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Assessing Ecosystem Services: a Quantitative Approach in a Changing Urban Environment

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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Abstract

The acceleration of the processes resulting from the ongoing climate change represents a threat both for the health of terrestrial ecosystems and for human beings. Cities are the main collectors of such reactions, where air pollution, high soil sealing rate and high population density meet. In order to contrast these consequences and reverse the negative trends linked to the aforementioned processes, a valid solution is represented by the restoration of public green spaces: in this regard, the understanding of the mechanisms through which vegetation produces beneficial effects on the surrounding urban environment is important but still first, it is crucial to identify an evaluation method that is as realistic as possible, relevant to the surrounding context without betraying the nature of the processes involved. The purpose of the thesis is to investigate the issue of ecosystem services in urban areas and, specifically, to use an evaluation method that is able to include the different values of which they are constituted.

An assessment of the benefits produced by green areas in urban areas may encounter difficulties, both in terms of methodology, quantification (cultural category) and relevance to the reference context (economic value). Starting from this observation, the first part of the thesis focuses on analyzing the topic from a methodological point of view, identifying a tool that will be implemented and tested along the thesis in its application chapters. Subsequently, a first part of results is presented with reference to parks and urban green areas of different sizes, types and scenarios considered, within the Turin metropolitan area. The theme of ecosystem services is related to the variation of land cover in the city, to the role of green areas to mitigate the effects of climate change and to future territorial planning according to hypothetical scenarios tested through the chosen methodology. In the second part, the scale is expanded to the urban level and the focus is specifically on the role of trees (both belonging to green areas and street trees) in providing benefits to the city of Boadilla del Monte. In this context, the cultural category of ecosystem services is explored through the involvement of citizens: through a questionnaire,

citizens collaborated in outlining the main socio-cultural indicators of urban green areas, in defining general knowledge about ecosystem services and in evaluating the effects of climate change in the city.

In short, this thesis contributes to our understanding of: (i) how to deal with Ecosystem Services (ES) evaluation and quantification in an urban context, (ii) the role of green areas and trees in the regulation of different phenomena at an urban scale. Furthermore, the methodology applied in the study emphasizes the importance of a transversal approach, characterizing all three spheres of which ecosystem services are composed: environmental, economic and social.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The growth of the population, climate change, and resulting pollution levels have brought up concerns regarding human health and the state of natural and man-made ecosystems. The exploitation of resources transformed into over-exploitation, creating a demand for natural materials that is not sustainable and resulting in a global deficit. The Global Footprint Network estimates a use equal to 1.75 planets Earth for 2019, calculated through the ecological footprint of countries worldwide and measured in equivalent hectares of land required to supply demands and absorb waste generated. Sadly, the results of this consumption model include environmental impoverishment and damage due to various phenomena, such as a decrease in the ozone layer, loss of biosphere integrity, chemical pollution, climate change, ocean acidification, freshwater consumption, land use, nitrogen and phosphorus flows in the biosphere and oceans, and atmospheric aerosol load. The impact of these factors is further compounded by the escalating effects of climate change. The Earth has suffered significant loss of its glaciers, leading to a rise in sea level of 10 to 20 centimeters in the last century, as reported by the Intergovernmental Panel on Climate Change (IPCC).

Moreover, there has been an uncontrollable process of urbanization worldwide, with urban areas growing from representing 30% of the global population in 1950 to more than 50% nowadays (Mexia et al., 2018) and the United Nations predicts that by 2050, 68% of the world population will be urban (United Nations, 2019). The urban environment is functionally incomplete, as it involves consumption of natural resources and human activities (Reid et al., 2005). Cities are a vital source of ecological pressure causing changes in the earth's ecosystem through emissions, pollution, and resource consumption (Hodson and Marvin, 2010). Urban centers consume 75% of natural resources, including water, food, and soil materials, leading to soil functionality reduction, ecological landscape alterations, and a decrease in biodiversity, despite urban areas only covering 2.4% of the Earth's surface with high population density (Millennium Ecosystem Assessment, 2005).

Cities also consume 67% to 76% of global energy and generate three-quarters of global carbon emissions (Fragkias et al., 2013; IPCC, 2014). As a result, air pollution has become an increasingly important issue in urban areas, leading to the implementation of specific regulations to prevent exceeding pollution limits (Urrutia-Pereira et al., 2021). Fossil fuel combustion is the main cause of climate change, contributing to increased concentrations of anthropogenic greenhouse gas emissions (Siddik et al., 2021). The aforementioned over-exploitation of natural resources led to the threat of extinction of many plant and animal species and the loss of biodiversity (United Nations Environment Programme, 2021; Reynolds & Peres, 2006). As Deelstra and Girardet (2000) noted, it appears that we are becoming an urban species. This increase in population requires cities to expand, resulting in exacerbating environmental difficulties already prevalent within these urban centers (Sala et al., 2000). Finally, it should be underlined the significant rise in flood risk, associated with a high impervious cover rate in urban environments, which leads to an increase in flooding peaks and volumes (Li & Bortolot, 2022).

In this context, the following research work was initiated in 2019 with the intention of conducting a comprehensive study on a specific adaptation solution to climate change in an urban setting, with a focused emphasis on the city of Turin. The motivation behind dedicating the three-year doctoral program to this endeavor stemmed from the initial review of the state of the art on the topic, which revealed the need for in-depth exploration. Following the initial months of literature research, the decision was made to delve into the realm of ecosystem services, considering them as key aspects within an urban environment that will inevitably need to adapt its form and function to accommodate future changes. The presented topic delves into a particularly intriguing research area, which holds great potential, as indicated by recent scientific literature. However it lacks consolidated scientific foundations since it can be considered a relatively "recent" line of scientific research. The focus on the urban domain centers around the impacts associated with urban greening as a provider of multiple benefits, encompassing environmental, social, and economic aspects. With a specific emphasis on the active role in the process of climate change adaptation and mitigation, the study employs a quantitative analysis of temporal comparisons, while a more qualitative deepening has been dedicated the socio-cultural assessment. Through various collaborations with diverse municipal entities, the dissertation has gained a practical connotation, aligning with the need to normalize the inclusion of such topics within territorial planning documents, specifically at the urban scale in this specific context.

1.1 Aims and objective

The objective of this Dissertation is to focus on the urban scale about the provisional potential in terms of ecosystem services, through an evaluative-quantitative approach that winks at the practices of mitigation and adaptation to climate change on the urban scale. Quantitative software applications and the use of social survey tools have been used with the following objectives:

1) To investigate the ability to generate environmental benefits (also translated into economic terms) of some large green areas in a metropolitan city

2) To analyze the role of urban trees in an entire small-sized city area on the producibility of effects capable of mitigating climate change

3) To investigate the cultural category of ecosystem services through the active participation of citizens to obtain socio-cultural indicators defined in the literature and to investigate the general knowledge of environmental issues related to future sustainability

4) To extend the investigation of ecosystem services to green roofs and coastal environment through qualitative and quantitative analyses respectively.

1.2 Dissertation Outline

The Dissertation is composed by four Chapters. Chapter 2 contains a general introduction on the in-depth topic, accompanied by the methodology from the literature and applied in the practical applications subsequently presented in Chapter 3 and Chapter 4, which are structured as stand-alone (i.e. paper-like). Finally, the main findings are summarized together with suggestions for the future research about the topic in the conclusion.

1.3 Novel contributions and publications

The following publications have been extracted from this Doctoral Dissertation:

- Busca, F., Gómez-Villarino, M.T., Revelli, R. The interconnection between urban green areas and cultural ecosystem services: a case study in Boadilla del Monte (Spain), 2023b [under review].
- Busca, F., Gómez-Villarino, M.T., Revelli, R. Influence of urban trees on the provision of ecosystem services: A case study in Boadilla del Monte (Spain), 2023a [under review].
- Busca, F., Revelli, R. Green Areas and Climate Change Adaptation in a Urban Environment: The Case Study of "Le Vallere" Park (Turin, Italy), *Sustainability*, 2022, 14, 8091. https://doi.org/10.3390/su14138091
- Busca, F., Tinivella, I., Revelli, R. Urban sustainability: The role of ecosystem services provided by an Italian green infrastructure, *Geam. Geoing. Ambient. Min.*, 2021, 163-164, 46-55. https://dx.doi.org/10.19199/2021.163-164.1121-9041.046

Furthermore, some portions of this project have been/will be presented (as oral presentation or poster) at the following conferences:

- *40th International Association for Hydro-Environment Engineering and Research (IAHR) World Congress*, Vienna, Austria, August 2023.
- *European Geosciences Union (EGU) General Assembly*, Wien, Austria, April 2023.
- *3rd International Association for Hydro-Environment Engineering and Research (IAHR) Young Professionals Congress,* online, November-December 2022.
- *39th International Association for Hydro-Environment Engineering and Research (IAHR) World Congress*, Granada, Spain, June 2022.
- *European Geosciences Union (EGU) General Assembly*, Vienna, Austria, May 2022.
- *XXXVII Convegno Nazionale di Idraulica e Costruzioni Idrauliche (IDRA)*, online, June 2021.
- *European Geosciences Union (EGU) General Assembly*, online, April 2021.
- *European Geosciences Union (EGU) General Assembly*, online, May 2022.

Chapter 2

Ecosystem Services (ES) Evaluation

2.1 Introduction

In recent years, safeguarding approaches and environmental management initiatives have been adopted to promote sustainable use and restoration of natural resources in order to manage the consequences of climate change (e.g. urban flooding, drought and water scarcity, food insecurity) (Ramarojaona & Failler, 2016). The depletion of natural capital (Beddoe et al., 2009) and the advancement of knowledge in ecosystem ecology (Costanza et al., 2017) are two factors that led to a deeper understanding of the role of natural systems and the services they provide in the latter half of the 20th century. The well-being of inhabitants in highly-modified urban ecosystems can be influenced by the state of ecosystems (Chiabai et al., 2018) and ecosystem processes have contributed to the growth of human society throughout history (Butler, 2003; Littlefield et al., 2019). The concept of Ecosystem Services (ES) emerged in the 1970s under the name "environmental services" (Wilson and Matthews, 1970) and was later renamed "ecosystem services" in the 1980s (Ehrlich and Mooney, 1983) to draw public attention to the conservation of biodiversity (Westman, 1977; Ehrlich and Ehrlich, 1981; De Groot, 1987) and later integrate an economic evaluation (Costanza et al., 1997). The meaning of the term has evolved over time, addressing various phenomena that emerged in recent decades such as uncontrolled urbanization, climate change, and declining human well-being. The current definition of ecosystem services is "benefits people obtain from ecosystems," according to the Millennium Ecosystem Assessment (MA) (Reid et al., 2005), referring to elements of natural capital that provide intangible benefits, products, and services for enhancing human well-being and quality of life (de Groot et al., 2012). Several classification systems have been developed since the beginning of the 21st century, including Millennium Ecosystem Assessment (MA, 2005), The Economics of Ecosystems and Biodiversity (TEEB, 2010), the Common International Classification of Ecosystem Services (CICES, 2013) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Haines-Young & Potschin, 2018; Diaz et al., 2018). Following the MA (2005), an international experiment conducted from 2001 to 2005 that aimed to identify the state of global ecosystems, evaluate the consequences of changes to ecosystems on human well-being and provide a valid scientific basis for the formulation of necessary actions for conservation and sustainable use", ecosystem services are classified into four types (Brauman et al., 2007): (i) provisioning, i.e. consumption goods directly extractable from ecosystems such as food, raw materials, freshwater, biological diversity; (ii) regulating, those related to the regulation of the hydrological cycle, climate, and hydrogeological disasters; (iii) supporting, i.e. necessary for the realization of all other services (e.g. creation of soil, support for reproduction, evolution of animal species); finally (iv) cultural, immaterial benefits offered to humans such as inspiration for art, music, architecture. TEEB refined the classification by replacing the supporting category with 'habitat services' and emphasizing the importance of ecosystems in preserving genetic heritage. CICES simplified the classification by reducing the number of main categories to three and expanding the regulation category to "regulating and maintenance services." (Haines-Young & Potschin, 2018). IPBES defines all nature's contributions to human quality of life as Nature Contributions to People (NCP), categorized into regulatory, material, and non-material contributions. Regulatory contributions modify environmental conditions and provide tangible and intangible benefits, material contributions provide natural resources necessary for daily life, and non-material contributions influence the quality of cultural life. Starting from highlighting biodiversity loss risks as a pedagogical purpose, ES have now become a fundamental political and economic tool (Gómez-Baggethun and Martín-López, 2015), that identified the state of global ecosystems, assessed the consequences of changes on human well-being and provided a scientific basis for conservation and sustainable use (Reid et al., 2005).

