciate or acknowledge the value of green spaces. Therefore, it is very important to understand how urban inhabitants perceive and value green spaces and specifically trees, in order to devise successful planning, design and management of green spaces. Otherwise, a cultural gap between the community's expectations and top-down greening initiatives may lead to negative outcomes, both culturally and environmentally.

To understand the perception of citizens in Porto regarding street trees, a questionnaire was developed specifically for this purpose (Appendix B) and applied in Porto to a sample of 819 people aged 18 years or older. The interviewees were randomly approached in Porto's streets between February and May of 2017, and were asked about how much importance or agreement they attributed to a set of statements about benefits (cultural, regulating and economic) and losses / costs caused by street trees. A set of three additional questions aimed to assess perceptions relative to the value of larger versus smaller trees, and to the overall satisfaction concerning tree quantity in Porto. For each interviewee, information about age, gender and school level was also collected.

The subsequent statistical testes applied to the resulting dataset highlighted that people in Porto attributed more value to environmental benefits (particularly air quality improvement) than cultural ones.

[3] All the results briefly mentioned and discussed here are presented in full detail in Graça et al. (2018b).

However, the most remarkable finding was the association between the socioeconomic characteristics of respondents with specific patterns of response. School level was the variable that determined more pronounced differences in mean responses: people with lower academic level tended to value less the benefits provided by street trees in Porto and attribute more importance to losses and damages, in comparison to people who attended university or achieved higher academic degree. This is a particularly relevant result, because more than 70% of inhabitants aged 18 years or older in the socioeconomic stratum *Campanhã* hold the 9th grade or below. Therefore, while the results for UES estimates across Porto suggest that *Campanhã* is the top priority in terms of enhancing tree plantation and green area development to improve environmental equity, caution is necessary to avoid well-intended but potentially negative greening initiatives that may contribute to foster frustration and disempowerment feelings by the local community.

Age also accounted for some differences in mean responses, underlined by the increased concern that older people showed about losses and costs.

In addition, cultural benefits were more important for women than for men.

One other relevant finding stemming from the research was that people in Porto tend to consider smaller trees as more beneficial than larger specimens, regardless of age, gender or school level. Although most interviewed people valued more environmental benefits provided by street trees, there seems to be general unawareness that regulating UES are directly influenced by tree's size, and that more leaf area and biomass generate considerably better outcomes. These results suggest that the information people have can strongly affect their perception of benefits and losses / costs of trees. On the other hand, in Porto many street trees are planted very close to houses, possibly generating direct annoyances to local inhabitants and influencing their overall opinions about trees. Therefore, proper selection of species and planting locations, together with appropriate management of green spaces, may help to improve the relationship between Porto's citizens and trees. Nevertheless, it is possible that if people have access to better information about the benefits of trees and urban nature, they may become more tolerant to nuisances.

8| Recommendations for planning, management and design of green spaces

The findings from this research highlighted a number of challenges concerning UES supply across Porto, with significant impacts in terms of environmental justice and urban resilience:

- Relatively low tree cover in Porto, limiting total delivery of UES supply;
- Large dominance of small trees across the urban forest, suggesting that few specimens have the chance to fully develop and deliver their maximum potential in terms of UES supply;
- Significant heterogeneity across Porto in terms of UES supply, privileging the socioeconomically wealthier western areas of the city in detriment of the more deprived eastern parish of *Campanhã*;
- Unbalanced composition of types of green spaces across the five analyzed socioeconomic strata, reflected by a strong dominance, in *Campanhã*, of the green type yielding the poorest UES performance (*Vacant lots & wastelands*) amongst eight different types of green spaces analyzed in Porto;
- Low tree density and size in *Campanhã*, in comparison with the rest of the city, negatively affecting total tree leaf area and biomass, and consequently UES supply;
- Dominance of the invasive species *Acacia melanoxylon* in the historic center of Porto, and also in green spaces included in *Civic & Institutional;*
- Low species diversity in some areas and types of green spaces in the city (respectively *Campanhã* and *Vacant lots & wastelands*) potentially decreasing the resilience of the urban forest to pests, diseases and unforeseen environmental changes;
- Top abundant tree species in the city are mainly high BVOC-emitter species that can potentially contribute to degrade air quality especially in light of climate change;
- Lack of large trees in *Private gardens & backyards,* suggesting a cultural preference of home owners towards smaller specimens that hampers UES supply;

- Incorrect placement of the few large trees with potential impact in energy savings of residential buildings, resulting in increased energy use, suggesting lack of information by steward and landowners;
- Gap between the overall perception, by citizens, that the environmental benefits of trees (particularly regulating UES) are of uppermost importance, and the acknowledgment of how large trees are crucial to deliver them;
- Potential conflicts between specific socioeconomic groups concerning top-down institutional greening initiatives that may risk increasing perception of nuisances and discontentment in some areas of Porto, eventually causing rejection or disempowerment feelings in more deprived communities.

Building from the challenges identified above, a general list of recommendations for urban planning of green spaces in Porto is suggested below:

To increase overall UES supply and resilience of the urban forest in Porto:

- <u>Increase the quantity of healthy trees</u>

  Tree health affects directly UES supply and BVOC emission. Therefore, it should be a major concern for the municipality. Proper establishment of trees (enough space for crown and root growth, light, appropiate soil and water), particularly during the adaptation period (first two years after plantation) is critical to insure good development of specimens and avoid stressful conditions with negative outcomes. Moreover, Soares et al. (2011) demonstrated in a case study for Lisbon that for every $ invested in street tree management, residents receive more than four times the same amount in benefits (energy savings, CO_2 reduction, air pollution removal, avoided runoff and increased real estate value). This cost-benefit ratio was estimated for a specific type of tree (street trees), a limited set of benefits, and according to municipal expenditure for Lisbon, therefore caution is advised in assuming its validity for Porto. Nevertheless, as street trees are typically the urban trees that require more management operations in Porto, it is possible that specimens planted in other types of green areas offer even better cost-benefit ratios, especially if more types of benefits are considered;

- Develop a municipal plan for trees and green areas

  New tree plantations should be planned in areas where specimens can develop to full size without significant constraints, taking advantage of patches of vacant or protection land under municipal or governmental management (e.g. protection areas near motorways, roundabouts, institutional green spaces such as hospitals, schools, public services …). A "greening plan" for the city should be specifically developed to insure a municipal coherent tree strategy for Porto, identifying the available areas for new tree plantations (not necessarily corresponding to new green areas), and setting targets, phasing and execution. In addition, other UES not addressed in this research should be considered in greening initiatives, in order to render an urban forest as multifunctional and resilient as possible (e.g. connectivity of green corridors – even if reduced to street trees - is essential to support urban wildlife, air flow …);

- Plant evergreen trees in more polluted areas

  This will maximize deposition of particulate matter year-round and reduce human exposure to degraded air;

- Increase permeable areas under tree crown

  Rainwater not intercepted by leaves and branches will infiltrate into the soil, and reduce even further surface runoff;

- Plant trees in strategically planned water retention basins

  If water retention basins are established in strategic urban areas, in relation to the characteristics of existing hydrological basins, trees will help to mitigate flooding risk. In addition, they will contribute to purify the water, which may be stored and reused;

- Plant new deciduous trees around buildings, in energy conserving locations

  Proper orientation of trees will promote energy savings and avoid emission of pollutants generated by power plants. In summer, trees may help cooling naturally buildings nearby, by providing shade; in winter, the lack of leaves will avoid sun blocking, and unnecessary heating (trees should be within a distance below 18 m to construction, and at least 5 m height, to have energy impacts). Trees may also block cold winter winds, and reduce even more heating needs;

- <u>Choose species with low maintenance and long life-spans to avoid maintenance operations</u>

  Hardy, long-living species help to avoid fossil fuel use in maintenance operations, and consequently reduce the emission of pollutants in the medium and long term;

- <u>Promote diversity of tree species</u>

  In new green areas, the diversity of species should be encouraged to increase the resilience of the urban forest to pests and disease outbreaks, and to extreme climatic events (particularly heatwaves and severe drought). New plantations of trees should include native, low BVOC-emitter and hardy species with well-documented use and impacts in the region;

- <u>Plant shade trees (especially in parking lots)</u>

  Shade reduces vehicular VOC emission. In addition, larger trees can potentially generate more shadow than smaller specimens, and therefore contribute further to mitigate heatwaves, regulate microclimate and reduce ozone formation due to BVOC and VOC reactions across the city. Therefore, shady species should be preferred for new plantations whenever possible;

- <u>Increase the quantity of street trees</u>

  Due to their easier establishment in densely built areas, new plantations of street trees are advised when possible, to increase the supply of local UES (such as air pollution removal or microclimate regulation) and the direct exposure of citizens to their beneficial effects in health. Moreover, this research has demonstrated the overall good performance of this type of green space in providing regulating UES. However, street trees species and planting locations should be carefully chosen in order to allow full growth, minimized pollutant trapping in street canyons, and avoid losses or damages to nearby residents. It is preferable to select smaller species for narrower areas, or not to have trees at all if the distance of the tree to the nearest building facade does not allow full crown development to adult size without substantial pruning;

- <u>Create incentives for planting new trees in private land</u>

  Trees in private areas influence strongly the overall UES supply by Porto's urban forest. In order to improve UES supply in private land, municipal incentives such as tax reductions should be established to support tree plantation of adequate species (low BVOC emitter-species, resilient to climate change, preferably native), their development to full size and conservation. These incentives could also include supply of seedlings by the municipality, and training concerning tree plantation and maintenance, in conjunction with NGOs: the "FUTURE: project of the 100.000 trees for Porto" (www. http://www.100milarvores.pt/) is an example of an award-winning and very successful project illustrating how volunteer citizens and several institutions were able to produce and plant more than 98.000 native trees (to this moment, as the project is still ongoing) in the metropolitan area of Porto, between October 2011 and April 2017;

- Avoid unnecessary pruning of urban trees

  Pruning should be restricted to fitossanitary purposes, clear risks for safety, and correction of shape in young specimens, in order to avoid unnecessary loss of tree leaf area and biomass;

- Control invasive species

  Invasive species destroy native biodiversity and disturb ecosystem processes, although they also provide some UES (e.g. regulating UES). Yet, they pose greater risks than benefits for the urban forest. A specific plan should be developed to better assess and control spreading of the invasive *Acacia melanoxylon* in Porto, particularly in green areas enclosed by building blocks in the city center, and in vacant areas across the city;

- Replace dead trees by new, healthy specimens;

  This will help to maintain the current carbon pool and level of UES already provided by the urban forest in Porto;

- Choose tree species less prone to cause allergic reactions

  Allergies were the issue identified as the top negative aspect related with street trees in Porto. Nevertheless, it is important to inform the population that some negative perceptions regarding tree allergies are misconceptions (e.g. the case of species of the *Populus* genus, frequently demonized because people often associate erroneously the cause of allergies to the release of "cotton" by female specimens in springtime; yet, male poplars release their pollen much earlier, before the period in the year usually perceived as the allergy peak due to pollen release);

- Raise public awareness about the benefits of large trees

  An informative campaign targeting citizens about the benefits of large trees for human health and wellbeing, and correct practices to increase UES supply (location in relation to construction, avoid unnecessary pruning …) is probably one of the best ways to influence positive behavior towards the urban forest in Porto, with potential positive effects in tree cover over time;

- Monitor the evolution of the urban forest

  A municipal monitoring plan of the evolution of the urban forest is critical to assess if specified goals are met over time, and support necessary adjustments in planning, management and design of green spaces.

To tackle environmental inequity in Porto:

- Support conversion of vacant lots and wasteland to other types of green spaces, particularly in *Campanhã*

  Vacant lots and wasteland yielded the lowest performance in UES supply amongst eight green types analyzed in this research, and currently constitute more than half of all green spaces of *Campanhã*. Therefore, conversion of these areas to other types of green spaces may help to increase UES supply in this area of the city. Nevertheless, converted green spaces will only be effective if new trees are planted and maintained, following the general guidelines provided above.

- Set priority areas for new green spaces and tree plantation in *Campanhã* and *Paranhos & Ramalde*

  Excluding *Vacant lots & wasteland*, the sum of the remaining green types in Porto covers just 24% of *Paranhos & Ramalde* and 25% of *Campanhã*. These are much lower amounts than in *Aldoar, Foz do Douro & Nevogilde* (36%) and *Lordelo & Massarelos* (40%). In addition, *Campanhã* holds by far the lowest tree density amongst the socioeconomic strata analyzed in this research, followed by *Paranhos & Ramalde.* Therefore, these two area should be considered as priority areas for new greening initiatives. It should be noted that although *Historic Center & Bonfim* also presents similar percentage of green area (excluding *Vacant lots & wasteland*) to the priority areas, it is more densely built, preventing the establishment of new green areas and tree plantations.

- Implement a participatory approach to devise new greening initiatives in priority areas, especially *Campanhã*

  Results concerning perception of street trees by citizens in Porto suggested that conflicts due to top-bottom institutional greening initiatives are more likely to take place in *Campanhã*. A participatory approach to develop and fine-tune a greening strategy can contribute to foster acceptance and valuing of green spaces by local residents, increasing proactive behavior and supply of cultural UES.

Conclusion and perspectives

In an increasingly urbanized world facing pressing challenges like climate change, green areas in cities can deliver a crucial contribution for human wellbeing by generating vital ES, many of which need to be provided locally.

This thesis argues that the supply of UES is highly influenced by the composition and structure of vegetation, the most abundant element of green spaces. Therefore, planning, management and design of green spaces can have a strong impact in UES delivery by manipulating intentionally vegetation according to desired outcomes. However, a solid foundation of evidence-based knowledge is required to guide decision-making processes and ensure positive changes. Although UES research has risen extraordinarily in the last few years, the uptake of the growing body of scientific knowledge it has fostered has not yet made its way into practice.

The gap between UES research and practice-oriented concerns was addressed in the thesis in a two-fold way. First, using the city of Porto (Portugal) as case study, this research developed and tested scientific methods to analyze and measure UES delivered by urban green spaces in a manner to generate thematic and spatial detail that can support evidence-based action (Papers 1, 2, 3). Secondly, the operationalization section of the thesis provided an illustrative example of how scientific knowledge can be translated into specific orientations for planning, management and design of green spaces.

The scientific methods used allowed to identify which variables of trees have the highest impact in regulating UES performance (Paper 1). In addition, the research contributed with methods to unravel patterns of regulating UES supply according to a gradient of socioeconomic status (Papers 1, 2) and according to types of green spaces (Paper 2), highlighting how UES supply is affected by socioeconomic patterns and by distinct types of functions, management and regulations differentiating green spaces (Paper 2). The results evidenced that the most deprived area of Porto presented the poorest UES performance, despite having the largest proportion of green area amongst the socioeconomic strata analyzed. These findings demonstrate that qualitative aspects of green spaces strongly affect UES supply and open new perspectives to future research, especially when considering the links between UES and human health. Most research focusing on the impact of green spaces in health has relied predominantly in using quantitative measures of green (such as area) to establish associations, rendering inconclusive results for specific relationships. It remains largely unexplored how the qualitative attributes of green space, particularly those related with vegetation structure and composition, affect human health. Future contributions to better understand these links between quality of green spaces and health may provide decisive support to nature-based solutions and green infrastructure, particularly in urban contexts of intense dispute for land by competing interests.

Considering that cities are complex social-ecological systems in which humans are the main shaping driver, it is also critical to better understand sociocultural variables that may affect urban ecosystems, and consequently UES delivery. Building on the reasoning that people's perception of green space value reflects their relationship with nature, and consequently their use of and behavior towards urban ecosystems, the thesis explored how perception of green features by communities may influence UES supply (Paper 3). The results of the research suggested potential gaps between the community's expectations and top-down objectives concerning urban trees, which may compromise the cultural and environmental success of greening initiatives detached from their local beneficiaries. These findings point to the need to investigate further trade-offs between UES and ecosystem disservices, because enhancing the supply of a specific set of services may simultaneously generate negative outcomes. In addition, it has been demonstrated in other studies that perceptions about ecosystem disservices affect the use, management, development and experience of urban green areas configuring a research topic of relevance for practice-oriented disciplines.

The greatest contribution of this thesis for Landscape Architecture is to propose a new paradigm for planning, managing and designing urban green spaces, based in solid evidence and in approaching complex urban realities in a scientifically sound manner. To realize the full potential of the profession, it is proposed that landscape architects take the leadership of building scientific knowledge to expand the horizons of the discipline of Landscape Architecture. Scientific research supporting EBLA offers immense opportunities to accomplish such ambitious goal, simultaneously strengthening the role of landscape architects in tackling the extreme challenges that our cities are facing in the XXI century.

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Appendix A | i-Tree Eco overview[4]

What is i-Tree Eco?

i-Tree Eco is a free modelling tool developed by the USDA Forest Service that uses tree measurements and other data to estimate ecosystem services and structural characteristics of the urban or rural forest. Eco is a complete package that provides:

- Sampling and data collection protocols - For plot-based sample projects, total population estimates and standard error of estimates are calculated based on sampling protocols. For complete inventories, Eco calculates values for each tree;
- Flexible data collection options – Use the mobile data collection system with web-enabled smartphones, tablets or traditional paper sheets;
- Automated processing - A central computing engine that makes estimates of the forest effects based on peer-reviewed scientific equations to predict environmental and economic benefits;
- Reports - Summary reports that include charts, tables and a written report.

i-Tree Eco is currently in its version v6, with added functionalities when compared with the former version (v5).

How does i-Tree Eco work?

Tree measurements and field data are entered into the Eco application either by web form or by manual data entry; they are merged with local preprocessed hourly weather and air pollution concentration data. These data make it possible for the model to calculate structural and functional information using a series of scientific equations or algorithms (Fig. 1).

What does the Eco Model estimate?

i-Tree Eco is currently designed to provide estimates of:

[4] Information adapted from www.itretools.org

- Urban forest structure - Species composition, number of trees, tree density, tree health, etc.
- Pollution reduction - Hourly amount of pollution removed by the urban forest, and associated percent air quality improvement throughout a year. Pollution removal is calculated for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, particulate matter 10 (<10 microns) and particulate matter 2.5 (<2.5 microns).
- Public health impacts – Health incidence reduction and economic benefit based on the effect of trees on air quality improvement for the United States only.
- Carbon - Total carbon stored and net carbon annually sequestered by the urban forest.
- Energy Effects - Effects of trees on building energy use and consequent effects on carbon dioxide emissions from power plants.
- Avoided runoff - Yearly avoided runoff attributed to trees summarized by tree species or strata.
- Forecasting (version v6 only) - Models tree and forest growth over time; considers factors like mortality rates, tree planting inputs, pest and disease impacts and storm effects. Some ecosystem services including carbon and pollution benefits are also forecasted.
- Bioemissions - Hourly urban forest volatile organic compound emissions and the relative impact of tree species on net ozone and carbon monoxide formation throughout the year.
- Values - Compensatory value of the forest, as well as the estimated economic value of ecosystem services.
- Potential pest impacts - based on host susceptibility, pest/disease range and tree structural value.

All reporting options may not be available depending on project configuration, data options and project country location.

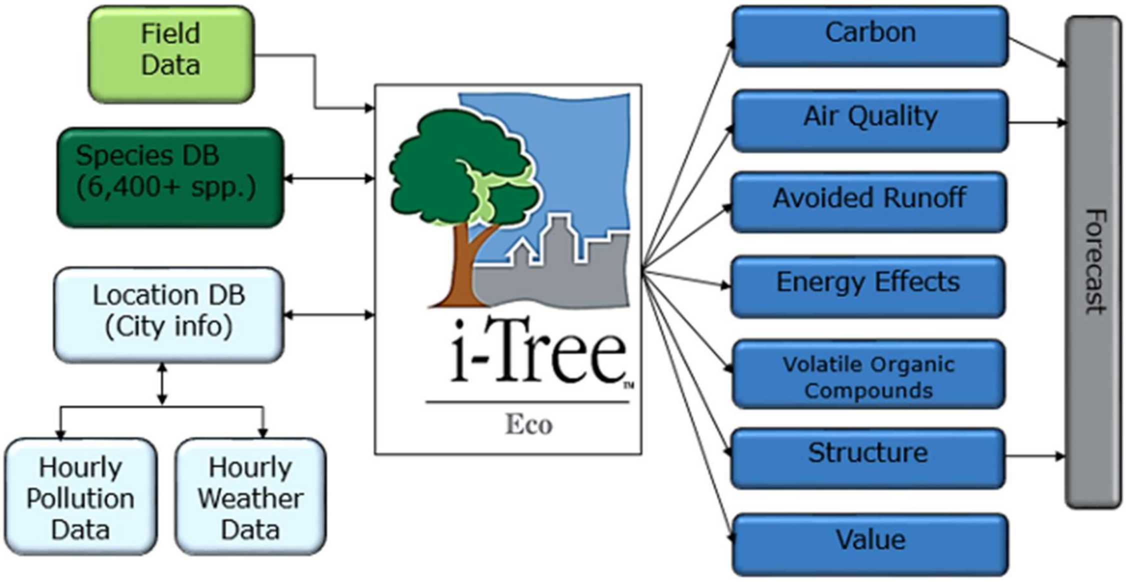

Figure A1 – Diagram illustrating the input data (left side) required by the modelling tool i-Tree Eco to generate information about forest structure and its impacts (right side). The forecast modelling feature is available in version v6 and projects estimates for the evolution of the forest structure, air pollution removal, carbon sequestration and storage. Source: https://www.itreetools.org/eco/overview.php.