2.2 Urban Context

To ensure the sustainability of urban areas, a deeper understanding of their relationship with ecosystems, although predominantly anthropogenic, is necessary; examining ES derived from urban ecosystems within the larger city context could be useful in highlighting the connection between humans and these functions. Urban green infrastructures offer a feasible option for study. However, research gaps exist in the area of urban ecology, with only 217 publications relating to Urban Ecosystem Services (UES) reported worldwide in 2014, primarily in North America, Europe, and China (Haase et al., 2014). Moreover, research discrepancies exist between urban-type ecosystems and others like wetlands or forests (Caprioli et al., 2020). Hence, many authors emphasize broadening the study of cities as ecosystems and their impact on ecosystems themselves to guarantee urban ecological safety (Hodson and Marvin, 2010; Solecki et al., 2013, McDonnell, 2015; Jennings et al., 2017). Green Infrastructure (GI) has been identified as a valid strategy for the recovery of biodiversity and ecological functions (Vargas-Hernández & Zdunek-Wielgołaska, 2021). Specifically, Urban Green Infrastructures (UGI) offer a promising solution to achieve urban sustainability and mitigate the impact of climate change (Kabisch et al., 2015; Meerow & Newell, 2017; Semeraro et al., 2017). GI is a term with multiple interpretations, but we adopt the European Commission's definition of as “Strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings”(European Commission, 2014). UGI are increasingly recognized as essential providers of ecosystem services (ES) in cities (Chen et al., 2020; Graça et al., 2018; Hegetschweiler et al., 2017), and this acknowledgement is critical, given their contribution to city resilience (Revelli & Porporato, 2018), a better quality of life, and ultimately, urban sustainability (Brzoska & Spāģe, 2020; Meerow & Newell, 2017). However, this scientific recognition has yet to be fully embraced by urban planners (Brzoska & Spāģe, 2020), particularly in urban development design (Chapman & Hall, 2022), necessitating quantitative appraisals to validate the significance of ES provided by UGI and obtain support. These evaluations impel credible and realistic assessments of environmental benefits offered by urban nature (Brink et al., 2016; Pandeya et al., 2016; Selmi et al., 2016) and integrate an ecosystem services approach into urban design processes (Gren & Andersson, 2018).

At the city level, there are a variety of features that can constitute GI: such as sidewalk trees, private or community gardens and parks, green roofs (Cristiano et al., 2020), green walls (Costamagna et al., 2022), sustainable drainage systems (Chapman & Hall, 2022) and more, since “they are part of an interconnected network and are delivering multiple ecosystem services” (Gómez-Villarino et al., 2021), contributing “to the ecological, aesthetic, and public health needs of the urban environment” (Taylor & Hochuli, 2017). Urban greening, which encompasses green areas, public and private parks, green roofs and green walls, represents a valid solution for climate change mitigation (Nero et al., 2017) and adaptation (Fryd et al., 2011) among other alternatives such as sustainable agriculture or architecture. The primary requirement is that these green spaces are connected and able to provide ecosystem services (Chatzimentor et al., 2020; Hegetschweiler et al., 2017). In Gren & Anderson (2018), urban green areas are seen as "semi-natural habitats", with a function in providing different "rural" ES and crossing the traditional urban-rural divide. Meanwhile, Liu & Russo (2021) examine the role of urban green areas as key components of GI through an innovative planning approach for ES aimed at improving urban resilience. Gillefalk et al. (2021) highlighted the importance of vegetation management in sustainable water and land use planning practices for enhancing cities’ resilience to climate change and other environmental factors, emphasizing the choice of vegetation type in urban green spaces. Green spaces within an urban context represent one possible strategy to counter the greenhouse effect through carbon dioxide sequestration and storage by plants (Locatelli, 2016). The air matrix also benefits from vegetation in terms of reducing noise and light pollution, thermoregulation, and mitigating Urban Heat Island (UHI) effects (Kim et al., 2018). UHI is a phenomenon where urban land temperatures are significantly higher than surrounding natural and rural environments, causing thermal discomfort due to overheating caused by city activities, gray infrastructures, and city size and location (Rospi et al., 2017). Green spaces provide necessary hydrological services such as the interception, storage, infiltration, and evapotranspiration of water by vegetation and soil, and they alterates the land cover distribution and increase the permeable soil percentage, having a positive regulating effect on the urban hydrological cycle. They generates a reduction in surface water runoff produced, relieving the burden on urban drainage systems, which typically transport surface runoff to receiving water bodies and helping to mitigate problems related to the management of urban runoff volumes (Yao et al., 2015). This adjustment counteracts the soil overbuilding typically found in urban areas, minimizing the hydrogeological risk of the city (Busca & Revelli, 2022). Urban parks are also significant sources of urban biodiversity and, while not as critical as those obtained from global ecosystems, the local nature green spaces in cities offers various educational, moral, and practical advantages to evaluate the direct benefits to communities and integrate ecological considerations into city planning. The type and supply of ES are influenced by context and community use, particularly cultural ES which can be negatively impacted by neglect or population values towards green areas. Park size is a crucial factor with larger parks offering more regulation services and smaller parks providing more cultural services (Bolund & Hunhammar, 1999).

The significance of trees within these infrastructures is also essential, as they have numerous benefits such as storing carbon dioxide, producing oxygen through photosynthesis, and providing socio-cultural values (Tor-ngern & Leksungnoen, 2020), energy savings, and temperature regulation through canopy shading and evapotranspiration, respectively (Moody et al., 2021). Specifically, in cities, they contribute to climate change adaptation in terms of stormwater management through hydrological processes such as evapotranspiration, storage and infiltration and moderating urban temperatures (Fryd et al., 2011), affecting the energy requirements of buildings for heating and cooling. Indeed, trees absorb part of the visible radiation, reducing solar radiation incident on buildings and modifying long-wave radiation exchanges between surfaces and the environment (NCC, 2019). They are also capable of eliminating air pollutants, improving air quality and human well-being (Nowak et al., 2006). In Pinto et al.'s analysis (2022) of urban green spaces (UGS), a lack of scientific research on urban trees is highlighted, both in Spanish territory and elsewhere. In addition, for their contribution to climate change mitigation, more analyses on provisioning and regulating ES should be conducted (Pinto et al., 2022), and engagement with stakeholders and users should be encouraged to guarantee prolonged support (Collins et al., 2019). Furthermore, in Ding et al.'s study (2023), a water-energy-food nexus (WEF-Nexus) should be used to promote sustainable development through matching and regression assessments of urban ES supply-demand. Lastly, Blanco et al. (2022) suggest that a regenerative design of neighborhoods must be encouraged in urban environments, amplifying urban ES production.

Green spaces in urban areas will play a significant role in achieving various Sustainable Development Goals (SDGs) (Damtey et al., 2022), particularly those that aim to "ensure healthy lives and promote well-being for all at all ages" (Goal 3), "make cities inclusive, safe, resilient, and sustainable" (Goal 11), and "take urgent action to combat climate change and its impacts" (Goal 13) (Turner &

Overland, 2009; United Nations, 2015). In relation to the latter objective, it should be noted that the relationship between ecosystem services and climate change is interdependent (Chiabai et al., 2018). As several studies (Chiabai et al., 2018; Fryd et al., 2011; Nowak et al., 2014) have demonstrated, ecosystem services mitigate climate change by moderating urban temperatures, managing stormwater, storing carbon, and improving air and acoustic quality and ES restoration is considered one solution to mitigate the negative consequences of climate change and other ecological imbalances (Zerb et al., 2013). Indeed, climate change will result in more intense rainfall events (Jentsch & Beierkuhnlein, 2008) and ES provision in cities will accommodate for excess surface runoff through urban greening and related hydrological processes (Busca & Revelli, 2022). However, climate change is also impacting ecosystem services (Berhanu Zawude Bakure, 2022; Gacheno & Amare, 2021), which can threaten these services even though public awareness is often lacking (Collins et al., 2019).

The current dissertation, within the wider framework described by Montoya-Tangarife et al. (2017), concentrates on urban environments and their associated Ecosystem Services (ES) pertaining to land use (specifically changes in urban residential areas), air quality and water (containing pollutants and mitigating flood damage in surface, sub-surface, and groundwater flows). The current dissertation specifically investigates the regulatory and cultural category of ES that have a significant impact on the urban air pollution regulation, water cycle and people well-being.

For what concerns the regulation of ecosystem processes, surface runoff control in the urban water cycle is one of the main services deepened, including the avoided surface runoff, which controls the flow of rainwater on the soil surface in urban areas. Different variables, such as the intensity, duration, and distribution of rainfall events, land use, soil cover, and slope, affect the volume and features of runoff (Shanmukha et al., 2018), Urban areas typically collect precipitation in drainage systems that transport it to the nearest water body. However, the increasing urbanization and waterproofing of surfaces create issues related to the management of runoff (Booth, 1991), amplified quantities due to vast impervious surfaces that prevent infiltration of precipitation into the soil, as explained by Hirabayashi (2012). Green areas within urban environments can mitigate these problems by increasing the permeability of surfaces. Citizens and public administrations have shown a lack of interest in sustainable urban water management (Conte et al., 2012), while dependence on higher governance levels has complicated climate change adaptation strategies in medium-sized cities (Özerol et al., 2020). Urban ecosystem services play a critical role in climate change adaptation (Loftus et al., 2011), and it is suggested that flexible and forward-thinking water planning in urban areas could be a practical strategy to implement adaptation measures to tackle climate change. Several cities across the globe have already implemented adaptation plans or taken specific actions to enhance their ability to cope with the impact of climate change. Sustainable Urban Drainage Systems (SUDS) have been suggested as an efficient solution to attenuate urban runoff volumes.

Instead, cultural Ecosystem Services (CES) are defined as "non-material benefits people derive from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences" (Reid et al., 2005). Over time, the term has come to be associated with non-monetary benefits in common understanding (Hirons & Comberti, 2016). Although scientific research has faced difficulties in quantifying these benefits through methods and software (Barbier, 2013; Barbier, 2019), issues related to evaluating CES are even more pronounced (Fagarazzi et al., 2021), as the concept cannot be measured through traditional means, particularly through an economic lens (Hernández-Morcillo, 2013). Several scientific studies have shown that citizens' and visitors' preferences for recreational activities and aesthetics have an impact on tourism and its revenue, contributing to covering management costs and enhancing economic opportunities (Eagles et al., 2002; Dumitras et al., 2017; Franceschinis et al., 2021). Therefore, an economic interpretation of CES might consider the willingness of users of urban greenery to pay to support the economic value of these services, reducing their intangible aspect, as is the case in similar contexts such as national parks or protected areas, to validate bequest and aesthetic function values (Acharya et al., 2021), the conservation of nature (Zydroń et al., 2021), or recreational facilities (Liu & Yang, 2019), but also for urban (Dinda & Ghosh, 2021) and suburban (Kalfas et al., 2022) green spaces. In addition, numerous publications have examined the relationship between green spaces and well-being (Reyes-Riveros et al., 2021; Hekrle, 2022). Urban residents view parks and natural areas as restorative environments, and green infrastructure in cities can enhance environmental health and positively impact human health, including reducing stress (Allard-Poesi, 2022) (Felappi et al., 2020). Similarly, like ES classification, CES have primary typologies (Hirons & Comberti, 2016). Based on CICES (Haines-Young & Potschin, 2018), the "cultural" section can be divided into two categories: one linked to direct and outdoor interactions with ecosystems based on "presence in the environmental setting" and another connected to indirect and remote connections with living systems. Each section comprises groups, which are then further divided into classes. Additionally, MA (2005) previously described CES through several categories, such as spiritual and religious values, aesthetics, social relationships, cultural heritage values, and more (Reid et al., 2005; Sarkar & Das, 2016).

2.3 Ecosystem Disservices (EDS)

It is important to acknowledge the multifaceted nature of ecosystem services and their implications for human well-being and lifestyle. However, it is crucial to recognize that ecosystems can also generate negative outcomes known as ecosystem disservices (EDS) (Wu et al., 2021). These disservices encompass a range of detrimental effects on humans, including the spread of diseases, degradation of infrastructure, biological damage, geophysical damage, and animal attacks. Examples of ecosystem disservices include the adverse impacts of severe weather conditions, the presence of predators and poisonous prey, all of which result in negative consequences for agriculture and land use. Although there is no universally accepted definition of ecosystem disservices (Lyytimäki & Sipilä, 2009), the most suitable definition, according to literature, characterizes them as products of the socio-ecological system that are perceived as harmful by human beings due to their negative influence on well-being and quality of life (Teixeira et al., 2019).

To evaluate and measure ecosystem disservices, three types of indicators have been identified: socio-cultural, economic, and ecological indicators. These indicators serve to assess the adverse effects of ecosystems on society, culture, and the economy. While economic impacts can be quantified using existing methodologies, the quantification of psychological impacts, such as the discomfort caused by animal feces or poorly maintained green spaces, remains a challenge (Wu et al., 2021). It is important to note that ecosystems generate functions and processes independently of human intent (Costanza et al., 2011), resulting in both positive and negative impacts on humans. Ecosystem disservices can be perceived when there is a decline in ecosystem services or a negative influence on them, such as the rise in temperatures due to carbon dioxide emissions. Furthermore, the variability of disservices in different locations and over time makes their prediction and definition challenging. Moreover, the perception of disservices may evolve over time (Guo et al., 2022), as exemplified by the transformation of green spaces from perceived hazards (Noël et al., 2021) to recreational areas (Jabbar et al., 2022).

The subjective nature of disservice perception adds to the difficulty of quantification.

In the contemporary world, monitoring social well-being and understanding how environmental changes affect people's lifestyles are increasingly important. Similar to ecosystem services, ecosystem disservices negatively affect these aspects of life. The absence of well-being leads to imbalances within the social system, driven by individuals' discomfort resulting from the impact of ecosystem disservices (Wu et al., 2022). For instance, in urban environments, trees often damage infrastructure such as roads and sidewalks due to their expanding roots, posing aesthetic displeasure and hazards for wheeled transport. This creates risks and anxiety for cyclists, thereby diminishing the potential enjoyment of the environment. Persistent disservices not only affect individual well-being but also lead to the abandonment of areas or infrastructure (Thorn et al., 2021), appearing wasteful to taxpayers. Consequently, the impact of ecosystem disservices on human well-being should be meticulously studied, considering both temporal and spatial dimensions, as they can contribute to public dissatisfaction (Lee & Choi, 2020). The impact is not solely dependent on the type of disservice but also on the affected population's level of accustomedness to its presence. Additionally, the damage caused by the environment to human activities, such as the destructive effects of heavy rainfall resulting from global warming, is considered a disservice despite being vital for the planet's functionality.