Appendix B | i-Tree Eco data collection form used in the sample inventory of the urban forest in Porto, conducted during 2014[5]

PLOT ID=	DATE=	CREW=	GPS COOR X Y	PHOTO ID=

PLOT SKETCH AND NOTES FOR PLOT RELOCATION

(Note distance and direction from plot center to fixed objects; sketch fixed objects in relation to plot center)

Plot address=
Notes:

Plot contact info:
Name and Title:_______________
Phone #______________________

LOCATING REFERENCE OBJECTS/LANDMARKS (Identify at least 1 object)
Measure Reference Object (1) description_______________________________________
Distance to Reference Object (1)______________
Direction to Reference Object (1)_____________
Measured Reference Object (2) description______________________________________
Distance to Reference Object (2) ______________
Direction to Reference Object (2)_____________
Tree Measurement Point (TMP): Reference Object (1) used Y/N
Reference Object (2) used Y/N
Measurement Unit: M/E

Percent Measured________

ACTUAL LAND USE=	PERCENT IN=	PLOT TREE COVER (%)=	SHRUB COVER (%)=	PLANTABLE SPACE (%)=
ACTUAL LAND USE=	PERCENT IN=			
ACTUAL LAND USE=	PERCENT IN=			
ACTUAL LAND USE=	PERCENT IN=			

GROUND COVER	%BLDG	%CMNT	%TAR	%ROCK	%SOIL	%DUFF/ MULCH	%HERB/ IVY	%MAIN. GRASS	%UNMAIN GRASS	%H2O

SHRUBS	SPECIES	HEIGHT	% AREA	% MISSING	SPECIES	HEIGHT	% AREA	% MISSING	SPECIES	HEIGHT	% AREA	% MISSING

[5] Available in the i-Tree Eco v5 Manual, and directly from the software. See Appendix C for an explanation of each variable in the form (in Portuguese).

PLOT ID=				TREE SPECIES			DBH						HEIGHT			CROWN WIDTH							TREES NEAR BUILDINGS						
TREE ID	STAT	DR	DS	LAND	USE	HT DBH	1	2	3	4	5	6	TOT	LIVE TOP	CROWN BASE	N-S	E-W	% MISS	DB	% IMP	% SHRUB	CLE	D1	S1	D2	S2	D3	S3	TREE SITE

Appendix C | Description of variables in the i-Tree Eco form, and instructions provided to field work crews about how to collect data (in Portuguese)[6]

INSTRUÇÕES PARA PREENCHIMENTO DAS FICHAS DE INVENTÁRIO I-TREE ECO

Deve ser preenchida uma ficha por cada uma das amostras (círculos com raio de 17,84m) distribuídas pelo concelho do Porto. Descreve-se abaixo qual a informação /parâmetros a recolher/medir, e quais os procedimentos gerais a adotar.

A. PÁGINA FRONTAL DA FICHA DE INVENTÁRIO

Destina-se à recolha de dados que permitam caracterizar a amostra e a equipa que desenvolveu o trabalho.

Campos de informação geral:

PLOT ID: Número da amostra

DATE: Data

CREW: Equipa (especificar o nome de todos os elementos)

GPS COOR: Coordenadas x,y do centro da amostra (opcional)

PHOTO ID: Nºs das fotografias tiradas (opcional)

PLOT SKETCH AND NOTES FOR PLOT RELOCATION: Esboço da parcela e notas para futura relocalização da amostra

PLOT ADDRESS: endereço da parcela (opcional)

PLOT CONTACT INFO: apenas se disponível, registar nome e telefone de alguém responsável pelo acesso. Não pedir esta informação em parcelas residenciais;

NOTES: Desenhar aqui o esboço da parcela, marcando a distância e a direção do centro a objetos fixos.

LOCATING REFERENCE OBJECTS/LANDMARKS: Identificação de objetos ou pontos de referência (identificar pelo menos 1)

É necessário identificar pelo menos um ponto de referência visível a partir do centro de cada amostra. Nas amostras mais difíceis de identificar recomenda-se que se indiquem dois pontos de referência. Estes pontos não precisam de estar localizados dentro da amostra.

[6] Translated and adapted and from the i-Tree Eco v5 Manual.

Caso se tenha definido previamente um TMP (Tree Measurement Point), deverá ser utilizado como um dos pontos de referência.

Devem selecionar-se objetos com menor probabilidade de serem removidos no futuro próximo. É também útil fotografar os objetos de referência. Deve descrever-se com o máximo de especificações o objeto na ficha de inventário (ex: poste de eletricidade a 1,5 metros do lancil à esquerda da estrada, no sentido Boavista – Palácio de Cristal, em frente à loja x). Devem medir-se as distâncias e direções (1-360º) para cada objeto de referência, a partir do centro da parcela, e indicar se algum dos objetos de referência foi utilizado como TMP.

PERCENT MEASURED / Percentagem da parcela inventariada: Corresponde ao total da parcela a que a equipa de campo conseguiu ter acesso para medições, quer diretamente quer por estimativa. Isto permite recolher dados numa parcela com acesso parcial. Se uma parte da parcela está inacessível (por exemplo, atrás de uma vedação alta de um jardim privado em que não se consegue entrar, ou de um edifício), recolhem-se os dados para o resto da parcela. Porém, se for possível ver a parte da parcela inacessível e estimar as coberturas de árvores, arbustos e revestimento do solo, bem como DBH e outras medições necessárias, a percentagem da parcela medida será de 100%.

A utilização deste parâmetro também é útil no caso de amostras estratificadas (isto é, distribuídas por estratos) em que a amostra cai em mais do que um estrato, embora o seu centro esteja no estrato que está a ser inventariado. Neste caso, recolhe-se informação apenas da porção da parcela que está no estrato designado, e utiliza-se o parâmetro da percentagem da parcela inventariada para documentar o ajuste. Por exemplo, se um centro de parcela está no estrato de uso do solo "comercial" mas inclui dentro do seu limite alguma área florestada, mede-se apenas a vegetação que está na parte da parcela correspondente ao uso do solo "comercial" e especifica-se qual a percentagem da parcela que foi medida. Desta forma, evita-se incluir no cálculo dos resultados a vegetação de um outro estrato, que pode ser bastante diferente.

TABELA 1: Usos do solo – CAMPOS A PREENCHER:

ACTUAL LAND USE / Usos do solo atuais: esta informação é utilizada para fazer ajustes ao modelo no i-Tree Eco, quanto ao crescimento e características de valorização das árvores. É recolhida no local pela equipa de campo, e não a partir de mapas de ocupação do solo. As categorias possíveis são as seguintes:

- **Residencial (R)**: habitações unifamiliares servindo uma a 4 famílias cada;
- **Multifamiliar Residencial (M)**: habitações contendo mais do que 4 unidades familiares;

  (Nota: um bloco de habitações ligadas para 1-4 famílias é considerado Multifamiliar Residencial; um complexo residencial constituído por muitas estruturas construídas para 1-4 famílias e espaço verde comum também é considerado Multifamiliar Residencial).

- **Comercial/Industrial (C):** Para além de uso do solo claramente comercial e industrial, esta categoria inclui áreas exteriores para armazenamento e parques de estacionamento nas áreas do centro urbano que não estão relacionadas com um uso institucional ou residencial;

- **Parques (P):** inclui áreas com e sem manutenção;
- **Cemitério (E):** inclui todas as áreas sem manutenção dentro da área do cemitério;
- **Campo de Golfe (G);**
- **Agricultura (A):** inclui lavouras, pomares, pastagens, vinhas, viveiros, quintas de produção e edifícios conexos, culturas e/ou plantações que mostrem evidência de atividade agrícola ativa;
- **Desocupado / Vacant (V):** inclui parcelas sem uso claro. As estruturas e edifícios abandonados devem ser classificados de acordo com o seu uso intencionado original.
- **Institucional (I):** Escolas, hospitais, complexos de saúde, colégios, edifícios religiosos, edifícios governamentais, …;

Nota: se uma parcela contém amplas áreas sem manutenção, possivelmente para expansão ou outras razões, deverá considerar-se Desocupada (V). Porém, pequenas ilhas de floresta numa paisagem mantida devem considerar-se na categoria Institucional (I);

- **Infraestruturas / Utility (U):** inclui infraestruturas elétricas, infraestruturas de tratamento de esgotos, reservatórios cobertos ou descobertos, bacias de retenção e canais de controlo de cheias, condutas;
- **Água / zonas húmidas (W):** ribeiros, rios, lagos e outros corpos de água (naturais ou construídos). Piscinas de pequena dimensão e fontes devem ser classificadas de acordo com o uso do solo adjacente;
- **Transporte (T):** inclui estradas de acesso limitado e espaços verdes associados (como autoestradas com rampas de aceleração e saída), estações de caminhos-de-ferro, estaleiros, aeroportos,… Se a parcela incluir outro tipo de estrada, ou faixa central associada, classificar de acordo com o uso do solo adjacente mais próximo;
- **Outros (O):** Usos do solo que não podem ser incluídos em nenhuma das categorias anteriores. Como este uso do solo não fornece mais informação ao modelo, deve ser utilizado o mínimo possível, e sempre clarificando o porquê da seleção nas notas na ficha de inventário.

NOTA: Para edifícios de uso misto, o uso do solo é baseado no uso dominante, isto é, o uso que gera a maioria do trânsito pedestre. Este uso dominante pode nem sempre ocupar a maior parte do espaço no edifício. Por exemplo, um edifício com uso comercial no R/c e apartamentos nos andares superiores deverá ser classificado como Comercial /Industrial).

<u>PERCENT IN / Percentagem do uso atual do solo:</u> para usos que incluem apenas um tipo de uso do solo, este valor é de 100%. Para parcelas que incluem dois ou mais usos do solo, estimar que percentagem da parcela é ocupada por cada tipo de uso do solo. Por exemplo, uma amostra que inclua a linha divisória entre uma habitação particular e uma loja de conveniência poderá ser 40% residencial e 60% comercial/industrial.

NOTA: *as diferenças de uso do solo devem ser claramente identificáveis na parcela, com uma mudança clara no tipo de utilização do terreno, não apenas na sua cobertura ou proprietário.*

PLOT TREE COVER (%) / Percentagem da canópia das árvores que cobre a parcela: Corresponde à área da amostra que estaria à sombra se o sol estivesse diretamente por cima, de 0 a 100%. A cobertura das árvores de árvores localizada fora da amostra também é incluída, por isso parcelas sem árvores podem ter cobertura de árvores. Os valores de percentagens intermédias são contabilizados em valores médios de intervalos de 5% (3, 8, 13, 18, etc.).

SHRUB COVER (%): Percentagem da parcela coberta por arbustos: Assume valores de 0 ou 100%, com valores intermédios contabilizados em valores médios de intervalos de 5% (3, 8, 13, 18, etc.). Importante: não fazer contagem dupla quando há várias camadas de arbustos.

PLANTABLE SPACE / Espaço plantável: Corresponde à estimativa da área total da amostra em que ainda se podem plantar árvores, ou seja, da área de solo que não está sob outras árvores e não tem constrangimentos por cima (ex: linhas elétricas muito baixas, coberturas construídas, etc…), ou restrições devido ao tipo de uso (ex: campo de futebol, caminhos,…). Assume valores de 0 ou 100%, com valores intermédios contabilizados em valores médios de intervalos de 5% (3, 8, 13, 18, etc.). Normalmente corresponde ao somatório da área de solo, mulch, herbáceas, relvado/prado com e sem manutenção.

TABELA 2: Revestimento do Solo – CAMPOS A PREENCHER:

GROUND COVER / Revestimento do solo: nesta tabela devem indicar-se as percentagens dos vários tipos de revestimento do solo (com exceção das árvores e dos arbustos, que são considerados separadamente). As categorias são as seguintes:

- **%BLDG (Building /Edifícios);**
- **% CMNT (Cement / Cimento);**
- **% TAR (Tar / Alcatrão);**
- **% ROCK (Rock / Rocha):** inclui superfícies permeáveis como gravilha, lajes e tijolo em caminhos e pátios (sem argamassa). Inclui areia nos jardins infantis, ou como revestimento do solo existente. Grandes afloramentos rochosos devem ser considerados Cimento (CMNT);
- **SOIL (Bare soil / Solo nu):** inclui areia de ocorrência natural;
- **%DUFF/MULCH (Resíduos de vegetação e mulch):** agulhas de pinheiros, folhas caídas, material orgânico solto;
- **%HERB/IVY (Herbs / Herbáceas):** revestimento herbáceo do solo (exceto relva), incluindo culturas agrícolas;
- **% MAIN GRASS (Maintained grass / Relva com manutenção);**
- **%UNMAIN GRASS (Unmaintained grass / Relva sem manutenção);**
- **%H2O (Água):** inclui piscinas.

NOTA: A percentagem de cada tipo de revestimento deve ser estimada ao mínimo de 5%, a menos que seja residual (aí admite-se 1, 2, 3%, etc…). A soma das proporções de todos os revestimentos deve resultar em 100% da parcela.

TABELA 3: Informação sobre Arbustos – CAMPOS A PREENCHER

Esta parte do inventário refere-se somente à % da parcela considerada no parâmetro SHRUB COVER (%) da tabela 2, que se refere à percentagem de arbustos que a ocupam. Para o inventário, os arbustos devem ser agrupados em massas de espécies iguais e altura aproximada. Por exemplo, se a parcela incluir 5 azáleas de alturas semelhantes em locais diferentes, podem juntar-se num só grupo. Uma árvore com DBH < 2.54 cm é considerada um arbusto. Pode recolher-se informação para um máximo de 12 grupos de arbustos. Se houver mais de 12, recolhem-se as medições para os primeiros 11 grupos e agrupam-se os restantes arbustos no grupo 12.

<u>SPECIES / Espécie de arbusto:</u> tem de se identificar a espécie, ou pelo menos o género. Se não for possível, recolhe-se uma amostra para identificação posterior;

<u>HEIGHT (Altura)</u>**:** mede-se a altura do grupo de arbustos até ao valor mais próximo de 0.1 m. Quando a variação da altura não é muito grande, podem agrupar-se mais arbustos e utilizar um valor médio;

<u>%AREA (Percentagem da área total de arbustos):</u> corresponde à área total de arbustos (ou seja, não à área total da parcela) para cada um dos grupos que está a ser inventariado. O somatório da área de todos os grupos registados deve ser 100%. Quando há mais de duas camadas de arbustos, regista-se a área total da massa de arbustos mais alta, e somente a parte não sombreada da massa de arbustos mais baixa;

<u>%MISSING (Percentagem de arbustos em falta)</u>**:** corresponde ao volume (altura x área de revestimento) da massa de arbustos que não está ocupado com folhas, ou seja, o que está em falta. Assume-se que a folhagem das massas arbustivas começa logo na sua base, junto ao solo. A medição deste parâmetro permite ajustar as medições de altura e área de arbustos para revelar o volume real de folhagem;
Esta medição deve respeitar a disposição natural do arbusto (mais denso, menos denso), mas é necessário inspecionar o interior das massas arbustivas para melhor estimar as porções em falta.

TABELA 4: Informação sobre Árvores

O preenchimento desta parte do inventário faz-se na tabela que está nas costas das fichas individuais.

<u>NOTAS GERAIS:</u>

- A recolha de dados inclui árvores vivas e mortas, e começa na árvore mais distante a Norte, progredindo no sentido dos ponteiros do relógio;
- Quando o centro da parcela é inacessível e foi definido um TMP, este deve ser utilizado para medir distâncias e direções. Porém, isto não altera os limites reais da parcela, pelo que apenas se recolhem dados sobre as árvores dentro da mesma;
- Todas as árvores com DBH ≥ 2,54 cm devem ser inventariadas, se pelo menos metade do seu tronco estiver dentro da amostra.
- Quando existirem muitas árvores numa amostra, dever-se-ão assinalar com giz à medida que se forem inventariando, para evitar dupla contagem ou esquecimento de espécimes.

Para aplicação do i-Tree ECO os arbustos são definidos como material lenhoso com DBH < 2,54 cm; as árvores possuem DBH ≥ 2,54. As plantas lenhosas com menos de 30,5 cm de altura são consideradas coberto herbáceo.

CAMPOS A PREENCHER (por ordem de preenchimento):

a) **Tree ID (Número de identificação da árvore):** cada árvore dentro de uma amostra tem de ter um número identificador único, sequencial, começando em 1;
b) **DR (Direção a partir do centro da amostra):** direção em graus/azimutes (ex: Norte=360°; Este=90°; Sul= 180°). Se o centro da amostra estiver inacessível, medir a direção a partir do TMP, que deverá ser registado na secção de objetos de referência do inventário.
c) **DS (Distância ao centro da amostra):** distância mais curta, em metros, do centro da amostra à casca do tronco da árvore no DBH, medida paralela ao solo;
d) **LAND USE (Uso do solo):** selecionar umas das categorias atrás referidas, e indicar qual o uso do solo no local onde a árvore se encontra;
e) **SPECIES (Espécie)**: se não for possível identificar a espécie, recolher e numerar uma amostra num bloco de notas (ex: Amostra#xxx desconhecida#1). Cada vez que a mesma espécie desconhecida for encontrada na mesma parcela, deve ser identificada com o mesmo número. Se não for possível de todo identifica a espécie (por exemplo devido a hibridização), recolher pelo menos o género. No caso das árvores mortas, quando a espécie ou o género não puderem ser determinados, registar como MACLASS as angiospérmicas e com PICLASS as coníferas;
f) **TREE SITE (Local da árvore):** indicar se é uma árvore de arruamento (S) ou não (N);
g) **STAT (Estado):** escolher umas das seguintes categorias: P – Plantada, I – Espontânea; U – Desconhecido. Deve evitar-se ao máximo selecionar esta última categoria, porque não fornece informação ao modelo;

COMO INTRODUZIR ÁRVORES MORTAS (apenas se contabilizam as que ainda estão de pé):

DBH: mede-se;

Altura da árvore: mede-se;

Altura até ao topo da parte viva: introduzir o código -1;

Altura até à basa da copa: introduzir o código -1;

Largura da copa: introduzir o código -1;

Percentagem da copa em falta: introduzir 100%;

Mortalidade na copa: introduzir 100%;

Exposição da copa à luz: introduzir o código -1;

h) **HEIGHT TOT (Altura total da árvore):** medição da altura total da árvore até ao seu topo (vivo ou morto). Para árvores mortas em pé e árvores vivas muito inclinadas, a altura é considerada a distância ao longo da haste principal, desde o chão até ao topo (não são incluídas árvores mortas no chão);

i) **HEIGHT TO LIVE TOP (Altura ao topo vivo):** esta altura corresponderá à altura total da árvore, exceto nos casos em que a árvore está viva mas o topo da copa está morto.

j) **HEIGHT TO CROWN BASE (Altura até à base da copa viva):** a base da copa corresponde ao ponto do tronco principal que é perpendicular à folhagem mais baixa do ramo mais baixo na copa viva. Ou seja, o ponto é determinado pela folhagem viva e não pelo ponto de intersecção do último ramo com o tronco. Logo, se a folhagem tocar no chão, a altura até à base da copa viva será zero.

k) **CROWN WIDTH (Largura da copa):** medida (em metros) da copa em duas direções: Norte-Sul e Este-Oeste ou de acordo com constrangimentos de segurança e acessibilidade. Se a árvore estiver caída ou inclinada, medir a largura da copa perpendicularmente ao tronco da árvore;

l) **% MISS (Percentagem da copa em falta):** corresponde à percentagem do volume da copa que não está ocupado por ramos e folhas. Este parâmetro deve ser medido por duas pessoas em pé, em ângulos perpendiculares à árvore (Fig. 1). Para obter esta medição, deve imaginar-se o contorno típico da copa como uma silhueta definida pela largura da copa viva, altura total, e altura até à base da copa viva, simétrica à volta do ponto central da largura medida da copa, e preenchida com folhas como se fosse uma árvore saudável em excelentes condições. A partir desta imagem, é mais fácil estimar a percentagem da folhagem que está ausente devido a podas, partes mortas, queda de folhas, copa desigual, ou folhas escassas e pequenas. Não se devem incluir no volume em falta os vazios existentes devido à sombra das folhas. Deve considerar-se a forma natural da espécie particular em análise (Fig 2).
Registar os valores de copa em falta de 0 a 100%, ou como pontos médios de intervalos de 5% (3, 8, 13, 18, etc…).

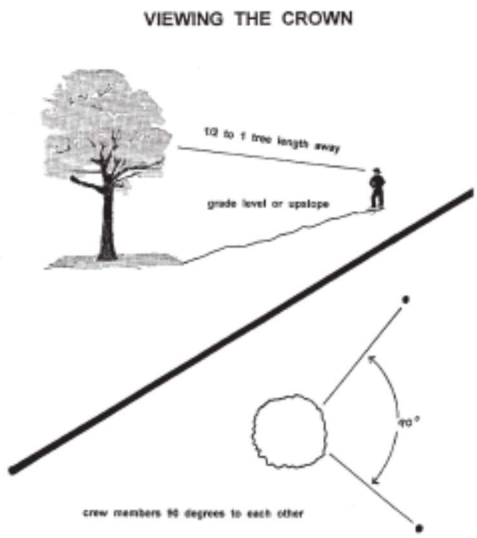

Figura C1: Posicionamento do(s) observadores para medição da copa.