EDS arise from the interaction between the ecological system and human activity and, as well known, the urban environment is a context in which human activity reach high level of concentration. Urban EDS must be studied and predicted in order to implement urban planning interventions without compromising wellbeing and lifestyle due to disservices caused by changes in the urban environment. Ecosystems are a source of harmful agents, especially in urban environments, such as diseases, waste, infrastructure degradation, animal attacks, allergens, poisonous organisms, and even geophysical damage caused by drainage problems. Firstly, it is necessary to mention those ecosystem disservices resulting from lack of maintenance, which transform a place into a source of discomfort (Arvanitidis, 2008). For example, an abandoned building might be simply a source of visual disturbance initially, compromising the aesthetic appearance of a neighborhood. Over time, it would become not only unsightly but also dangerous. The risks produced by such situations are no longer just psychological, such as fear of approaching or aesthetic deficiencies, but also physical risks (Netten et al., 2020).

In that particular environment, due to the lack of human activity, a favorable situation is created for the uncontrolled growth of plants and shrubs, which inevitably attract a large quantity of insects. In addition to insects, in such a context, many other forms of life will find a habitat that is favorable to them, such as mice, spiders, and stray cats. This implies that this will be an area where a high density of health risks is localized, due to the fact that the type of fauna that characterizes this type of environment often carries diseases, as well as being a source of discomfort. Another ecosystem disservice related to maintenance is the one caused by tree roots that raise the pavement (Speak et al., 2018). One could choose not to carry out maintenance, leaving the infrastructure raised, or implement a maintenance plan. In the case of the latter, maintenance and labor come at a cost. Because the cost is related to the damage caused by a tree's roots, which is by definition part of the ecosystem, this is classified as an economic ecosystem disservice. Furthermore, another widespread urban ecosystem disservice is that of allergenic agents (Britvec & Ljubičić, 2022), especially in areas with extensive green areas. Due to the high population density typical of urban areas, many individuals are affected by pollen in the air and other allergenic agents. This type of disservice is not only a health issue but also an economic one, as some families must procure medicine in case of severe allergic reactions.

In addition to health and aesthetic disservices, the presence of green areas within an urban environment also creates logistical economic problems and mobility issues (Corazon et al., 2019). Summed to the damage caused to structures and their related maintenance costs, green areas have a construction cost that, except in extremely rare cases, is never recovered, since they are used for public use without payment at the entrance. Furthermore, due to their presence, which often occupies vast areas, an obstacle is created for the transportation and movement of goods and people, which must be bypassed by circumnavigating the area. This implies higher costs both in the project phase and in the infrastructure implementation phase, or, in some cases, the abandonment of the project. In addition, the presence of trees or bushes contributes to a reduction in road visibility (Kocur-Bera & Dudzińska, 2015), creating potentially dangerous situations. Another significant aspect to consider is maintaining green areas, which is usually the responsibility of the public administration. Due to a lack of economic resources available to public entities, more and more green zones remain without maintenance and botanical care, generating a perception of neglect and discomfort for people living or frequenting those areas (Moran et al., 2022). Regarding a contingent situation, it should be noted that for their maintenance, the administration relies in part on private companies. Many of these, however, have only recently resumed their activities due to the restrictions imposed to contain the effects of the new Coronavirus, and have had evident repercussions on the forest heritage of some cities. For example, even the numerous parks in Rome have suffered, and only a small part of them have returned to public use with significant resonances of discomfort for those living in those areas.

Another problem related to urban greenery is the production, by trees, of the so-called BVOCs, i.e. biogenic volatile organic compounds. These plant products, which are also the only ecosystem disservice that current evaluation systems are able to quantify fairly precisely, interact with pollution present in the urban area, particularly with nitrogen oxide, to form secondary substances also called photochemical smog (Döhren, 2019). It is mainly composed of ozone and nitrogen dioxide, which are harmful to human health and infrastructure as they are degrading agents.

From all these examples, it can be inferred that the structure of the urban forest, which is defined as the set of all shrubs, trees, plants, and green zones present in urban areas, regulates how functions occur in the city, determining the quantity and quality of ecosystem services and disservices present in the study area. The amount of services and disservices inevitably affects lifestyle, wellbeing, and population habits (Dobbs, 2014). However, it can be stated that the structure of the urban forest is dynamic rather than static and is capable of changes caused by demographic data alteration and economic situations, as well as by management policies.

2.3.1 The role of cities

Cities, as complex biological systems, rely on their surrounding regions and engage in metabolic processes involving water, materials, and energy. With the growth of population and urban areas, cities have escalated their resource demands. The environmental impact of cities resulting from population size is calculated by multiplying the population with per capita consumption and the technological impact associated with each unit of consumption. Unfortunately, the impact of cities has been rising due to increasing per capita consumption and population, while technological advancements struggle to keep pace (Newmann, 2006). In an attempt to minimize local impact, cities typically import goods from other regions, often from developing countries. However, this approach inadvertently amplifies the impact of the city, which would have otherwise been negligible, as it exacerbates the depletion of non-renewable resources in impoverished regions.

Theoretically, cities concentrate various destinations within a limited area, aiming to reduce travel between two points. However, empirical data reveals that the distance traveled by vehicles increases as the urban area expands. To quantify resource consumption, an index called the ecological footprint has been introduced. This index can serve as a valuable tool in formulating control policies that strive to maintain resource consumption below a certain threshold.

As densely populated areas, cities significantly contribute to the emergence of ecosystem disservices. This is attributed not only to the concentrated human population but also to the fact that cities function as artificial ecosystems with immense energy consumption and dispersion. Consequently, cities can trigger behavioral changes in their surrounding environments, both locally and globally.

One disservice resulting from the high population density of cities is the presence of parasites that disrupt urban markets. These parasites, originally inhabiting rural areas, occasionally infiltrate cultivated fields. The majority of agricultural produce is intended for sale in urban markets, providing these parasites with ample opportunities to attack humans due to the high population density. Furthermore, this scenario can potentially lead to epidemic outbreaks. The disservice in this case lies in the fact that the concentrated population in a limited area facilitates the spread of diseases, as interpersonal interactions are more frequent in an urban environment.

Cities also generate a disservice by fostering a culture of material possession, leading to an incessant rise in mass production that invariably impacts the planet through resource exploitation and emissions. Cities actively promote consumption, and individuals tend to consume more, accumulate possessions, and rely heavily on energy resources. Lastly, the consequences of overexploitation, such as localized temperature increases, result in urban heat islands and rising sea levels due to melting glaciers caused by excessive greenhouse gas emissions. These phenomena have a direct impact on coastal cities like Amsterdam and Venice, resulting in flooding.

In the context of evaluating and understanding ecosystem disservices in urban environments, the city of Beijing, China, provides a relevant case study (Wu et al., 2021). Specifically, disservices can be classified as provisioning disservices (when the ecosystem fails to provide necessary products for the population), regulating disservices (when the ecosystem causes damage or costs), or cultural disservices (when the ecosystem results in intangible harm). This study (Wu et al., 2021) evaluates three negative impacts related to green areas in Beijing. Firstly, vegetation-induced damage to infrastructure requires additional investments for maintenance and repairs. The repair costs are calculated by multiplying the ecosystem maintenance costs in Beijing by the percentage of maintenance costs allocated to repair. Secondly, there is a disservice caused by a reduction in water quantity, resulting in additional expenses to address the water deficit. The water shortage costs are determined by considering the amount of water consumed by a single plant, the local price of water for ecological purposes, the amount of water needed for agricultural production, and the local price of water for agricultural purposes. Lastly, the third disservice involves diseases and injuries caused by plants and animals. The costs associated with flora and fauna are determined based on factors such as the population of Beijing, the incidence rate of specific diseases or injuries, the percentage of patients affected by the disease, and the cost of combating the disease per person. These experimental models enable the assessment of specific ecosystem disservices in an urban area, providing valuable insights for informed decision-making in urban design and ecosystem disservice management. The ultimate goal is to minimize the perceived impacts of disservices and enhance overall well-being.

2.3.2 Relation between ES and EDS

The intricate relationship between ecosystem services and disservices emerges from the intricate interplay between humans and the ecosystem. A key commonality lies in their connection to users' perception, a factor devoid of objectivity. The divergence between services and disservices lies in their evaluation, with users often harboring stronger negative sentiments towards the adverse effects stemming from the interaction between the ecosystem and society, rather than fully appreciating the positive ones.

Concrete examples, such as urban parks, illustrate this phenomenon. Some stakeholders perceive these parks as sources of recreation and tranquility, while others view them as habitats for rodents, insects, and wildlife, which they believe negatively impact the well-being of park users. Similarly, the case of Helsinki, Finland, highlights the influence of users' perception on ecosystem management decisions (Lyytimäki et al., 2008). The first aspect focuses on rows of trees in certain areas of the city, particularly linden trees, which provided ecosystem services like air purification and aesthetic value. However, these trees started emitting a foul odor due to biological processes. Despite the benefits offered by the trees, a decision was made to remove them because the city's population was more negatively affected by the unpleasant odor than they benefited from the positive aspects. The second aspect pertains to the management of Barnacle Geese, a protected species that was highly appreciated by Helsinki residents for its beauty and rarity. As urban green spaces expanded and their quality improved, these geese began perceiving the areas as favorable habitats, lacking their natural predator, the fox. Consequently, the number of geese in the city increased, causing inconveniences such as issues with their droppings. This led to a loss of public interest in the aesthetic value of the geese, resulting in the decision to remove many of them from Helsinki. Furthermore, the text highlights the lack of research on ecosystem disservices compared to services. The qualitative approach used to observe and document disservices has hindered the development of quantitative assessment models, which are available for ecosystem services. This oversight sometimes leads decision-makers to disregard the existence of disservices and their impact on the population, requiring them to backtrack on their decisions, as was the case with the removal of the linden trees in Helsinki.

In conclusion, comprehending the interdependence of services and disservices is crucial, as their effective management necessitates the consideration of users' perception and the cultivation of a more objective evaluation of the ecosystem's benefits and drawbacks. In this doctoral thesis, we aimed to conduct a comprehensive analysis that encompasses both categories, namely: (i) from a quantitative perspective, the assessment of volatile organic compound (VOC) production was coupled with the quantification of key ecosystem service provisioning in both the urban area of Turin (Chapter 3) and Boadilla del Monte (Sub-chapter 4.1); (ii) from a qualitative standpoint, Sub-chapter 4.1 is entirely dedicated to exploring the socio-cultural value of green areas in the Spanish town, implicitly investigating the concept of ecosystem disservices (DSEs) through the questionnaire administered to the residents.

2.4 Methodology

Despite the availability of other SE evaluation tools, i-Tree was chosen due to its specificity on vegetation. I-Tree is a collection of analysis and evaluation tools designed and developed by the United States Forest Service, a division of the United States Department of Agriculture (USDA) in the early 2000s. This suite includes various tools designed to measure the ecosystem services provided by the vegetation within a particular region, such as trees, parks, urban neighborhoods or an entire region. Specifically, i-Tree Eco, alongside its auxiliary tool i-Tree Database, was utilized in this instance. The software suite encompasses a set of applications that are categorized into (i) core set, which comprises flagship tools; (ii) utilities, which are additional instruments for the former; (iii) research; and (iv) legacy. Figure 2.1 shows a concept map of the i-Tree suite and its related modules (some of which are currently only available in the United States), with a specific focus on Eco, Hydro, Canopy and Database functions.

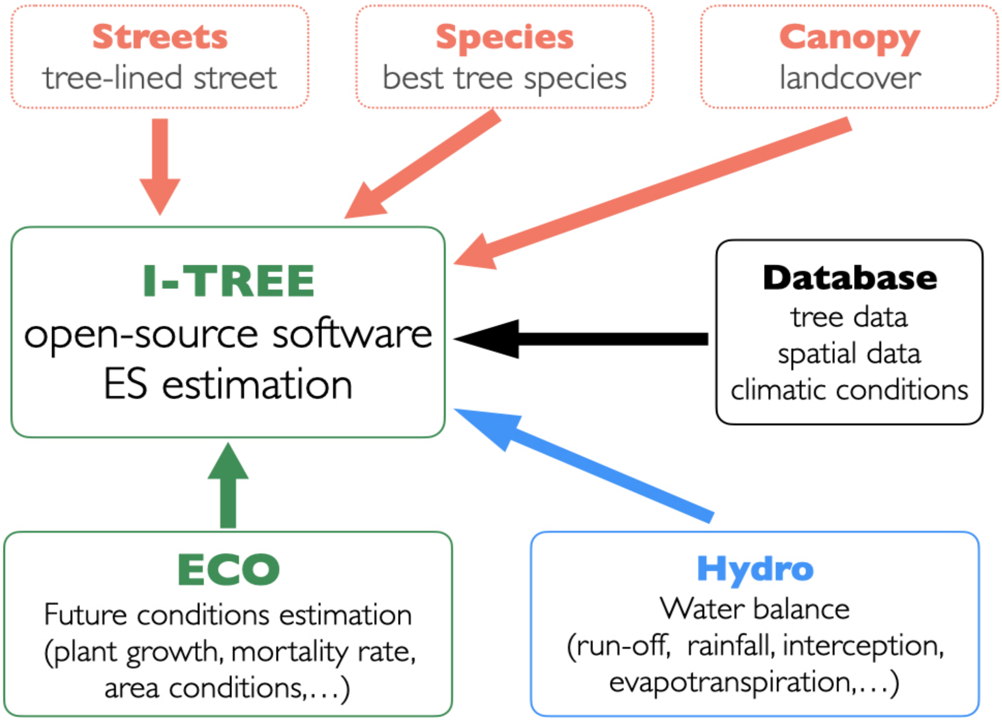

Figure 2.1: i-Tree structure.