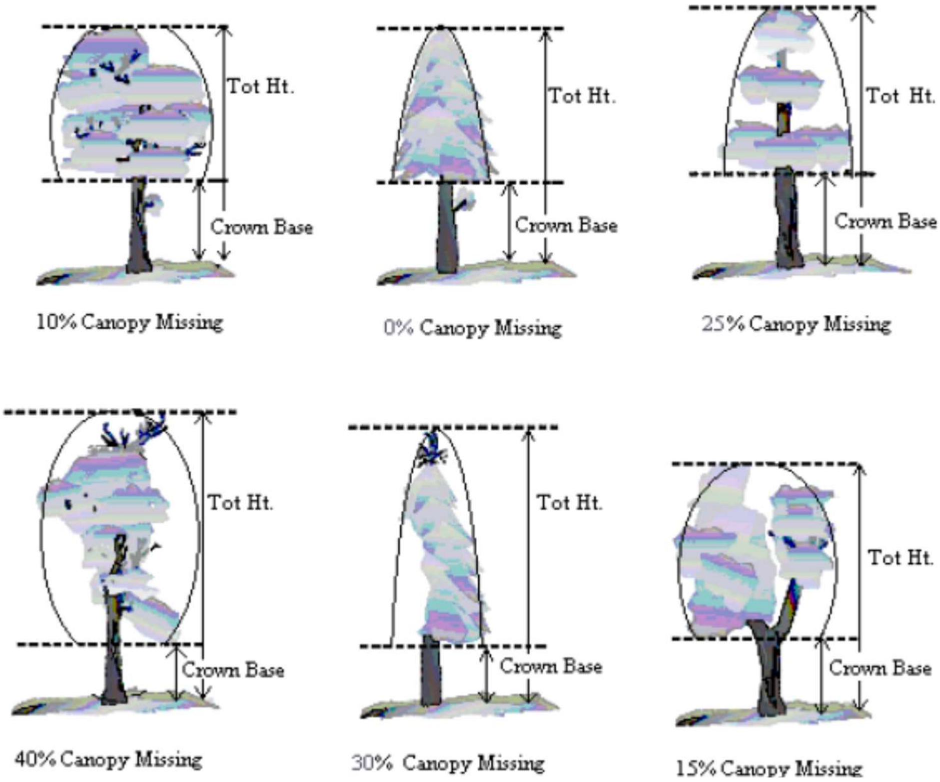

Figura C2: Exemplos de medição da altura até à base da copa viva e da percentagem da copa em falta.

m) **DB (Crown dieback/ Mortalidade na copa):** corresponde à percentagem de mortalidade na copa, mas não inclui a morte natural e normal de ramos (devido à competição na copa ou ao sombreamento na parte mais baixa da copa). Porém, a morte de ramos nos lados e no topo da copa devido ao sombreamento de edifícios ou outra árvore deve ser considerada;
Mede-se como uma percentagem da área viva da copa, incluindo a área onde há mortalidade. Assume-se o perímetro da copa como um contorno a duas dimensões desde a ponta de um ramo à outra, mas excluindo grandes buracos ou intervalos na copa, bem como ramos salientes. A medição deve ser obtida por duas pessoas, utilizando binóculos, em boas condições de luminosidade.
Registar os valores de 0 a 100%, ou como pontos médios de intervalos de 5% (3, 8, 13, 18, etc…);

n) **CLE (Crown light exposure / Exposição da copa à luz):** Número de lados da árvore que recebem luz do sol direta (máximo de 5 lados – o topo da árvore conta com 1 lado). Para obter-se a medição, divide-se a copa da árvore verticalmente em 4 lados iguais, e conta-se o número de lados que receberia luz direta se o sol estivesse mesmo por cima da árvore. Um terço da copa viva tem de receber luz direta para o respetivo lado se qualificar para contabilização. Códigos a utilizar:

-1: árvores mortas;

0: A árvore não recebe luz total porque está à sombra de outras árvores, videiras ou outro tipo de vegetação;
1: A árvore recebe luz total no topo ou apenas num dos lados;
2: A árvore recebe luz total no topo e num lado (ou em dois lados, e não no topo);
3: A árvore recebe luz total no topo e em dois lados (ou em três lados, e não no topo);
4: A árvore recebe luz total no topo e em 3 lados;
5: A árvore recebe luz total no topo e em 4 lados.

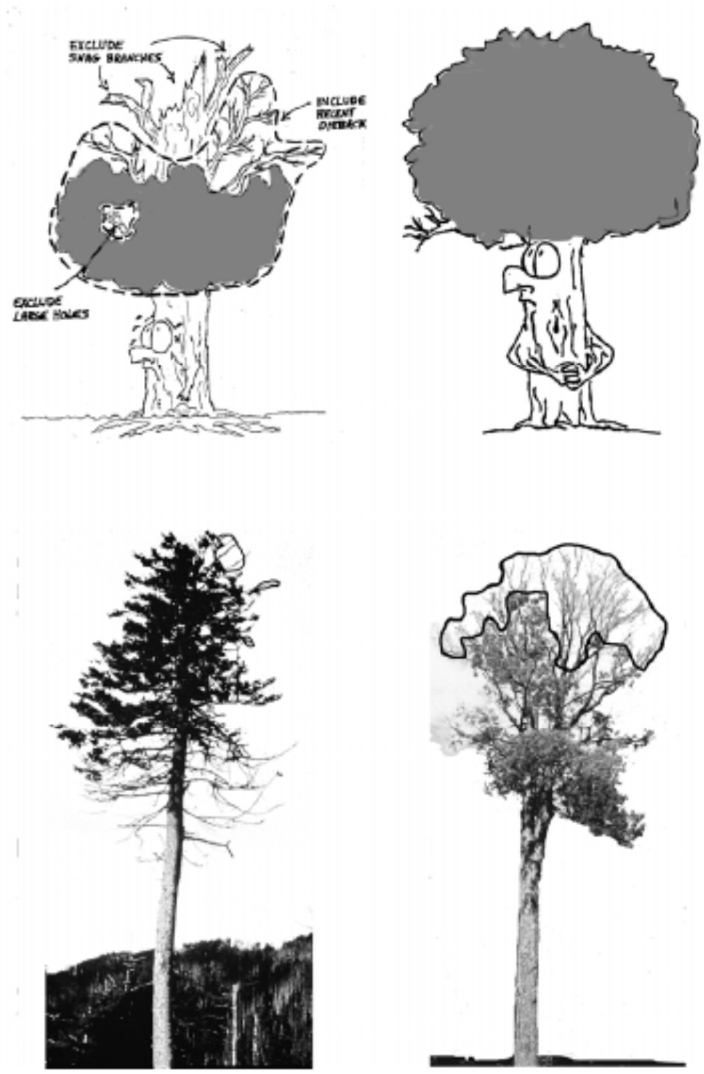

Figura C3: Exemplos de medição da mortalidade na copa.

o) %IMP (Percent impervious surface under the tree / Percentagem de superfície impermeável debaixo da árvore): Este parâmetro serve para aplicação do i-Tree HYDRO, não se mede neste projeto.

p) **% SHRUB (Percent shrub cover under the tree / Percentagem de coberto arbustivo debaixo da árvore):** Este parâmetro também só serve para utilização no i-Tree HYDRO, e não se mede neste projeto.

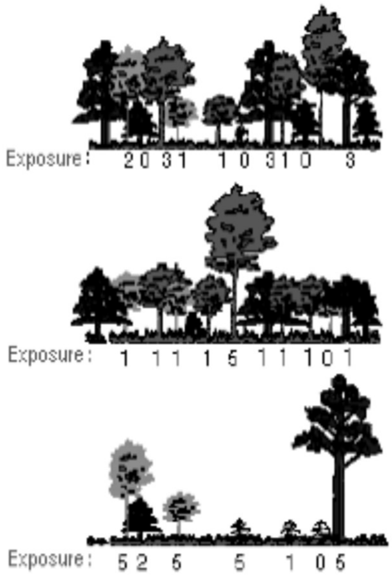

Figura C4: Exemplos de medição da exposição da copa à luz.

q) **DBH (Diameter at breast height / Diâmetro à altura do peito):** mede-se em cm, com exatidão ao nível 0.1 cm.

<u>Situações particulares na medição do DBH:</u>

- **Árvores multicaule:** se o ponto de separação das hastes está acima do solo, a planta é considerada uma só árvore, e dever-se-ão medir os DBH de até 6 hastes; se a árvore tiver mais de 6 hastes, reduzir a altura de medição para 30,48 cm (1 pé) acima do solo, e registar o DHB para as seis hastes com maior diâmetro. Se o ponto de separação das hastes estiver abaixo do solo, cada haste é considerada uma árvore independente;
- **Rebentos / toiça:** todos os rebentos com DHB ≥ 2,54 cm devem ser medidos como árvores independentes. Os rebentos com DHB inferior podem ser ignorados;
- **Árvores com alargamento no colo:** medir estas árvores a 46 cm acima do fim do alargamento se este se estender por mais de 91 cm acima do solo;
- **Árvores com irregularidades no DBH:** nas árvores com inchaços, depressões, ramos, etc..., o diâmetro será medido imediatamente acima da irregularidade, onde a irregularidade já não afeta a forma normal do tronco;

- **Árvores em declive:** mede-se a 1,4 m do chão, ao longo do tronco, no lado de cima da árvore (ou seja, na parte mais elevada);
- **Árvores inclinadas:** mede-se o DBH a 1,4 m no lado do tronco que está virado para baixo;
- **Árvore viva derrubada pelo vento:** mede-se 1,4 m a partir do topo do colo da árvore;

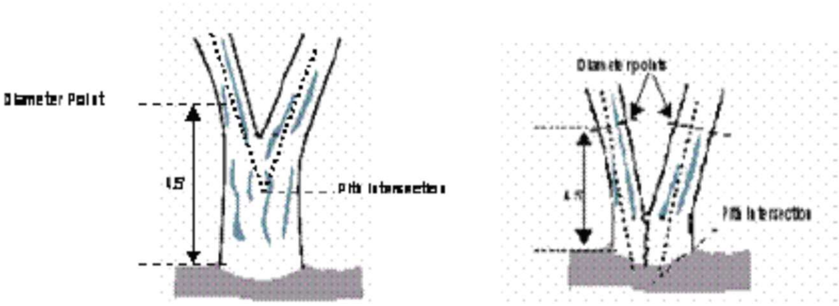

Figura C5: Medição do DBH em árvores bifurcadas (multicaule).

r) **HT DBH (DBH height measurement /altura de medição do DBH):** se o DBH não foi medido à altura padrão (1,4m), regista-se neste campo qual foi a altura considerada para a medição.

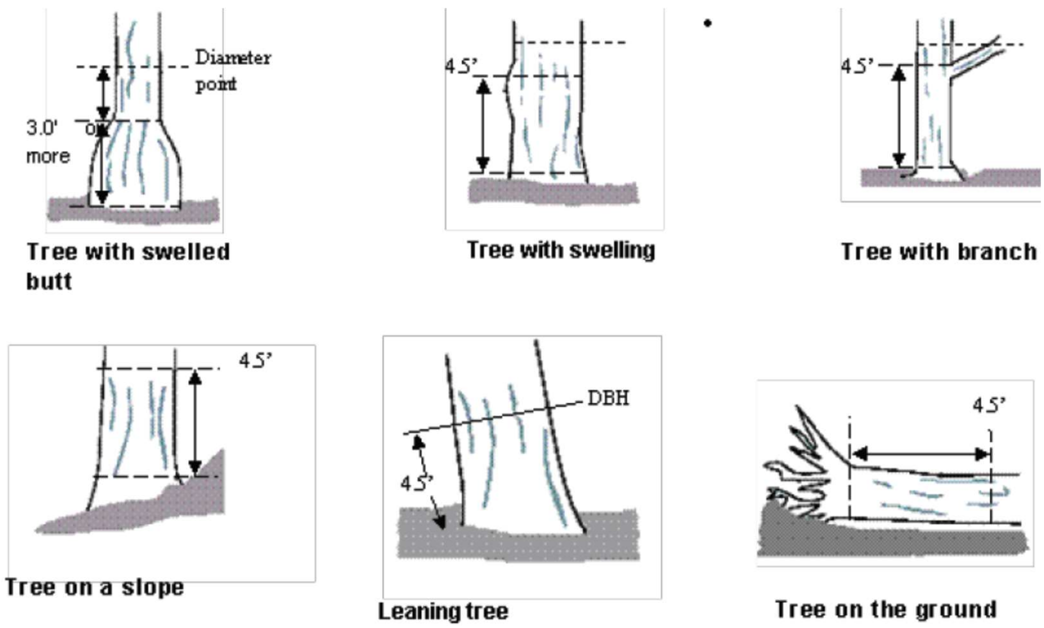

Figura C6: Medição de DBHs em árvores com irregularidades.

s) **TREES NEAR BUILDINGS (Árvores próximas de edifícios):** a medição de variáveis referentes a este parâmetro destinam-se ao cálculo dos efeitos das árvores na energia.

Variáveis a medir:

- **Direction to building (Direção em relação ao edifício):** Para árvores com mais de 6,10 m localizadas a menos de 18,28 m de edifícios residenciais com 3 pisos ou menos, registar a direção (azimute em graus) da árvore à parte mais próxima do edifício. Para habitações multifamiliares, tratar todas as unidades de um edifício como uma só. O edifício não necessita de estar localizado na parcela. Recolhe-se informação referente a até 3 edifícios, e preenchem-se os campos D1/D2/D3;

- **Shortest distance to building (Distância mais curta até ao edifício):** para os edifícios considerados na variável anterior, medir a distância mais curta da árvore até à parte mais próxima do edifício (em metros). Árvores mortas que cumpram as condições anteriores devem ser consideradas. Registar a informação nos campos S1/S2/S3.

Appendix D | Questionnaire applied between February and May of 2017 to a sample of 819 people with at least 18 years, in the streets of Porto (Portugal) – original version(in Portuguese)

Escola:	Rua:	Equipa:	Data : / /

Por favor dê a sua opinião sobre a importância dos seguintes benefícios e prejuízos prestados pelas árvores de arruamento.

Indique o grau de importância dos seguintes benefícios das árvores:	**Nada importante**	**Pouco importante**	**Importante**	**Muito importante**	**Sem opinião**
Estimular novas ideias, pensamentos, expressões artísticas, …					
Embelezar a rua, a cidade, as vistas, …					
Promover lugares de encontro com amigos, vizinhos, …					
Fomentar o recreio e turismo, ao proporcionar locais agradáveis para passear, correr, andar de bicicleta, …					
Reforçar o sentido de lugar com o sítio onde se vive, com a cidade…					
Representar valores espirituais, religiosos, pessoais ou outro significado excecional.					
Despertar conhecimento sobre ciclos da natureza, espécies vegetais e animais, …					
Ter importância para a história e cultura local.					
Melhorar a qualidade do ar.					
Regular o clima através do armazenamento de carbono no tronco, raiz e ramos.					
Melhorar o microclima através da sombra, temperatura local, vento, …					
Regular o escoamento da água da chuva e reduzir o risco de cheias.					
Reduzir o ruído de carros ou de atividades específicas.					
Constituir um habitat ou refúgio para aves e outras espécies.					
Aumentar o valor da propriedade imobiliária, pois edifícios em zonas com árvores são tendencialmente mais caros.					
Dinamizar o comércio e turismo, pois lojas e serviços em zonas com árvores têm mais clientes e maior atividade comercial.					
Aumentar a eficiência energética, pois imóveis em zonas com árvores podem gastar menos energia .					

Outros benefícios que considere importantes: ____

Indique o seu grau de concordância sobre os seguintes prejuízos causados pelas árvores de arruamento:	**Discordo muito**	**Discordo**	**Concordo**	**Concordo muito**	**Sem opinião**
Danos a bens e estruturas como carros, passeios, muros, …					
Alergias					
Sombra indesejada e impedimento da entrada de luz solar em casa					
Menor visibilidade para a rua					
Risco para pessoas devido a queda de árvores ou ramos					
Acumulação de resíduos devido a queda de folhas, frutos,…					
Insegurança pois favorecem pouca visibilidade e atividade criminosa					
Mau aspeto ou ar desleixado devido a má manutenção ou mau estado das árvores					
Custos de manutenção					

Outros prejuízos que considere importantes: ____

Indique o seu grau de concordância com as seguintes afirmações:	**Discordo muito**	**Discordo**	**Concordo**	**Concordo muito**	**Sem opinião**
As árvores trazem mais benefícios do que prejuízos					
Árvores maiores trazem mais benefícios do que árvores pequenas					
A cidade do Porto necessita de mais árvores					

Idade: __________ Sexo: ☐ Feminino ☐ Masculino

Escolaridade: ☐ Até 9º ano ☐ Até 12º ano ☐ Frequência universitária ou licenciatura ☐ Mestrado ou superior

Obrigado pela sua colaboração.

Appendix E | List of inventoried tree species in Porto, including estimates for total number of trees, carbon storage, carbon gross and net sequestration, leaf area and leaf biomass by species.

Notes:

1. Field data collected in 2014 from 255 samples, and processed using i-Tree Eco modelling tool. According to i-Tree Eco field guidelines, vegetation was recorded as tree when the diameter of trunk or bole at breast height (DBH) was greater than or equal to 2.54 cm.
2. SE: Standard Error.

	Number of Trees		Carbon (t)		Gross Seq (t/yr)		Net Seq (t/yr)		Leaf Area (km^2)		Leaf Biomass (t)	
Species	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**
Quercus robur	15 035	8 804	2 325,8	1 716,2	95,7	53,8	78,9	42,8	0,8	0,4	50,8	26,7
Populus nigra	11 687	5 545	1 242,0	556,6	45,9	19,1	43,9	18,4	0,6	0,3	43,7	18,0
Quercus suber	11 085	5 852	2 652,8	1 186,5	108,2	53,5	81,6	39,8	0,6	0,3	112,4	53,3
Cornus sp.	10 858	10 842	27,6	27,6	8,3	8,3	8,1	8,1	0,0	0,0	0,7	0,7
Cupressus sempervirens 'Stricta'	9 765	7 972	85,8	61,5	13,7	11,1	13,5	11,1	0,1	0,1	19,4	16,8
Acacia melanoxylon	9 126	6 288	900,8	736,2	50,9	39,7	46,4	36,7	0,4	0,2	65,4	39,4
Cupressocyparis x leylandii	9 095	9 089	98,3	98,3	13,8	13,8	11,1	11,1	0,1	0,1	13,7	13,7
Populus nigra 'Italica'	8 822	8 809	1 260,7	1 258,8	65,3	65,2	58,8	58,7	0,1	0,1	9,3	9,3
Platanus x acerifolia	8 721	4 928	2 299,4	1 093,3	76,1	33,6	69,2	30,1	2,3	1,0	101,4	45,1
Camellia japonica	7 372	2 636	737,0	413,1	41,8	18,8	37,8	16,5	0,5	0,2	34,6	17,4
Acer negundo	6 843	2 662	1 442,8	547,0	61,5	21,0	50,7	18,8	1,5	0,6	134,5	55,4
Pyracantha coccinea	6 359	6 355	34,7	34,7	10,3	10,3	9,9	9,9	0,0	0,0	1,3	1,3
Pittosporum tobira	6 194	5 305	88,4	59,8	9,3	6,6	6,3	4,1	0,1	0,1	8,5	5,2
Ligustrum lucidum	5 625	2 721	606,3	336,8	35,2	17,4	32,6	16,0	0,3	0,2	27,0	13,7
Pinus pinaster	5 408	2 700	1 461,4	936,9	35,8	22,9	29,1	19,5	0,9	0,6	90,4	55,6
Arbutus unedo	4 792	4 133	39,8	25,3	4,3	3,2	3,9	3,1	0,0	0,0	2,8	1,9
Magnolia x soulangiana	4 769	2 407	313,3	159,6	19,1	9,1	16,0	7,5	0,4	0,2	26,1	14,7
Nerium oleander	4 653	2 931	704,0	613,2	46,5	37,1	42,3	34,6	0,1	0,0	12,7	7,0
Vitis vinifera	4 234	3 000	10,3	7,6	2,9	2,1	2,9	2,1	0,1	0,1	7,0	5,0
Prunus domestica	4 046	1 545	952,7	540,4	41,6	19,2	39,6	18,3	0,3	0,2	22,4	16,1
Thuja plicata	3 925	2 803	53,1	42,1	1,9	1,2	1,7	1,0	0,2	0,2	45,6	33,5

	Number of Trees		Carbon (t)		Gross Seq (t/yr)		Net Seq (t/yr)		Leaf Area (km^2)		Leaf Biomass (t)	
Species	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**
Chamaecyparis lawsoniana	3 851	1 814	88,1	52,1	7,6	4,1	6,9	3,6	0,1	0,0	20,8	8,6
Laurus nobilis	3 463	1 130	226,8	112,2	16,3	7,1	13,9	6,6	0,2	0,1	15,4	7,2
Acer pseudoplatanus 'Spaethii'	3 103	1 475	368,9	160,9	21,8	9,0	20,7	8,6	0,4	0,2	22,8	9,5
Crataegus laevigata	3 054	3 049	41,9	41,8	5,8	5,8	5,7	5,7	0,1	0,1	6,2	6,2
Actinidia deliciosa	3 025	1 821	273,4	251,3	13,0	9,4	12,8	9,3	0,1	0,1	7,8	4,4
Eriobotrya japonica	2 931	1 748	97,8	69,5	14,1	9,6	13,4	9,0	0,1	0,0	5,1	3,4
Prunus persica	2 928	1 320	116,9	80,7	11,6	5,7	11,2	5,4	0,1	0,0	6,1	2,6
Picea abies	2 833	1 346	248,7	139,3	11,6	5,9	9,8	4,9	0,6	0,3	94,1	54,3
Populus x canadensis	2 678	1 591	1 010,3	624,2	35,6	21,9	29,9	19,0	0,5	0,3	43,9	26,4
Quercus rubra	2 616	2 047	360,4	255,0	18,8	13,4	15,8	11,2	0,3	0,3	25,7	21,2
Citrus limon	2 610	1 337	60,3	38,9	9,4	5,4	8,7	5,1	0,0	0,0	4,2	2,3
Pinus pinea	2 540	1 592	401,9	319,4	12,2	8,3	9,2	5,8	0,3	0,2	30,0	19,3
Liquidambar styraciflua	2 513	1 307	511,4	352,7	17,3	9,8	15,3	8,6	0,7	0,4	30,3	18,2
Metrosideros excelsa	2 350	2 346	16,0	16,0	4,5	4,4	4,3	4,3	0,0	0,0	0,9	0,9
Acer pseudoplatanus	2 160	1 064	184,3	105,7	11,4	5,6	10,7	5,2	0,3	0,1	17,5	9,8
Prunus laurocerasus	2 032	1 723	35,4	32,1	4,5	3,5	4,3	3,4	0,0	0,0	2,2	1,6
Sambucus nigra	1 993	1 119	211,3	149,8	13,5	8,9	12,9	8,5	0,1	0,1	10,1	6,7
Tilia americana	1 938	1 503	69,9	61,7	5,6	4,5	5,4	4,4	0,2	0,1	5,2	4,1
Fatsia japonica	1 891	1 096	423,6	419,0	19,6	18,3	17,9	16,7	0,0	0,0	1,1	0,7
Tilia platyphyllos	1 702	1 002	452,0	295,5	13,5	7,6	12,0	6,7	0,5	0,3	29,3	16,0
Pyrus communis	1 664	917	85,5	60,1	5,5	3,5	5,2	3,3	0,0	0,0	1,6	1,0
Prunus cerasifera	1 543	886	183,9	134,8	14,1	7,8	13,3	7,3	0,0	0,0	2,7	1,6
Crataegus monogyna	1 515	1 221	87,9	70,6	6,7	5,3	6,3	5,0	0,1	0,1	11,4	8,1
Buxus sempervirens	1 451	1 070	6,0	4,6	1,4	1,0	1,3	1,0	0,0	0,0	0,4	0,3
Sequoia sempervirens	1 451	1 448	300,0	299,4	12,4	12,4	12,2	12,2	0,2	0,2	30,7	30,6
Celtis australis	1 365	942	477,6	352,6	18,1	12,6	16,7	11,7	0,7	0,5	39,2	27,9
Cedrus libani	1 357	1 355	1 517,4	1 515,2	21,0	21,0	10,3	10,3	0,8	0,8	121,0	120,9
Softwood unidentified species	1 336	717	5,9	3,3	0,5	0,4	0,0	0,5	0,0	0,0	0,5	0,5
Hardwood unidentified species	1 292	577	455,8	361,5	10,3	10,3	-17,6	25,9	0,0	0,0	0,0	0,0
Ilex aquifolium	1 292	855	60,0	51,6	7,2	5,8	6,9	5,6	0,1	0,0	6,8	4,9