2.4.1 i-Tree Database

The i-Tree Database is an online tool designed for users who wish to perform analyses outside of countries already included in i-Tree Eco. Within the database, users can access all information related to tree species, pollution, and rainfall that is formatted for their specific study area. If a user is conducting a project in an area that is not supported by the program, they can transmit data related to the new location or tree species to the United States Forest Service, who will format and validate it, incorporate it into the database, and make it available in a new version of i-Tree Eco for all users (i-Tree Database).

The database is divided into two sections: one covering tree species and the other focusing on localities. The tree species section includes over 7,000 trees and shrubs, with information such as botanical classification (e.g. scientific and common names, genus, family, class), leaf density, growth rate, and leaf characteristics (e.g. shape, size, period of fall). The locality section has all the locations already present in the database for which users have entered data.

All species analyzed (except for cut trunks, which are substituted with generic shrubs) are listed in Table A.3 of Appendix A. For locality information, Table A.1 in Appendix A summarizes the main details, with Villaviciosa de Odón (8 km away) serving as the nearest city of reference in the database, along with total population and population density data for Boadilla del Monte.

2.4.2 i-Tree Eco

i-Tree Eco is a collection of forest analysis tools that provides information about the greenery composition in urban areas and its environmental impacts. i-Tree Eco provides us with environmental data related to the study area and estimates various ES provided by trees and shrubs: specifically, about volatile organic compounds (VOCs), storage and sequestration of carbon, removal of atmospheric pollutants (O_3, CO, etc.), production of oxygen (O_2), and avoided water flow (through interception, evaporation and plant transpiration).

The required input data vary depending on the size of the study area: for smaller areas (such as the one under consideration), a "Complete Inventory" was conducted through a pinpoint inventory of tree and shrub species and a precise definition of soil types and uses. On the other hand, the analysis of larger areas can be carried out through statistical sampling (Plot-Based Sample Inventory) of parameters and characteristics.

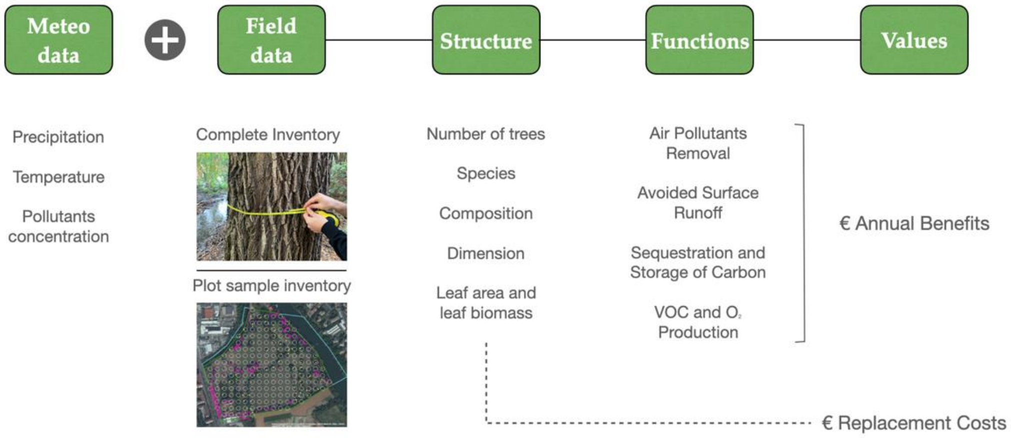

Figure 2.2: i-Tree Eco summary [Busca et al. (2023), adapted from Groot et al. (2019)].

Figure 2.2 illustrates an overview of the software composition and functioning, where input and output data have been better deepened in Table 2.1. The input data is contingent upon the inventory typology. two main types of input data are needed: (i) meteorological data such as precipitation, temperature, and pollutant concentrations, every hour, for a specific year; (ii) field data on land cover and tree population, gathered through on-site inspection (Busca et al., 2021). The objective of i-Tree Eco is to assess and measure the benefits a green area provides to its surroundings, which includes CO_2 sequestration and storage, removal of atmospheric pollutants, emissions of Volatile Organic Compounds (VOC), and avoiding water runoff. The precision of these outputs depends on the accuracy and quantity of the input data, some of which require an on-site inspection. The monetary value associated with each ecosystem service is estimated by determining an overall impact value of the area, based on the unitary benefit prices as determined during the input phase. Eco is rooted in the validated mathematical model of Urban

Forest Effects (UFORE), which uses a random sampling technique to monitor urban forest structure and estimate ES. The model incorporates local environmental data like pollutant concentration and meteorological data, and a greater understanding of the forest structure leads to more precise benefits estimation.

Table 2.1: Summary of i-Tree Eco (A) input and (B) output data.

(A)	**Input**
Weather station	CO_2, NO_2, O_3, SO_2, PM 2.5 concentration [ppm]
	PAR [W/m^2]
	Rainfall [cm/h]
	Temperature [°C]
Inventory	Species
	DBH
	Land Use
	Ground Cover
	Tree Height/Height to crown base
	Tree crown dimension and condition
	Crown light exposure
	GPS coordinates
Benefit prices	Electricity [€/kWh]
	Eating [€/therm]
	Carbon [€/ton]
	Avoided runoff [€/m^3]

(B)	Output
	Dry deposition of pollutants per canopy cover unit [g/m^2/h]
	DBH distribution:
	-Leaf area [ac]
	-Leaf biomass [ton]
	VOC [lb/yr]:
	-Monoterpene
	-Isoprene
	Stored carbon [ton]
	Gross sequestered carbon/Equivalent in CO_2 [ton/yr]
	Potential evapotranspiration, Evaporation, Transpiration, Intercepted rainfall [m^3/yr]
	Avoided surface runoff [m^3/yr]
	Air pollutants removal [ton]
	Monetary values [€]

Nowak (1996) states “Accurate estimates of tree leaf area and leaf biomass in both urban and surrounding natural areas are critical in assessing evapotranspiration, atmospheric deposition, biogenic volatile organic emissions, light interception, and other ecosystem processes”. In UFORE-A this principle is affirmed, through Equations (1) and (2), that are regression equations produced to measure the total leaf area and total leaf dry-weight biomass of “open-grown urban trees” (Nowak, 1996): Eq. (1) varies with the *DBH* (Diameter at Breast Height) while Eq. (2) is a function of the height (*H*) and width (*D*) of the crown.

$$ln(Y) = b_0 - b_1 \cdot DBH + b_2 \cdot S \tag{1}$$

$$\ln(Y) = b_0 - b_1 \cdot H + b_2 \cdot D + b_3 \cdot S + b_4 \cdot C \tag{2}$$

where Y is leaf area (square meters) or leaf dry-weight biomass (g); b_0, b_1, b_2, b_3, b_4 are regression coefficients; S is a species-specific shading factor defined as the percentage of light intensity intercepted by the canopy of trees; C is the canopy external surface (Gacka-Grzesikiewicz, 1980), as

$$C = \pi \cdot D(h + D)/2 \qquad (3)$$

In Eco simulations the leaf area index (LAI) is another fundamental parameter

$$LAI = -\ln{(I/I_0)}/k \qquad (4)$$

where I is the light intensity under the canopy while I_0 is the light intensity above it; k is the light extinction coefficient (0.52 for conifers, 0.65 for hard woods). The ratio between I and I_0 represents the shading factor. LAI is a dimensionless index that represents the leaf area (square meter) per surface unit (square meter) and that is defined on the basis of Beer-Lambert law (Nowak, 1996).

The parameter on which UFORE-D is based, fundamental for the analysis carried out, is the flow of atmospheric pollutants removed (gram per square meter per second), (Hirabayashi et al., 2011).

$$F = V_d \cdot C \qquad (5)$$

where V_d is the deposition rate (meter per second) and C is the pollutant air concentration (gram per cubic meter). The deposition rate for CO, NO_2, SO_2 and O_3 is calculated as the reciprocal of the sum of resistances to pollutant transport (second per meter), (Baldocchi et al., 1987).

$$V_d = 1/(R_a + R_b + R_c) \qquad (6)$$

where R_a is the aerodynamics resistance, i.e. the resistance opposed by the air to the pollutant molecules; R_b the quasi-laminar layer resistance, meaning the resistance encountered by the particles at the air-leaf interface surface; R_c is the canopy resistance, or the resistance opposed by the plant tissues and the stomal openings. In Baldocchi et al. (1987) an insight about the calculation of the three resistance types is present.

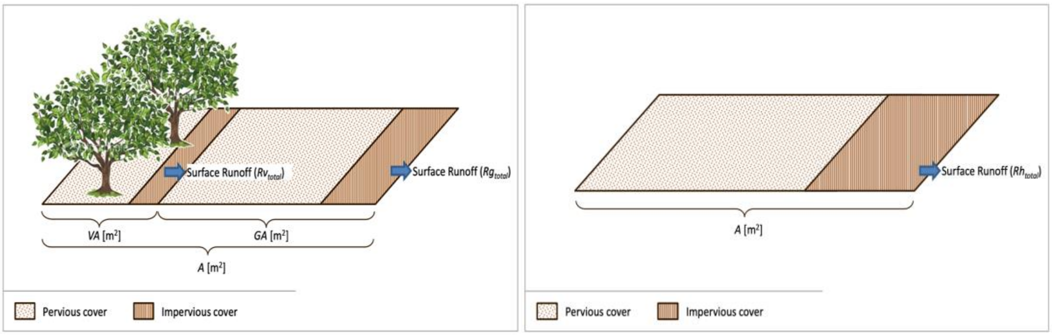

Figure 2.3: Example of actual (on the left) and hypothetical (on the right) scenario [taken from Hirabayashi, 2013].

For what concerns the water retaining ability of an area of interest characterized by a vegetative presence, i-Tree Eco considers the ability of rainfall interception, storage and evaporation from the vegetation. The avoided surface runoff in i-Tree Eco is obtained by comparing two scenarios: (i) the actual study area, which includes vegetation; and (ii) a hypothetical scenario of the same study area without any vegetation. This difference can be calculated using the equation provided in Hirabayashi's study (2013). S can be calculated using Eq. (7).

$$S = Rh_{total} - Ra_{total} = \mathrm{k} \cdot [\sum Rg_t \cdot A - (\sum Rv_t \cdot VA + \sum Rg_t \cdot GA)] \tag{7}$$

Rh_{total} in cubic meters represents the runoff from the impervious cover of the hypothetical scenario. A represents the total area in square meters, and Rg_t is the overland runoff at time t, in meters. The total runoff from the actual scenario, Ra_{total}, is given by the sum of the runoff from impervious cover in the areas covered by vegetation and not covered by vegetation. VA represents the area covered by vegetation, and GA represents the complementary area not covered by canopy, both in square meters. Rv_t and Rg_t are the overland runoff in VA and GA at time t, respectively, both in meters. The coefficient k comes from Nowak and Greenfield (2012), where it is estimated that 25.5% of the urban space is covered with impermeable soil (k equal to 0.255).

2.4.3 i-Tree Canopy

Canopy uses satellite images or shape files (Groot et al., 2019) to make a statistical estimate of land cover (trees, grass, buildings, roads, etc.). The information provided by this tool is utilized as input parameters in the i-Tree Hydro simulation. The program produces results on the percentage of land cover, which are evaluated through a statistical analysis (see Table 2.2). The process involves (i) defining the project area by tracing boundaries on a Google Maps image or with a georeferenced shapefile; (ii) entering locality information; (iii) attributing cover class to each randomly generated point by the program; and (iv) exporting reports containing graphs and tables about the outputs.

Table 2.2: Land cover classes in i-Tree Canopy.

Cover Class	**Abbreviation**
Tree—Pervious (T)	T
Tree—Impervious (NT)	NT
Grass—Herbaceous (G)	G
Impervious Ground (IG)	IG
Water (W)	W
Soil—Bare Ground (S)	S

It is worth mentioning that the classification related to tree cover takes into account the differentiation between tree cover on permeable surfaces (Tree-Pervious, T) and on impermeable surfaces (Tree-Impervious, NT). This includes all instances of trees planted in parking lots, courtyards, streets, and so on, which fall under the NT category.

The accuracy of the analysis depends on the user's ability to accurately identify the type of coverage using aerial images. The number of sampled points chosen by the user is arbitrary and depends on the desired level of accuracy, with the aim of minimizing the related standard error.

Regarding the cover class, the program provides the number of points related to each class along with their respective values (in percentage and square meters) and standard errors. This is achieved through a statistical analysis based on the Bernoulli process.

2.4.4 i-Tree Hydro

i-Tree Hydro is an application based on a specific urban hydrology model and it allows for simulations of the effects of different tree coverage scenarios on local hydrology in urban areas. It is a desktop program that is specifically meant for studying the hydrogeological impact of different types of coverage. The program uses a hydrological topographically-based model called UFORE-Hydro, which is still in development and is composed of two divisions: Hydro and Hydro+. The latter is the advanced version which is currently being researched. UFORE-Hydro follows an Object-oriented, Topographic (OBJTOP) structure and uses algorithms that modify interception, storage, infiltration, evaporation and runoff data to calculate hydrological impact. The model is user-friendly and requires minimal input data, making it ideal for researchers, urban planners, and environmental *technicians* (Wang et al., 2008). The version used for model updates involves an urban scheme of soil-vegetation-atmosphere exchanges represented by vertical layers, recognizing the surface as permeable or impermeable, with coverage percentage due to the presence of albedo quantified.