	Number of Trees		Carbon (t)		Gross Seq (t/yr)		Net Seq (t/yr)		Leaf Area (km^2)		Leaf Biomass (t)	
Species	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**
Pittosporum undulatum	1 269	792	344,2	287,9	13,7	9,7	12,3	8,7	0,1	0,1	7,9	5,1
Ficus carica	1 242	1 039	45,7	34,5	7,2	5,8	7,0	5,6	0,1	0,1	7,0	5,7
Quercus palustris	1 238	777	329,0	245,2	12,1	8,3	11,2	7,6	0,2	0,2	19,6	14,0
Diospyros kaki	1 234	834	52,9	34,2	6,7	3,9	6,4	3,8	0,1	0,0	3,9	2,4
Malus domestica	1 220	827	20,5	12,5	3,7	2,1	3,6	2,1	0,0	0,0	1,7	1,0
Pinus halepensis	1 175	1 173	183,5	183,2	5,0	5,0	3,1	3,1	0,3	0,3	24,5	24,5
Acer palmatum	1 135	936	361,0	302,1	16,4	14,1	15,0	13,0	0,3	0,3	18,5	17,5
Phoenix canariensis	1 122	567	48,7	27,4	0,3	0,1	-0,1	0,3	0,5	0,3	81,1	44,8
Castanea sativa	1 105	837	762,2	730,2	25,3	23,7	22,0	20,9	0,2	0,2	15,4	13,1
Olea europaea europea	1 069	861	291,2	288,8	14,5	14,1	13,4	13,0	0,0	0,0	1,4	1,0
Abies nordmanniana	1 065	824	44,7	33,0	3,7	2,8	3,6	2,7	0,1	0,1	13,7	9,8
Buddleja davidii	1 018	1 016	17,3	17,3	2,0	2,0	2,0	2,0	0,0	0,0	1,5	1,5
Lagerstroemia indica	1 018	741	25,7	25,5	2,5	2,4	2,4	2,3	0,0	0,0	0,5	0,4
Osmanthus heterophyllus	1 018	1 016	125,9	125,7	7,1	7,1	6,8	6,8	0,1	0,1	4,9	4,9
Cordyline australis	1 007	802	9,5	7,3	0,2	0,2	0,2	0,1	0,1	0,0	8,4	7,0
Robinia pseudoacacia	985	984	1,6	1,6	0,4	0,4	0,4	0,4	0,0	0,0	0,5	0,5
Euonymus japonicus	923	554	8,7	5,1	2,5	1,5	2,4	1,5	0,0	0,0	1,2	0,9
Salix x sepulcralis 'Simonkai'	920	719	74,1	54,0	6,7	5,3	6,2	5,0	0,1	0,1	6,0	5,3
Callistemon phoeniceus	908	908	122,6	122,6	10,1	10,1	9,6	9,6	0,0	0,0	1,0	1,0
Melaleuca hypericifolia	908	908	60,7	60,7	6,7	6,7	6,0	6,0	0,0	0,0	2,2	2,2
Myoporum acuminatum	908	908	115,7	115,7	9,6	9,6	9,2	9,2	0,1	0,1	7,0	7,0
Zelkova serrata	908	908	4,0	4,0	1,4	1,4	1,3	1,3	0,0	0,0	0,9	0,9
Viburnum tinus	908	628	19,1	17,4	3,2	2,6	3,1	2,5	0,0	0,0	1,1	0,9
Brugmansia sanguinea	827	826	240,8	240,7	12,7	12,7	11,7	11,7	0,0	0,0	3,0	3,0
Corylus avellana	827	826	5,0	5,0	1,5	1,5	1,4	1,4	0,0	0,0	1,6	1,6
Chamaecyparis obtusa	793	566	203,4	161,7	5,2	3,8	4,5	3,2	0,2	0,2	61,3	47,7
Pseudotsuga menziesii	778	565	7,3	5,2	0,4	0,3	0,4	0,3	0,1	0,0	8,2	5,9
Taxus baccata	771	770	1,4	1,4	0,5	0,5	0,5	0,5	0,0	0,0	0,8	0,8
Citrus sinensis	765	765	6,5	6,5	1,9	1,9	1,9	1,9	0,0	0,0	1,0	1,0
Prunus cerasus	765	765	38,4	38,4	4,0	4,0	2,9	2,9	0,0	0,0	0,6	0,6

	Number of Trees		**Carbon (t)**		**Gross Seq (t/yr)**		**Net Seq (t/yr)**		**Leaf Area (km^2)**		**Leaf Biomass (t)**	
Species	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**
Cupressus sempervirens	763	442	36,8	25,0	2,4	1,5	2,3	1,4	0,1	0,1	18,8	16,2
Plectranthus barbatus	756	574	1,0	0,9	0,0	0,0	0,0	0,0	0,0	0,0	2,1	1,7
Prunus lusitanica	752	751	7,4	7,4	2,3	2,3	2,3	2,3	0,0	0,0	0,7	0,7
Cupressus lusitanica	726	724	50,0	49,9	2,2	2,2	1,8	1,8	0,1	0,1	14,8	14,7
Citrus aurantium	681	680	5,1	5,1	0,9	0,9	0,9	0,9	0,0	0,0	1,8	1,8
Eucalyptus globulus	681	680	1 025,2	1 022,9	21,4	21,4	15,3	15,3	0,0	0,0	5,4	5,3
Aesculus x carnea	679	678	183,3	183,0	7,7	7,7	7,3	7,3	0,3	0,3	20,6	20,6
Pittosporum eugenioides	679	678	151,5	151,3	6,9	6,9	6,5	6,5	0,0	0,0	3,7	3,7
Populus simonii	679	678	82,5	82,4	6,7	6,7	6,3	6,3	0,0	0,0	2,4	2,4
Citrus reticulata	657	656	68,1	68,0	4,0	3,9	3,9	3,9	0,0	0,0	3,0	3,0
Yucca gloriosa	657	656	0,5	0,5	0,0	0,0	0,0	0,0	0,0	0,0	0,8	0,8
Cedrus atlantica	588	587	25,3	25,2	1,4	1,4	1,3	1,3	0,1	0,1	10,3	10,2
Weigela sp.	588	587	18,4	18,4	3,2	3,2	3,1	3,1	0,0	0,0	0,5	0,5
Magnolia grandiflora	581	416	159,4	157,1	6,5	5,9	5,9	5,3	0,1	0,1	10,6	10,4
Populus alba	581	416	168,3	164,1	5,4	5,1	4,3	4,2	0,0	0,0	3,8	3,8
Schefflera arboricola	566	408	11,2	9,4	1,9	1,6	1,9	1,6	0,0	0,0	3,6	3,6
Aucuba japonica	528	527	1,9	1,9	0,4	0,4	0,4	0,4	0,0	0,0	0,5	0,5
Alnus glutinosa	484	483	3,6	3,6	1,2	1,2	1,2	1,2	0,0	0,0	0,3	0,3
Betula pubescens	484	483	294,2	293,6	12,0	12,0	10,9	10,8	0,3	0,3	15,7	15,7
Catalpa bignonioides	484	483	107,2	106,9	4,9	4,9	4,1	4,1	0,1	0,1	3,0	3,0
Cercis siliquastrum	484	483	53,2	53,1	3,2	3,2	3,1	3,1	0,1	0,1	4,3	4,3
Chamaecyparis pisifera	484	337	31,3	27,3	1,8	1,4	1,5	1,2	0,0	0,0	8,0	7,1
Cyphomandra betacea	484	337	3,4	2,8	0,9	0,8	0,9	0,7	0,0	0,0	0,4	0,3
Juglans nigra	484	483	406,9	406,0	10,7	10,6	9,1	9,1	0,4	0,4	35,1	35,0
Prunus serotina	484	483	1,9	1,9	0,5	0,5	0,5	0,5	0,0	0,0	1,1	1,1
Acer platanoides	469	331	8,9	6,3	2,0	1,4	1,9	1,4	0,0	0,0	1,1	0,8
Bougainvillea glabra	469	331	2,2	1,6	0,7	0,5	0,7	0,5	0,0	0,0	0,2	0,1
Ligustrum sinense	469	331	7,3	5,6	1,7	1,2	1,7	1,2	0,0	0,0	1,8	1,6
Aesculus hippocastanum	339	339	22,0	21,9	1,7	1,7	1,6	1,6	0,1	0,1	4,8	4,8
Casuarina equisetifolia	339	339	129,9	129,7	3,3	3,3	3,0	3,0	0,1	0,1	10,9	10,9