The flow model uses the following US databases as inputs: National Elevation Data (NED) and National Land Cover Data (NLCD). Using these data sets, Topographic Index (TI) can be obtained from NED and estimates of Impermeable Cover (IC) and Tree Crown (TC) from NLCD. TI is the quotient of the area by the length of the contour and the tangent to the slope of the local pixel. IC and TC are defined based on each block of TI, which refers to groups of pixels with the same Topographic Index. The hydrological model also requires information on initial groundwater level, chemical composition of soil, physical parameters, meteorological data, and potential evapotranspiration.

The main output data generated by the program include the amount of precipitation intercepted by vegetation, infiltration, evapotranspiration, surface runoff, and lateral flows of the aquifer. Eq. (8) refers to the water balance modeled in Hydro, whose components are shown in Figure 2.4.

$$PR = VET + VI + S + PI + PF + IF + SF + GET \qquad (8)$$

where PR is precipitation, VET and GET are vegetation and ground evapotranspiration, respectively, VI is vegetation interception, S is storage in soil depressions, PI is permeable soil infiltration, and PF and IF are permeable and impermeable runoff respectively, while SF represents the groundwater flows. All terms are measured in millimeters.

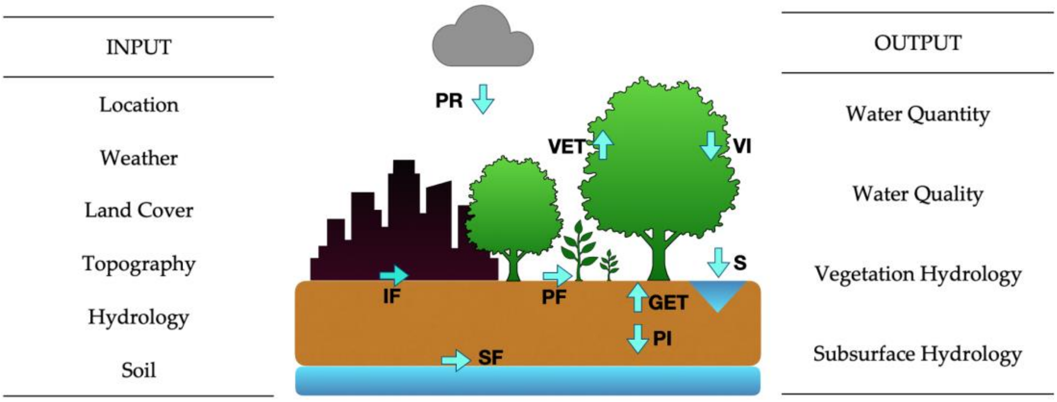

Figure 2.4: i-Tree Hydro: input data, water balance, output data [Busca & Revelli, 2022].

Figure 2.4 illustrates the five categories of input data required for i-Tree Hydro: (i) project area information, which includes the location, area size and simulation period; (ii) Weather data, manually uploaded from the nearest weather station; (iii) land cover data, categorized according to the definitions in i-Tree Canopy, which serves as an input for further analysis; (iv) elevation data, obtained by preparing and uploading the Digital Elevation Model (DEM) of the selected area; and finally, (v) hydrological and soil parameters, with suggested default values that can be altered to accurately represent the specific analysis. The primary output data is classified into four categories (Figure 2.4) including (i) Water Quantity, (ii) Water

Quality and advanced outputs, such as (iii) Vegetation Hydrology, and (iv) Subsurface Hydrology.

Among the land cover inputs, the Directly Connected Impervious Area (*DCIA*) is a crucial parameter that requires definition. It is defined as "the portion of waterproof area with direct hydraulic connection to the urban drainage system or to a watercourse through continuous paved surfaces, gutters, discharge or other transport and holding facilities that do not reduce the volume of outflow" (USEPA citation). This definition excludes insulated impermeable surfaces that do not have a direct connection with the sewer system, a river, or another body of water. The *DCIA* parameter is responsible for directing precipitation flows from impermeable surfaces and significantly affects the outflows in such areas (i-Tree Hydro).

Several methods can be employed to determine the *DCIA*. In case there is insufficient information, the program suggests a default value for this parameter. Alternatively, approximate estimates can be made using empirical methods based on knowledge of the site and the waterproof cover, which the United States Environmental Protection Agency (USEPA) (USEPA citation) recommends. This method estimates the parameter as a percentage based on the type of land use and the estimates of total impermeable surface.

In particular, for the case studies of this dissertation, it was determined that the equation applicable for "partially connected areas" would be used. This refers to areas where 50% of rainwater does not enter the urban drainage system but instead affects open section roads, depressions in grassy areas, unconnected residential roofs, and partially infiltrates the ground. The *DCIA* value, which is required for the program as a fraction of the impermeable area percentage, can be calculated as follows:

$$DCIA = 4 \cdot (\%IA)^{0.7} \qquad (9)$$

where *IA* is the percentage of the total impermeable area. Additionally, the software requests data regarding the crowns of trees and shrubs: Leaf Area Index (*LAI*), which is defined in Eq. (10) as the shrubs and herbaceous cover, with a specific focus on the percentage of evergreen trees.

$$LAI = \frac{Leaf\ area}{Tree\ canopy} \qquad (10)$$

LAI is an index that does not have any dimension and denotes the leaf area per unit of surface (Nowak et al., 2008). It is calculated as the ratio between the leaf area obtained from the results of the i-Tree Eco application, and the area occupied by the canopy of trees assumed to be the result of i-Tree Canopy.

The fundamental equations underlying the model are briefly summarized here, including the reference equation for rainfall interception:

$$\frac{\Delta C}{\Delta t} = P - R - E \qquad (11)$$

Where *C*, in meters, refers to the depth of the rain on the unit canopy at time *t*, *P* is the precipitation above the canopy, *R* is the precipitation under the canopy reaching the ground, and *E* is the evaporation rate. The unit of measure of Eq. (11) is meter per second, while Δt represents the time interval of the simulation. This deterministic algorithm was first proposed by Rutter et al. (1971, 1975), with a variation proposed by Valente et al. (1997) to consider sparsely distributed vegetation.

$$S = S_L \cdot LAI \qquad (12)$$

The expression for water storage S is given by Eq. (12), where S_L, measured in meters, denotes the maximum specific leaf storage capacity: a default value of 0.0002 meters (Dickinson, 1984) has been used for this project. Evaporation, quantified by the evaporation flow *E* in meters per second, depends on potential evapotranspiration E_p and affects the amount of water intercepted and stored, as shown in Eq. (13) (Noilhan and Planton, 1989; Deardorff, 1978). Wang et al. (2008) provide further information on potential evapotranspiration.

$$E = \left(\frac{C}{S}\right)^{2/3} \cdot E_p \qquad (13)$$

UFORE-Hydro uses TOPMODEL and modified Green-Ampt theory to divide water percolated from vegetation into ponding, infiltration and runoff (Wang et al., 2008). The infiltration rate, given by Eq. (14), depends on the soil depth *Z*, wetting front suction $\Delta\psi$ and hydraulic conductivity K_z in meters per second. The hydraulic conductivity decays exponentially with soil depth as described by Beven (1984).

$$i = \frac{dI}{dT} = \frac{\Delta\psi + Z}{\int_{Z=0}^{Z=Z} \frac{d_Z}{K_Z}} \qquad (14)$$

The total outflow per unit watershed area q_{tot} is the sum of subsurface flow $q_{subsurface}$, surface flow $q_{overland}$, and flow from impermeable areas $q_{impervious}$, as shown in Eq. (15).

$$q_{total} = q_{subsurface} + q_{overland} + q_{impervious} \qquad (15)$$

The overland runoff for permeable soils is the sum of surface flows due to excess of saturation and infiltration, as specified by Eq. (16) using TOPMODEL theory, where A_{sat} represents the saturated area, A is the total slope area, and P_W is the spatially weighted precipitation above and below the canopy.

$$Q_{overland} = \frac{A_{sat}}{A} \cdot P_W \qquad (16)$$

In contrast, subsurface flow represents water flowing from saturated soil areas. The output data will focus on the characteristics of runoff types produced by the green area.

2.5 The ES economic value

The evaluation of Ecosystem Services (ES), in general, can be carried out on three different planes of value:

(i) ecological value

"Relative value to “ecosystem functions, processes, and components on which ecosystem service delivery ultimately depends. They measure the ecological health and integrity of an ecosystem and its capacity to perform regulation and habitat functions [...]" (Baggethun et al., 2015);

(ii) sociocultural value

The importance that individuals or groups of people assign to (sets of) ES (Howarth, 2002) or "the aesthetic, artistic, educational, spiritual, and/or scientific values of ecosystems" (Costanza et al., 1997);

(iii) monetary value

Also known as VES (Value of Ecosystem Services), it refers to the expenditure that would be necessary to purchase the available ES at their shadow price

(Howarth, 2000). The shadow price is defined as "the marginal product of net primary production [of ES]" (Richmond, 2007).

In Gómez-Baggethun et al. (2010), a comprehensive depiction of the role of ecosystems in the economy is presented, spanning from classical to modern economics, culminating in the current sub-chapter and advancement of the concept itself.

From an economic standpoint, two primary phases are identified: the classical phase (18th and 19th centuries) and the neoclassical phase (20th century to the present). The classical phase centered on the notion of use value, which assesses the utility of an object based on its characteristics and usage. In this perspective, natural capital is regarded as the source of use value but it is external to exchange value, which arises from labor input into goods and land ownership, determined by market supply and demand. In the second phase, characterized by industrialization and a reduced emphasis on agricultural labor, exchange value gained increasing significance as the sole measure of commodity value. This led to the "emancipation" of the economy from natural capital. Notions such as the substitutability of natural production with ever-growing technological innovations and the self-regulating capacity of markets regarding potential resource scarcity resulted in a "shift from land and other natural inputs to capital and labor alone" (Hubacek et al., 2006).

When the market and the economy exclude the environment and the services and resources it provides, disregarding their impact, situations arise where "the pursuit of economic interests based on personal gain does not lead to the best outcome for society" (Silvis et al., 2013). This leads to market failures. Negative externalities occur when economic agents' actions, such as production or consumption, generate uncompensated effects on the ecosystem, resulting in social costs not accounted for by market mechanisms. These actions cause environmental damage that is typically overlooked by markets, as the lack of compensation implies the unintentionality of the effect and the absence of responsibility for the producer, unless specific legislative solutions are in place (Silvis et al., 2013).

Another inherent mechanism in market failures is the overexploitation of natural resources as public goods. Traditional markets are inadequate at effectively incorporating public goods, as they are defined by non-rival consumption (consumption by one person does not reduce availability for others) and non-excludability (it is not possible to restrict their use). This makes it impossible to sell them or find buyers (Bayon, 2004). As a result, there is a lack of economic incentives to sustain these resources, necessitating government intervention (Barton, 2011) to alleviate pressures on natural capital. These pressures primarily affect ecosystem services that are more challenging to privatize, such as cultural and regulatory services, and are further compromised by the use of provisioning services, which are traditionally associated with property rights (Duraiappah, 2006). The solution to these problems, based on the lack of recognition of the value of services provided by the environment, namely their exclusion from markets, lies in integrating them into economic analyses through the development of new disciplines. The two most important disciplines to date are environmental economics and ecological economics. Although they have similar names, their approaches are fundamentally different, with the former being more reformist and the latter more revolutionary.

Environmental economics aims to integrate the aforementioned externalities into the neoclassical analytical framework, thereby expanding the scope of research while upholding the principles and models of modern economics. Conversely, ecological economics takes a holistic approach, recognizing the inadequacy of the neoclassical approach in effectively addressing the environment and its resources, which are often regarded as public goods. From this perspective, economics itself is viewed as a "dissipative structure or a sub-system of global ecosystem […] which is more complex than understood by environmental economists" (Venkatachalam, 2007). A crucial aspect of ecological economics is its methodological pluralism and transdisciplinarity, aimed at tackling the inherently complex and multifaceted nature of the problem (Costanza, 1989).

These considerations, within the specific context of ES, have historically resulted in a shift from the initial informative function of highlighting the absolute value of biodiversity for humans to the assignment of value and the establishment of tangible international markets. The transformation of ES into tradable values has attained what Silvertown (2015) describes as industrial proportions and this trajectory is widely acknowledged by both critics and advocates of this paradigm shift as the primary trajectory followed by the concept of ES (Costanza et al., 2017; McAfee, 2012; Gómez-Baggethun et al., 2010). Table 1 provides a chronology of the various steps that have contributed to the contemporary conception of ES and the associated criticisms.

Table 2.3: Evolution of the ES concept in economic terms [Gòmez-Baggethun et al., 2010; Silvertown, 2015].

Name	**Period**	**Conceptualization**	**Criticality**
Ecosystems	1935	Abstraction of the concept of nature and introduction of ecosystem functions such as nutrient cycles.	Decrease in the intrinsic value of biodiversity compared to its generic role in ecosystem functions, for example, considering only the "biomass."
Ecosystem services	1960-1990	Ecosystem functions reinterpreted in a utilitarian perspective.	Introduction of a strongly anthropocentric perspective.
Attribution of value or monetization	1960 around, significant increase in the 1990s	Refinement of monetary valuation techniques for ES and MES[1]	Reduction of the intrinsic value of nature to only what can be monetized.
Appropriation	1970 around, significant increase in the 2000s	Clear definition of property rights for ES	Tension between the public good nature of ecosystem services and their privatization, which may lead to a reduction in their provision (Lockie, 2013)

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[1] Monetized Ecosystem Services, or S.E. that have been assigned a price (Silvertown, 2015); in other publications, they are referred to as Markets for Ecosystem Services, such as greenhouse gas (GHG) and sulfur dioxide (SO_2) emissions trading (Bayon, 2004).

Market creation or trade-off	2000s onwards	Institutional markets such as emission trading e PES[2]

Having described the relationship between ES and the economy, and especially highlighting the reasons for their progressive monetization, the initial and fundamental step in this process, which is the attribution of monetary value, will be deepened.

Since the pioneering and influential article by Costanza et al. (1997), the monetary evaluation of ES has been a highly active field of study (Scholtke et al., 2015) and publications related to this area have significantly increased after the early 2000s. There is a heated debate regarding the application of pragmatic criteria to ecological issues, and even the monetary valuation of ES is not exempt from this debate, despite its significant development. The issue of legitimacy, validity, or morality of this type of valuation has been present since the 1997: it states that it is not possible to assign a true value to ES since they are irreplaceable, i.e. necessary and imperative for any type of human well-being. However, it is possible to attribute them a marginal value, which is the value derived from the infinitesimal increase in the good itself. In fact, it is asserted that the evaluation itself (not necessarily monetary) is not a choice that can be deliberated upon because deciding not to consider a value is itself an implicit evaluation (this is reaffirmed in Costanza et al., 2017). Monetary valuation is then defended by emphasizing how it allows for reflecting the actual economic value of ES, thereby achieving various results (Silvis et al., 2013): (i) advocacy for the economic importance of ES, encouraging sustainable development; (ii) more informed, transparent, and fair decision-making processes by institutions; (iii) assessments of the damage incurred by ecosystems, especially in terms of market activities (Howarth, 2002); (iv) sustainable funding through taxes or charges to maintain the desired level of Ecosystem Services.

However, economic valuation is often perceived negatively due to the perceived devaluation caused by monetization itself, as there is a loss of the intrinsic

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[2] Payment for Ecosystem Services is a "voluntary transaction where a well-defined S.E. is 'bought' by a buyer from a service provider [who] ensures its provision" (Engel et al., 2008).

value of nature in the process (Silvertown, 2015; Gómez-Baggethun et al., 2011), and markets based on this valuation, such as Payments for Ecosystem Services (PES), are strongly criticized (McAfee, 2012). Schröter et al. (2014) state that human choices necessarily involve continuous evaluations, including economic considerations, and monetization can complement other ethical, ecological, or non-monetary considerations. Another aspect emphasized by many authors is the need to integrate monetization with the evaluation of other types of value or alternative approaches in order to fully represent the complexity of ecological systems (Howarth, 2002; Baggethun et al., 2015; Kallis et al., 2013; Scholte et al., 2015; Jacobs et al., 2018). Schröter et al. (2014) also highlight that economic valuation does not necessarily imply the creation of markets and that markets themselves are not the only institutional solution based on the value of ES. Furthermore, PES rarely utilize economic valuations and rely more on negotiation logic. Nevertheless, the economic valuation of ES aims to define the Total Economic Value (TEV), which is the aggregation of all the monetary values attributable to an ES (or a set of ES or an ecosystem, which, it is important to remember, is always part of the total value) (Turner et al., 1998). Figure 2.5 provides an illustration of the structure of TEV, which will be further discussed (Turner et al., 1998; Newcome et al., 2005; Silvis et al., 2013).

Firstly, there is a division between use value and non-use value, which implies benefits derived from either direct or indirect interaction with the resource or solely from the knowledge of the presence and maintenance of the ecosystem. Non-use value excludes tangible benefits but can also pertain to ES with a use value. Going in order, use value can be both commercial and non-commercial, and it is derived from consumptive use values (agriculture, water use, hunting, fishing, and gas extraction) and non-consumptive use values (aesthetic, educational, recreational use values), both defined as direct use values. Indirect values are derived from regulating and supporting ES and, in general, all life-supporting values. Non-use values are divided into existence values, which refer to the pleasure of knowing that an ecosystem continues to exist, bequest values, which encompass the pleasure of knowing that an ecosystem will exist for future generations to enjoy, and altruistic values, which entail the pleasure of knowing that other people can currently benefit from an ecosystem. Finally, there are option values, which represent the amount individuals would be willing to spend to maintain an ES for future use, and quasi-option values, which reflect the anticipated benefit of waiting for better information before proceeding with the exploitation and conversion of an ES. Thus, the TEV is a tool aimed at understanding all potential values of ES and guiding their evaluation.

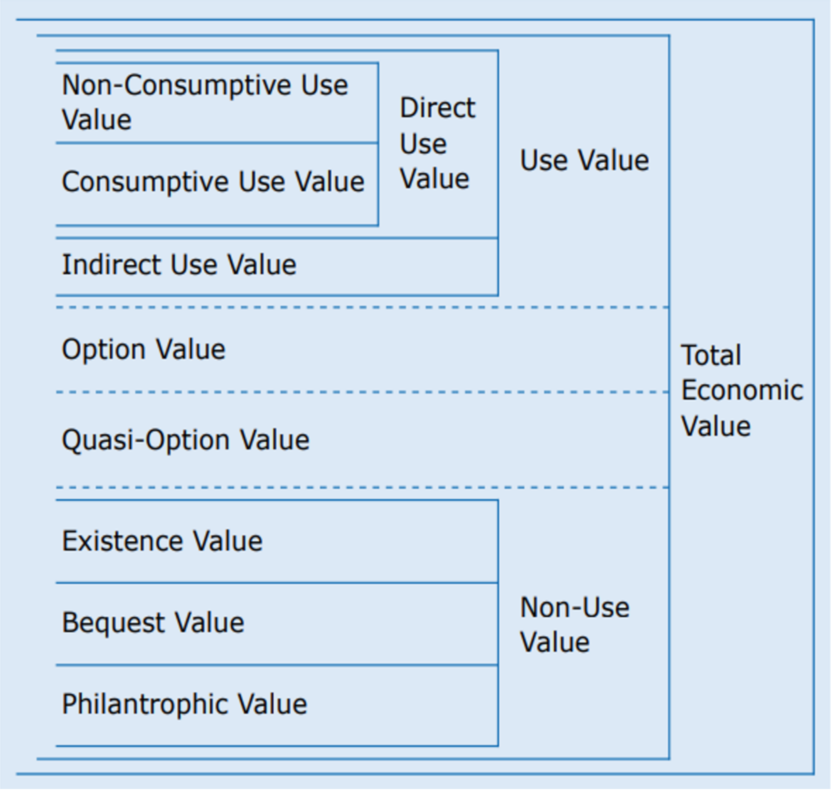

Figure 2.5: Structure of Total Economic Value (TEV) [adapted from Turner et al., 1998].

Overall, the evaluation of ES is a complex task closely tied to economic knowledge, and for a detailed discussion on the subject, reference is made to other publications (Costanza et al., 1997; Bateman et al., 2002; Hanley & Barbier, 2009; Braat & de Groot, 2012). In general, it can be stated that there is no optimal solution in the choice of evaluation criteria, and it is necessary to integrate multiple methods or make choices based on the specific issues at hand (Silvis et al., 2013). It is also important to consider the problems arising from ill-defined property rights, particularly in relation to public goods, and the economic considerations implicitly embedded within them (Duraiappah, 2006).

Chapter 3

Part I – ES in the metropolitan area of Turin

The work described in this chapter is partially derived from [Busca et al. 2021] and from [Busca et al., 2022].

3.1 Geographical and climatic context

The city covers an area of 130 square kilometers, with a population of about 850,000 inhabitants and an average altitude of 239 meters. The average annual precipitation is 927 millimeters, the average temperature is 12°C (Arpa Piemonte, 2018), according to Köppen and Geiger, its climate is classified as Cfa, humid subtropical climate. The Turin context offers a fascinating natural environment, surrounded by the Alps and crossed by four rivers: the Po, the Dora Riparia, the Stura, and the Sangone. Turin boasts a remarkable environmental heritage and stands out for its high standard of green space per inhabitant. To optimize the management of urban green spaces, classifications have been implemented based on green typologies, allowing for various forms of maintenance and administration. Through a resolution by the municipal council dated March 27, 2007 (Municipality of Turin, website), additional definitions of urban green typologies were established to promote more rational management and optimal city development, encouraging greater community involvement and placing value on grand tree-lined avenues, district-specific gardens, and neighborhood green areas The city also features more than 140,000 trees along its streets, within parks and gardens and additional 230,000 trees within hillside woods. Turin's green heritage is extensive and diverse, characterized by complex, precious, and delicate richness. Notable features include historical gardens such as the Royal Gardens and Valentino Park, hillside parks like Maddalena Park, Europa Park, Leopardi Park, and Nobile Park, as well as numerous centuries-old trees. A distinctive characteristic of green spaces in Turin is their carefully planned and organized layout. Starting from the historical gardens in the city center, the green system has expanded towards the peripheral areas, establishing connections through tree-lined avenues. Over the past decades, urban green spaces have increased from approximately 4 million to 20.8 million square meters, and when considering private green areas, the total available space amounts to 32,929,419 square meters, corresponding to 38 square meters per inhabitant (late 2020).

The meteorological data required by i-Tree Eco include pollutant concentrations (CO, NO_2, O_3, SO_2, PM2.5 and PM10), photosynthetically active radiation, rainfall measurements, and temperature for a specific year with a hourly time resolution. The meteorological data is based on the Torino-Bric della Croce weather station (45°02’N 07°44’E) for 2015, which was selected due to its availability and completeness of data in relation to the program's requirements. For the economic estimation related to ES (Ecosystem Services), the software requires a series of input data: the evaluation conducted on the city of Turin involved gathering data on unit prices of benefits contextualized to the Italian context or, where not available, to the European context, by inserting the following benefit unit prices:

(i) 1.902 €/m^3 for avoided surface runoff (default value, according to U.S. Forest Service's Community Tree Guide Series);

(ii) for pollution removal, 1,095 €/metric ton (CO), 34,620 €/metric ton (O_3), 5,171 €/metric ton (NO_2), 1,884 €/metric ton (SO_2), 1,201,677 €/metric ton (PM2.5); calculations were based on European average externality values (van Essen et al., 2011) or Ben MAP regression equations (Nowak et al., 2014) that included user-defined population calculations: for this reason, the values have been modified for the “Le Vallere” Park, according to population density of the city in which the green area is inserted (1,180 inhabitants per square kilometer for Moncalieri in 2020 while Turin 6,480 inhabitants per square kilometer for Turin in 2021);

(iii) no monetary value has been associated with oxygen production since tree benefit is relatively insignificant because of the large and relatively stable amount of oxygen in the atmosphere and extensive production by aquatic systems;

(iv) for carbon storage and gross carbon sequestration, the economic value has been modified according to the market price at the time of the individual case study, this has had a significant impact on the final output of benefit as the unit price of carbon has undergone a significant increase over the last 3 years, following important socio-political events. In particular: for “Via Revello” Park 83.01 €/metric ton updated at November 2019 (Sub-chapter 3.2); for “Le Vallere” Park 91.92 €/metric ton updated at October 2020 (Sub-chapter 3.3); for “Colonnetti” Park 219.60 €/metric ton updated at November 2021 (Sub-chapter 3.4) (European Union Emissions Trading System, EU ETS).

This project contributes to achieving the Sustainable Development Goals (SDGs) outlined in Agenda 2030 by the United Nations (UN), specifically SDG 3, which promotes good health and well-being, and SDG 11, which promotes sustainable cities and communities by protecting and restoring ecosystems.

3.2 “Via Revello” Park: a comparison of different land uses

3.2.1 Study area, changes in land cover/use and input data

The study focuses on urban areas and ES related to land use in urban areas or water use (i.e.. mitigation of damages caused by flooding events and containment of pollutant concentrations in surface, subsurface and groundwater flows). The aim of the study is to quantify some ES produced by a small urban park, “Via Revello” Park in Turin which, in the last years, shifted from a configuration at the time of the analysis (present scenario T_1, 2019) where the area was used as a park and it was mainly covered with grass, with the presence of 13 tree species to a configuration in which it was expected to change in view of future improvement interventions (future scenario T_2, 2022) with intensification of tree species and the introduction of 16 shrub species.

The park is located at the intersection of Via Revello and Via Fréjus, in the Cenisia neighborhood of Turin. At the time of the analysis, it preseneds as a small green area of approximately 5,100 square meters, with 13 trees including 6 *Tilia x europaea* (Common Lime), 2 *Platanus x acerifolia* (London planetree), 2 *Populus* (Cottonwood), 1 *Celtis australis* (European hackberry), 1 *Prunus cerasifera* (Cherry plum), and 1 *Robinia pseudoacacia* (Black locust). Most of the surface was covered by a grassy turf, except for a short gravel path around which a dozen benches were arranged. Previously, the area was occupied by a building, the headquarters of the Gabrio social center, which was later demolished as part of the redevelopment that led to the initial opening of the park in July 2018.

Figure 3.1: Some photos from the site inspection (May 2019).

Trees and land data were characterized through a Complete Inventory through field assessments conducted in May 2019 together with Dr. Francesca Vigliocco (Figure 3.1) and, in the case of species, by consulting the Geoportal of the Municipality of Turin, combined with on-site identification with digital support. Prices related to the input parameters mentioned have been provided previously. Table 3.1 presents a detailed list of the entered data for i-Tree Eco.

Table 3.1: i-Tree's input data for "Via Revello" Park.