	Number of Trees		Carbon (t)		Gross Seq (t/yr)		Net Seq (t/yr)		Leaf Area (km^2)		Leaf Biomass (t)	
Species	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**
Euonymus 146aponicas Aureo-marginatus	339	339	7,1	7,1	1,5	1,5	1,4	1,4	0,0	0,0	0,4	0,4
Photinia serratifolia	339	339	59,7	59,6	3,0	3,0	2,8	2,8	0,0	0,0	2,4	2,4
Tilia x flaccida	339	339	23,5	23,5	1,5	1,5	1,4	1,4	0,1	0,1	5,1	5,1
Tilia tomentosa	339	339	185,7	185,5	4,7	4,7	4,3	4,3	0,3	0,3	16,0	16,0
Elaeagnus umbellata	328	328	1,1	1,1	0,2	0,2	0,2	0,2	0,0	0,0	0,4	0,4
Passiflora x violacea	328	328	0,4	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,4	0,4
Thuja occidentalis	328	328	0,4	0,4	0,1	0,1	0,1	0,1	0,0	0,0	0,4	0,4
Abies x masjoannis	294	293	29,0	28,9	1,2	1,2	1,2	1,2	0,1	0,1	9,5	9,4
Coprosma sp.	294	293	5,4	5,4	1,2	1,2	1,1	1,1	0,0	0,0	0,5	0,5
Erythrina crista-galli	294	293	58,4	58,3	3,6	3,6	3,4	3,4	0,0	0,0	0,9	0,9
Gleditsia triacanthos	294	293	10,5	10,5	0,7	0,7	0,7	0,7	0,0	0,0	1,1	1,1
Salix cinerea	294	293	83,1	82,9	3,4	3,4	3,2	3,2	0,0	0,0	2,8	2,8
Prunus armeniaca	264	264	1,3	1,3	0,3	0,3	0,3	0,3	0,0	0,0	0,3	0,3
Yucca guatemalensis	264	264	0,4	0,4	0,0	0,0	0,0	0,0	0,0	0,0	1,0	1,0
Abelia triflora	242	241	31,4	31,3	1,8	1,8	1,7	1,7	0,0	0,0	1,2	1,1
Actinidia sp.	242	241	3,4	3,4	0,8	0,8	0,8	0,8	0,0	0,0	0,9	0,9
Ailanthus altissima	242	241	0,2	0,2	0,1	0,1	0,1	0,1	0,0	0,0	0,2	0,2
Betula pendula	242	241	8,9	8,9	0,9	0,9	0,9	0,9	0,0	0,0	2,3	2,3
Betula populifolia	242	241	0,5	0,5	0,3	0,3	0,3	0,3	0,0	0,0	0,0	0,0
Fraxinus angustifolia	242	241	13,1	13,1	1,0	1,0	0,9	0,9	0,1	0,1	3,7	3,7
Fraxinus excelsior	242	241	3,7	3,7	0,5	0,5	0,5	0,5	0,0	0,0	1,6	1,6
Juglans regia	242	241	1,0	1,0	0,4	0,4	0,3	0,3	0,0	0,0	0,1	0,1
Magnolia sp.	242	241	0,2	0,2	0,1	0,1	0,1	0,1	0,0	0,0	0,0	0,0
Philadelphus coronarius	242	241	2,3	2,3	0,4	0,4	0,4	0,4	0,0	0,0	0,2	0,2
Salix sp.	242	241	28,2	28,1	2,5	2,5	2,4	2,4	0,0	0,0	2,6	2,6
Salix atrocinerea	242	241	11,8	11,7	0,7	0,7	0,7	0,7	0,0	0,0	1,4	1,4
Syzygium sp.	242	241	0,5	0,5	0,2	0,2	0,2	0,2	0,0	0,0	0,2	0,2
Tecoma capensis	242	241	0,2	0,2	0,2	0,2	0,1	0,1	0,0	0,0	0,1	0,1
Callistemon glaucus	227	227	11,0	10,9	0,9	0,9	0,9	0,9	0,0	0,0	1,8	1,7

	Number of Trees		Carbon (t)		Gross Seq (t/yr)		Net Seq (t/yr)		Leaf Area (km^2)		Leaf Biomass (t)	
Species	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**
Cestrum nocturnum	227	227	6,3	6,3	1,2	1,2	1,1	1,1	0,0	0,0	0,3	0,3
Ginkgo biloba	227	227	56,5	56,4	2,5	2,5	2,3	2,3	0,1	0,1	4,3	4,3
Magnolia denudata	227	227	13,1	13,0	1,5	1,5	1,5	1,5	0,0	0,0	1,2	1,2
Melia azedarach	227	227	108,2	107,9	3,6	3,6	3,2	3,2	0,1	0,1	6,9	6,9
Prunus sp.	227	227	5,4	5,4	0,0	0,0	-1,5	1,5	0,0	0,0	0,0	0,0
Rosa sp.	227	227	2,2	2,2	0,7	0,6	0,6	0,6	0,0	0,0	0,2	0,2
Wisteria sp.	227	227	12,5	12,4	1,5	1,5	1,5	1,4	0,0	0,0	0,5	0,5

Appendix F | List of biogenic volatile organic compounds (BVOC) emitted by species in Porto, sorted by descending order according to a BVOC emission factor (in kilograms of total BVOC emitted per ton of leaf biomass).

Notes:

Total BVOC emission (in Kg per year) estimated using i-Tree Eco v5 modelling tool, which uses base isoprene/monoterpene emission values for genus from literature. Species-specific information is not available for most species. This table only presents the species found in Porto for which information exists in i-Tree Eco v5 BVOC database.

BVOC emission factor calculated dividing total BVOC emission per total leaf biomass per species.

Scientific name	BVOC (Kg/yr)	Leaf biomass (t)	BVOC emission factor (Kg/t)
Quercus palustris	1317.64	19.56	67.36
Quercus rubra	1730.58	25.69	67.36
Quercus robur	3424.1	50.83	67.36
Eucalyptus globulus	222.23	5.35	41.54
Liquidambar styraciflua	1077.23	30.28	35.58
Casuarina equisetifolia	356.83	10.88	32.80
Populus simonii	67.87	2.39	28.40
Populus alba	107.91	3.8	28.40
Populus nigra 'Italica'	264.66	9.32	28.40
Populus x canadensis	1247.46	43.93	28.40
Populus nigra	1240.36	43.68	28.40
Salix atrocinerea	33.91	1.42	23.88
Salix sp.	61.13	2.56	23.88
Salix x sepulcralis 'Simonkai'	143.51	6.01	23.88
Salix cinerea	65.9	2.76	23.88
Picea abies	1461.08	94.11	15.53
Plectranthus barbatus	31.03	2.06	15.06
Metrosideros excelsa	13.45	0.93	14.46
Platanus x acerifolia	1451.72	101.41	14.32
Syzygium sp.	2.2	0.21	10.48
Melaleuca hypericifolia	22.71	2.21	10.28
Ficus carica	67.57	6.98	9.68
Acacia melanoxylon	593.54	65.44	9.07
Pinus halepensis	222.21	24.5	9.07
Pinus pinaster	820.25	90.44	9.07
Sequoia sempervirens	278.16	30.67	9.07
Pinus pinea	272.35	30.03	9.07

Scientific name	**BVOC (Kg/yr)**	**Leaf biomass (t)**	**BVOC emission factor (Kg/t)**
Abies x masjoannis	85.79	9.46	9.07
Abies nordmanniana	123.78	13.65	9.07
Magnolia sp.	0.08	0.01	8.00
Magnolia grandiflora	81.47	10.61	7.68
Magnolia x soulangiana	200.18	26.07	7.68
Magnolia denudata	8.83	1.15	7.68
Yucca guatemalensis	6.96	0.96	7.25
Cordyline australis	60.89	8.41	7.24
Yucca gloriosa	6.08	0.84	7.24
Juglans nigra	247.55	35.1	7.05
Ginkgo biloba	30.03	4.28	7.02
Juglans regia	0.77	0.11	7.00
Callistemon glaucus	11.46	1.75	6.55
Callistemon phoeniceus	6.61	1.01	6.54
Phoenix canariensis	523.62	81.12	6.45
Robinia pseudoacacia	3.28	0.54	6.07
Aucuba japonica	2.25	0.46	4.89
Cornus sp.	3.32	0.68	4.88
Cedrus atlantica	49.8	10.25	4.86
Cedrus libanii	588.02	121.03	4.86
Pseudotsuga menziesii	39.78	8.19	4.86
Taxus baccata	3.51	0.77	4.56
Erythrina crista-galli	4.13	0.92	4.49
Citrus sinensis	3.88	0.98	3.96
Citrus reticulata	11.9	3.01	3.95
Citrus limon	16.4	4.15	3.95
Citrus aurantium	7.11	1.8	3.95
Acer palmatum	70.05	18.53	3.78
Acer negundo	508.55	134.53	3.78
Acer pseudoplatanus 'Spaethi'	86.15	22.79	3.78
Acer pseudoplatanus	66.22	17.52	3.78
Acer platanoides	4.04	1.07	3.78
Cupressus semprevirens	46.66	18.84	2.48
Cupressus lusitanica	35.52	14.76	2.41
Cupressus sempervirens 'Stricta'	45.34	19.39	2.34
Corylus avellana	3.4	1.59	2.14
Thuja occidentalis	0.8	0.43	1.86

Scientific name	BVOC (Kg/yr)	Leaf biomass (t)	BVOC emission factor (Kg/t)
Cupressocyparis leylandii	25.42	13.73	1.85
Thuja plicata	84.33	45.55	1.85
Olea europaea europaea	1.28	1.35	0.95
Crataegus monogyna	9.88	11.35	0.87
Crataegus laevigata	5.36	6.17	0.87
Catalpa bignonioides	2.62	3.02	0.87
Euonymus japonius	0.8	1.23	0.65
Euonymus japonicus 'Aureo-marginatus'	0.26	0.4	0.65
Schefflera arboricola	2.33	3.59	0.65
Fatsia japonica	0.7	1.08	0.65
Chamaecyparis obtusa	39.69	61.26	0.65
Chamaecyparis lawsoniana	13.45	20.76	0.65
Nerium oleander	8.22	12.69	0.65
Ilex aquifoilum	4.43	6.84	0.65
Chamaecyparis pisifera	5.16	7.97	0.65
Buxus sempervirens	0.28	0.44	0.64
Elaeagnus umbellata	0.22	0.43	0.51
Betula pendula	1.17	2.3	0.51
Celtis australis	19.91	39.21	0.51
Betula pubescens	7.98	15.72	0.51
Zelkova serrata	0.44	0.87	0.51
Wisteria sp.	0.26	0.52	0.50
Betula populifolia	0.02	0.04	0.50
Cestrum nocturnum	0.12	0.29	0.41
Actinidia sp.	0.35	0.86	0.41
Actinidia deliciosa	3.12	7.77	0.40
Brugmansia sanguinea	1.19	2.99	0.40
Cyphomandra betacea	0.16	0.41	0.39
Bougainvillea glabra	0.06	0.17	0.35
Arbutus unedo	0.99	2.84	0.35
Laurus nobilis	5.34	15.38	0.35
Tecoma capensis	0.03	0.09	0.33
Myoporum acuminatum	2.29	6.97	0.33
Osmanthus heterophyllus	1.47	4.9	0.30
Prunus lusitanica	0.2	0.7	0.29
Prunus cerasifera	0.76	2.7	0.28
Prunus laurocerasus	0.62	2.21	0.28

Scientific name	**BVOC (Kg/yr)**	**Leaf biomass (t)**	**BVOC emission factor (Kg/t)**
Prunus persica	1.7	6.07	0.28
Prunus domestica	6.27	22.39	0.28
Prunus cerasus	0.17	0.61	0.28
Melia azedarach	1.89	6.88	0.27
Cercis siliquastrum	1.18	4.3	0.27
Diospyros kaki	1.07	3.9	0.27
Prunus serotina	0.29	1.06	0.27
Fraxinus angustifolia	1.02	3.74	0.27
Fraxinus excelsior	0.43	1.59	0.27
Prunus armeniaca	0.09	0.34	0.26
Buddleja davidii	0.38	1.45	0.26
Alnus glutinosa	0.01	0.33	0.03
Abelia triflora	0	1.15	0
Coprosma sp.	0	0.51	0
Vitis vinifera	0	6.95	0