Parameters	Eco
Project configuration	Complete inventory
Number of trees sampled in T_1	13
Number of trees in T_2	25
Weather data	Bric della Croce (2015)
Air quality data	Bric della Croce (2015)
LAI	1.25%

3.2.2 Collaboration with Turin's Municipality and citizen co-planning

Prior to and following its opening, a design phase was undertaken with significant input from the local population in the neighborhood. Questionnaires were initially provided to participants to assess the park: some of the previously described socio-cultural ecosystem services can be recognized, such as attractiveness and feelings of safety and tranquility. There are also fields related to the conditions that make the park accessible to the public, such as the ability to easily identify and access it. Attention is also given to social inclusion provided by the green space, expressed in various aspects. Lastly, there are two open-ended questions regarding the appreciation and, therefore, evaluation of the park itself and the area in which it is located, highlighting the interaction between them that necessarily occurs in the urban context. In this perspective, the questionnaire represented a tool to measure the socio-cultural value of the park and, partly, the ecological value and it was useful in preparing for a subsequent design phase. Combined with the discussed study that follows, it provides an example of integrating different types of values with the common aim of informing the choices of the population and decision-making bodies.

Various workshops were then held, in which groups of citizens collaborated in defining the project for the park's future development. Special importance was given to the functions performed by the park. Those primarily considered were once again related to cultural services, such as the presence of spaces for socializing, relaxation, play, and sports, as well as natural experiences such as the presence of vegetable gardens and gardening areas (referred to as social green in the project) and opportunities for artistic expression or appreciation of existing art. Furthermore, the choice to focus on the safety and cleanliness of the park provides an example of the challenges in terms of EDS that a small park may present. Once the objectives were defined, targeted groups were formed specifically for the area's design by spatially identifying these functions, outlining various projects subsequently presented and evaluated by all participants during multiple meetings. The result of this participatory process, including the initial phase, took place in June and July 2018. It resulted in a preliminary project submitted in September, which was then approved, and its implementation began in June 2020. Figure 3.2 shows two images of the park: one from 2019, representing scenario T_1, the other about the above-mentioned project. Notable differences with the current state include the presence of more trees while still maintaining open areas to promote visitor recreation, as well as dedicated social areas such as a bookcrossing zone, a walking path to encourage socialization, and a mural-covered wall. The construction of additional infrastructure, from benches to a fountain and irrigation system, is also evident. Specifically, in i-Tree Eco T_1 has been supposed to be the future configuration in 2050 (considering the tree population to be fully mature) and it should be characterized by a total number of 25 trees, as follows: 5 *Tilia x europaea* (Common lime), 3 *Aesculus x carnea* (Red horsechestnut), 3 *Gleditsia triacanthos* (Honeylocust), 3 *Platanus x acerifolia* (London planetree), 3 *Tilia platyphyllos* (Bigleaf linden), 2 *Populus* (Cottonwood), 2 *Salix babylonica* (Babylon weeping willow), 1 *Celtis australis* (European hackberry), 1 *Parrotia persica* (Persian ironwood), 1 *Prunus cerasifera* (Cherryplum), 1 *Robinia pseudoacacia* (Black locust). One of the proposed functionalities is to predict the transformations of the area of interest over a certain period (a function called Forecast). In the case under consideration, it was not possible to directly utilize this feature because the species of interest in the future scenario could not be included in the program. Nevertheless, with access to the subsequent development project, it was possible to proceed by modifying the inventory to adhere as closely as possible to the anticipated conditions. Specifically, the number of input data was greatly reduced due to the obvious impossibility of collecting field data, while retaining those of T_1. The necessary plants were added, while the existing ones were updated by considering an increase in DBH (Diameter at Breast Height) up to the size of an adult plant, based on measurements from a city census. This increase was completed at the age of 30 years for the plant, and the health of the canopy was partially reduced. The resulting estimate, naturally, introduced additional uncertainties beyond those present in the UFORE model, but it still provides valuable information in describing the effects of the interventions undertaken.

Figure 3.2: Transformative process: (A) Satellite image of T_1, (B) configuration design of T_2.

3.2.3 Results and comparison of scenarios

The quantification was carried out using the i-Tree suite and aimed primarily to provide the managing entity with a series of quantifiable data that can be directly used during administrative-management decision-making processes and territorial planning. In addition, the application led to interesting considerations related more generally to the management of green infrastructure in urban areas, linked to the concept of smart cities and to actions for climate change mitigation and adaptation.

Table 3.2: Current structure of urban greenery of “Via Revello” Park (T_1).

Species	**Number of trees**	**Leaf Area [m^2]**	**Leaf Biomass [kg]**
Tilia x europaea	6	4,112	211
Platanus x acerifolia	2	1,380	70
Populus	2	1,329	86
Celtis australis	1	1,093	71
Prunus cerasifera	1	805	54
Robinia pseudoacacia	1	397	23
Study area	**13**	**8,935**	**515**

At the scale of urban greenery structure, some considerations can be deduced from the data in Table 3.2 for T_1 and in Table 3.3 for T_2. The total leaf area went from almost 9,000 square meters to almost 14,000 square meters, with a slight decrease in the value associated with *Tilia x europaea* in T_2, while the total leaf biomass recorded an increase of around 65%. In general, the new configuration provides for a composition of trees with contributions of leaf area and biomass more evenly distributed among the different species than at present, in which almost 50% of the total values come from the dominant species (*Tilia x europaea).* This condition certainly ensures greater resilience of the park to possible epidemics and/or attacks by parasites on specific species.

Table 3.3: Future structure of urban greenery of “Via Revello” Park (T_2).

Species	**Number of trees**	**Leaf Area [m^2]**	**Leaf Biomass [kg]**
Tilia x europaea	5	2,700	126
Aesculus x carnea	3	2,320	170
Gleditsia triacanthos	3	550	58
Platanus x acerifolia	3	1,780	82
Tilia platyphyllos	3	1,000	59
Populus	2	1,930	131
Salix babylonica	2	1,250	79
Celtis australis	1	500	30
Parrotia persica	1	1,040	78
Prunus cerasifera	1	360	22
Robinia pseudoacacia	1	300	16
Study area	**25**	**13,730**	**849**

i-Tree Eco was used between the current state of the park at the time of the study (T_1) and the configuration currently designed (T_2), which includes an increase in the number of plant species and a modification of soil permeability, with the aim of reducing runoff from meteorological events and improving the other beneficial effects. The outputs produced by the program have been compared in Figure 3.3. Firstly, it shows a doubling of the amounts of evaporation, transpiration and interception (resulting in avoided water runoff) with the new park arrangement.

Furthermore, the value of stored carbon for T_2 triples compared to T_1, while the removal of pollutants is almost twice as high. The production of O_2 also doubles, from a value of 1.72 to 3.42 tons per year. In general, the forecast, with good approximation, shows an almost doubling of all magnitudes related to the park from its current state (2019) to 30 years. This is certainly plausible given the doubling of the species and trees. However, the provided evaluation offers an estimate based on actual data and models, which, although approximate, as discussed, still provides evidence of the value represented by the park and justifies the investments made.

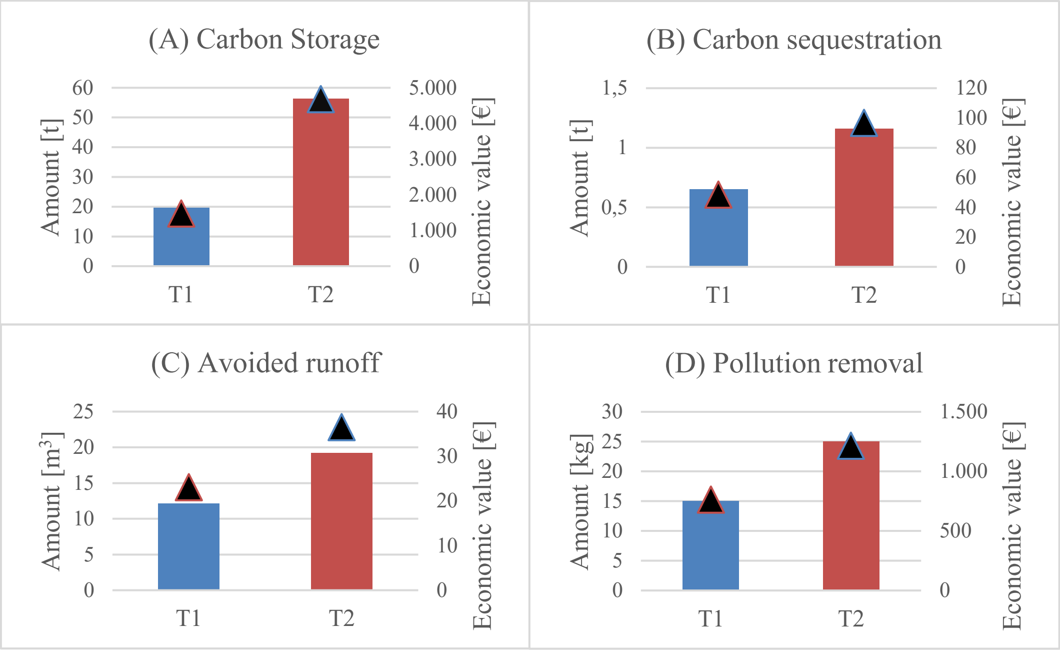

Figure 3.3: Comparison between T_1 (blue) and T_2 (orange) for "Via Revello" Park: (A) carbon storage; (B) annual gross carbon sequestration; (C) annual avoided surface runoff; (D) annual air pollution removal. Bars indicates the ES amounts while points indicates the economic values.

The leaf area, considering a certain physiological decrease due to the age of the plants, is projected to experience a significant increase according to the model, with all the positive aesthetic and non-aesthetic consequences that follow. The carbon sequestration, avoided runoff (which is particularly interesting as it is considered in the project itself), and removal of pollutants are all ES for which a clear increase is expected, bringing the park's incremental annual value to over 1,300 euros in T_2 (against the current value of 850 euros) while about 4,500 euros is the estimation for the carbon stored in the future configuration of the park. As already stated, the value of stored carbon is particularly significant as it more than triples, thanks to both the increase in trees and their growth. Lastly, the program provides a potential issue that may arise from the park, namely the nearly tripled production of VOCs: while the forecast demonstrates the benefits that the community can derive, it must not overlook the EDS that accompany the evolution of the urban park. From the results obtained, it can be deduced that the future intervention in the green area will have a beneficial effect both in economic and environmental terms, justifying its implementation.

The park's environmental significance is emphasized, highlighting the role of increasing permeable surfaces in cities and the importance of an accurate and transversal choice of the arboreal and vegetative configuration. This serves as an excellent example of the function of concepts related to the realm of socio-ecological services in the practice of urban green area design, and how they are useful in facilitating and guiding public participation. This type of knowledge is considered essential in the appreciation and recognition of green areas as necessary for urban life, and consequently, in the pursuit of sustainability for both urban and global communities. It is also worth noting the extent of decision-making power offered to the community, which can be seen in the overall costs of the planned interventions: in addition to an initial expenditure of approximately 90 thousand euros for the initial arrangement, the total costs amount to more than 200 thousand euros. This study is particularly interesting as i-Tree assigns an economic value as tot the evaluated services, thus complementing the participatory design experience. The collaboration with a public entity is also useful in demonstrating the informative capacity of such a study, especially in highlighting that even a small green area can have a role in contributing to the environmental embellishment and urban sustainability. The awareness that such an analysis can provide regarding the fundamental ES providers, such as urban parks and gardens, is considered significant from an informative and educational standpoint. Giving an estimation of the magnitude of the main ES provided by a small park of 5,100 square meters, it can be imagined the extent of those provided by the over 23 million square meters of green areas distributed in the Turin metropolitan area, considering that approximately 140,000 trees are present in the urban area Turin. Along this path, the research conducted has experimented with different green spaces in the metropolitan area, with different spatial scales and expanding the temporal perspective by winking at the effects of climate change (through the introduction of projections of future climate data in the city of Turin) and/or the identification of scenarios considered probable or better than current conditions.

3.3 “Le Vallere” Park: dealing with different future perspectives and climate change

3.3.1 Study area, input data and site inspection

This part of the work analyzes and quantifies the ES offered by an urban greenspace in Turin (Italy), comparing the present scenario of the park with two possible future scenarios defined by a climate model. The park is situated in Moncalieri, within the Metropolitan City of Turin (Northwestern Italy). The city spans across an area of 4,753 hectares and is home to 57,528 residents. Its location is 262 meters above sea level and it experiences a temperate and warm climate. Moncalieri receives an annual precipitation range of 750-1000 millimeters, distributed over 75 days, with the lowest levels in winter and highest in spring and autumn. The climate is classified as Humid Subtropical (Cfa) according to Köppen and Geiger.

The selected location is “Le Vallere” park, a vast semi-urban green area located at the intersection of Po River and Sangone Torrent, covering an area of 1.3 square kilometers. “Le Vallere” stems from the embankments constructed by the French in 1541 during the first French occupation of Piedmont. In the 1960s, the region was partially saved from urbanization, which resulted in the construction of the main street “Corso Trieste” and a residential neighborhood towards its west. The park came under the ownership of Piedmont Region and the management institution, ex “Ente di Gestione delle Aree Protette del Po Torinese,” established its headquarters during the 1990s. On 29th June 2009, Piedmont Region enacted a regional law that recognizes the park as a Nature Reserve, now open to the public. The regional law n.11/2019 established all protected areas within the Po river, from Casalgrasso to the Lombardy border, as a single preservation area: the “Piedmontese Po Natural Park” (“Parco Naturale del Po Piemontese” (Figure 3.4).

The land use design has been transformed from purely agricultural to a combination of intensive forage cultivation and clearings with groves. The coexistence of agricultural scenery and a public park, along with environmental and landscape restoration measures taken along the Po River's banks, has helped to create a section of the ecological network in the metropolitan area of Turin. The coexistence of an agricultural landscape and a public park, along with environmental and landscape restoration interventions on the banks of the Po River, has aided in re-establishing a crucial stretch of the ecological network of the Metropolitan Area of Turin. It highlights the area's significance in conserving biodiversity and preserving ecological functionality.

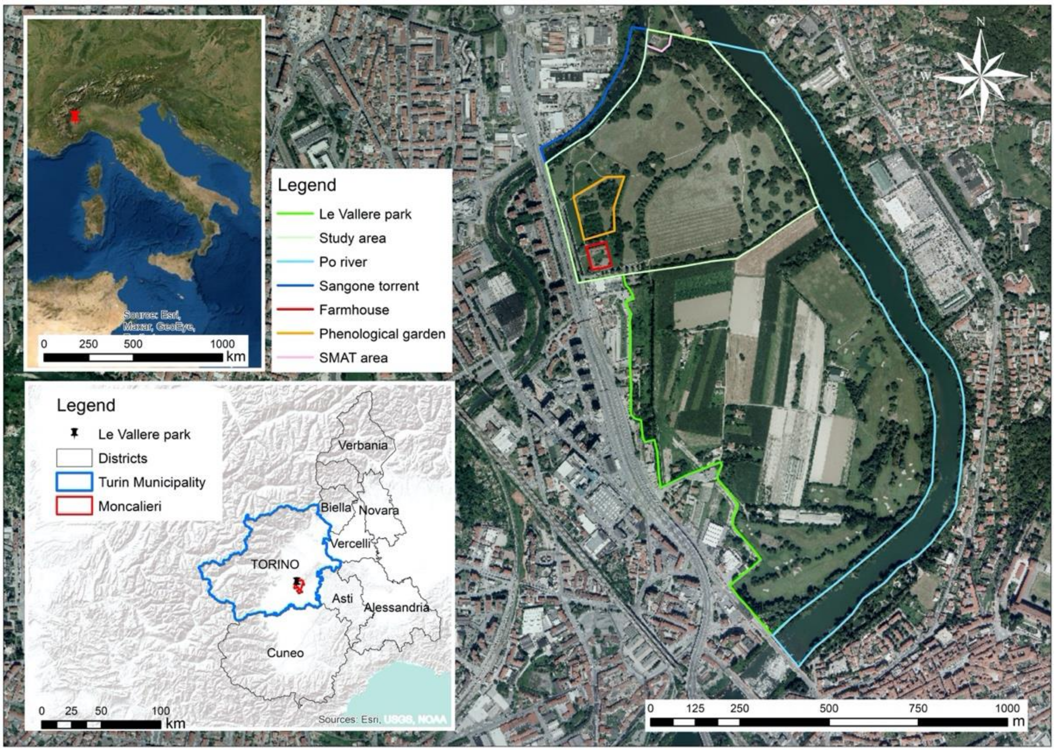

Figure 3.4: Geographical framework of case study “Le Vallere” park [Busca et al., 2021].

This study has focused on an area of the park of 340 thousand square meters. This section of the park encompasses recreational facilities, such as a children's playground, sports areas, picnic areas, two dog plots, a botanical-phenological garden, and various paths for hiking, mountain biking, and horse riding. The Carlo Allioni botanical-phenological garden was established between 2000 and 2002, and it studies species typical of continental climate regions to evaluate the impact of thermal anomalies, parasites, air, and soil pollution. The park also features a building managed by SMAT S.p.A., which is responsible for water management in the metropolitan city of Turin.

Collaborating with these institutions has provided up-to-date technical data on the park. A 4-days measurement campaign was conducted in July 2020 together with Dr. Ilaria Tinivella to collect datasets on the tree population for use in Eco and Hydro tools, such as species, tree diameters, the health and crown condition, land use and cover. The study area was divided into 192 circular plots distributed in a fixed grid pattern, with each plot covering one-twentieth of a hectare and a diameter of 12.62 meters. A single tree was analyzed per plot, as most of the plants in each plot had similar dimensional characteristics. In total, 102 trees were analyzed. Data were gathered through a "Plot-based sample inventory" during a 5-day inspection conducted in July 2020, together with Dr. Ilaria Tinivella (Figure 3.5).

Figure 3.5: Some photos from the site inspection (July 2020).

While for Eco simulations the selected station of “Torino-Brico della Croce” was maintained, for Hydro simulation climate data were customized by selecting a weather station representative of the entire study area: the "Torino Vallere" weather station (45°01’01.13’’N 07°40’26.03’’E) located within the park,managed by ARPA Piemonte, and data surveyed by the "Observatory of Carlo Alberto College, Italian Meteorological Society" in Moncalieri were used. The total annual precipitation recorded at this station was 915 millimeters, specifically in 2019. Eco simulation used all weather and air quality data from 2015, while Hydro simulation used data from 2019. Table 3.4 presents the input data required for Eco and Hydro simulation.

Table 3.4: i-Tree Eco input data for case study “Le Vallere” park.

Information	**Eco**
Project configuration	Plot – based sample inventory, unstratified sample
n. of plots sampled	192 (one tree for each plot)
n. of trees sampled	102
Weather data	Bric della Croce (2015)
Air quality data	Bric della Croce (2015)
LAI	1.74%
Benefit prices for air pollutants	1,100 €/t (CO); 3,490 €/t (O_3); 520 €/t (NO_2), 190 €/t (SO_2); 121,150 €/t (PM2.5)

In order to carry out a project using i-Tree Hydro, the initial step is to gather input data: it necessitates (i) land cover data for each category considered, (ii) hydrological parameters regarding the study area, and (iii) pollutant concentration coefficients. The project necessitates determining the percentages of land cover in relation to the total area of the project using the i-Tree Canopy online application, whose model has been explained in Sub-chapter 2.4. The park boundary shapefile was imported using ArcGIS.

The land cover distribution was determined by identifying 1,300 points on the park boundary and categorizing each of them according to the type of land cover (refer to Table 3.5) with a standard error lower than 3%. The values presented in Table 3.5 show that permeable cover such as herbaceous and tree cover occupy the majority of the area (approximately 90%) compared to other types of soil, while impervious cover accounts for less than 6% of the total area and was detected in only 70 points, including both Impervious Ground and Tree-Impervious categories. These percentages were then multiplied by the total park area to determine the square meters of coverage for each category.

Table 3.5: Land Cover distribution of the park (i-Tree Canopy).

Abbreviation	**Cover Class**	**Area ± SE (m^2)**	**% ± SE**
H	Grass/Herbaceous	196,200±4,700	57.15±1.37
IC	Impervious Cover	12,900±1,800	3.77±0.53
TI	Tree – Impervious	5,500±1,200	1.62±0.35
BS	Bare Soil	12,100±1,800	3.54±0.51
TP	Tree – Pervious	116,500±4,500	33.92±1.31
W	Water	0±0	0.00±0.00
Total		343,200	100.00

Besides the land cover percentages determined through i-Tree Canopy, the *DCIA* value was computed using the *IA* as 3.77%. Before performing the *LAI* calculation (1.74%), the leaf area was obtained through i-Tree Eco, equating to 213,300 square meters.

Then, the hydrological parameters, as listed in Table 3.6, were manually calibrated according to hydrogeological principles relevant to the project area and the available meteorological data. While default values suggested by the program were kept for most parameters, the *Annual Average Flow of Project Area* was manually modified. This value represents the average annual amount of water that flows through the examined territory and was used to calculate various terms pertaining to underground water flows, as well as soil moisture (Wang et al., 2006).

Table 3.6: Hydrological parameters (i-Tree Hydro).

Hydrological Parameter	**UM**	**Value**
Annual Average Flow of Project Area	m^3/s	9.986×10^{-3}
Soil Type	-	Sandy Loam
Wetting Front Suction	m	0.11
Effective Porosity	-	0.412
Surface Hydraulic Conductivity	cm/h	1.090
Max Depth of Water in Upper Soil Zone	m	0.05
Initial Soil Saturation	%	50
Leaf Transition Period	days	28
Leaf On Day	1–365	127
Leaf Off Day	1–365	280
Tree Bark Area Index	-	1.7
Shrub Bark Area Index	-	0.5
Leaf Storage	mm	0.2
Pervious Depression Storage	mm	1.0
Impervious Depression Storage	mm	2.5
Scale Parameter of Power Function	-	2
Scale Parameter of Soil Transmissivity	-	0.023
Transmissivity at Saturation	m^2/h	0.13

Unsaturated Zone Time Delay	h	10
Time Constant for Pervious Area and DCIA flow	h	40.0
Time Constant for Subsurface Flow	h	120.0
Soil Macropore Percentage	%	0.000001
Watershed area where rainfall rate can exceed infiltration rate	%	100

The initial value, based on rainfall intensity, was recalculated using the average value (1.05×10^{-4} meter per hour) calculated from hourly rainfall data during 2019. The values for *Wetting Front Suction* and *Effective Porosity* are based on the physical attributes of the soil, with the chosen *Soil Type* being sandy loam.

Table 3.7: Pollutant coefficients (i-Tree Hydro).

Pollutant	**Coefficient**
	mg/l
Total Suspended Solids (TSS)	216.64
Biochemical Oxygen Demand (BOD)	30.00
Chemical Oxygen Demand (COD)	127.93
Total Phosphorus (tP)	0.315
Soluble Phosphorus (sP)	0.129
Total Kjeldhal Nitrogen (TKN)	2.30
Nitrite and Nitrate (NO_2, NO_3)	0.658
Copper (Cu)	0.045
Lead (Pb)	0.058
Zinc (Zn)	0.472

Hydro requires the final set of parameters which focuses on pollutant coefficients to determine the quality of surface water. These coefficients, reported in Table 3.7, are crucial in estimating the annual load of each of the 10 standard water quality pollutants transported by runoff water into the urban drainage network. The coefficient values were obtained from bibliographic research, which customized the original default values provided by the program (Smullen et al., 1999) to suit the Italian (Ciaponi et al., 2002; Milano et al., 2002 and European (Ellis, 1986) context. The estimated annual surface runoff by the program is multiplied by the relative coefficient value to determine the pollutant load. Biochemical Oxygen Demand (*BOD*) and Chemical Oxygen Demand (*COD*) are commonly used water parameters to measure the organic content in polluted water. Phosphorus is measured in two ways; chemically active form, *SP*, which is directly absorbed by trees as well phosphorus in plant fragments suspended in water, *tP*. Total Kjeldahl Nitrogen (*TKN*) is determined through the sum of organic nitrogen and nitrogen in ammonia/ammonium (Domini et al., 2009) present in the water outflow.

3.3.2 Results for present scenario

i-Tree Eco. The initial output that i-Tree Eco provides for "Le Vallere" park evaluates the composition and structure of the urban forest based on field data. The evaluation reveals that the park has 487 (±29) trees which belong to 25 different species, covering roughly 31% of the park's area. The prevalent species include *Tilia x europaea* (67), *Salix alba* (62), *Tilia cordata* (43) and *Populus nigra* (38), and their distribution shows that the diameter measurements of class 45.7-61 centimeters are 50% for *Tilia x europaea* and 66.7% for *Tilia cordata*, the class 30.5-45.7 centimeters consists of 53.8% *Salix alba*, and the class 106.7-121.9 centimeters is occupied by 37.5% *Populus nigra* trees.

Taking the above results into account, i-Tree Eco estimates the leaf area and leaf biomass for each species and calculates the carbon storage contribution and gross carbon sequestration of each species accordingly. The total **carbon storage** estimate is 437 metric tons with a leaf biomass of 14 kilograms and a monetary value of approximately 40 thousand euros. Furthermore, the gross **carbon**

sequestration is around 13 metric tons in comparison to a leaf area of 2.13 square kilometers, corresponding economically to about 1.2 thousand euros. The monetary value is based on the price stated in Sub-chapter 3.1 for "Le Vallere" Park.

Populus nigra species proves to be the most efficient due to its large diameter structure and good crown health. *Tilia* and *Salix* genera also contribute to the process of carbon fixation in plant tissues and the elimination of carbon dioxide from the atmosphere through the chlorophyll photosynthesis. Even though they make up a larger number of individuals, approximately double that of *Populus*, the *Tilia* and *Salix* genera have less impact on carbon storage and carbon sequestration calculation.

An additional interesting outcome generated by i-Tree Eco is the calculation of the **atmospheric pollutants removed** annually by tree populations, resulting in an improvement in the air quality. Table 3.8 shows that the green area's removal of Ozone (O_3), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) surpassed the removal of particulate matter (PM2.5). The tool also highlights the non-linear correlation between the quantity of pollutants removed and their financial value. This inconsistency is linked to the potential impact that each pollutant may have on the environment and human health, which is taken into account by i-Tree Eco.

To accurately quantify ES provided by "Le Vallere" park, it is imperative to consider the biogenic volatile organic compounds (BVOCs) emissions produced by plants. These compounds significantly affect atmospheric chemistry and climate, especially the emissions of monoterpene and isoprene, which may lead to atmospheric pollution through the formation of O_3, CO and other tropospheric aerosols. Therefore, it was necessary to incorporate these compounds into the overall assessment of pollution removal provided by the study area. The study indicates that the removal of pollutants heavily relies on the trees' intrinsic characteristics, their size, and their vegetative cycle, not solely on their numerical quantity. The economic value attributed to air pollution removal is 9.5 thousand euros, derived from a quantity of pollutants equal to 437 kilograms per year.

Nevertheless, the Eco tool provides other hydrological outputs, including evaporation, evapotranspiration, flows interception by vegetated covers, and avoided runoff, which have not been analyzed as they were assessed using Hydro Tool based on more robust hydrological models with greater accuracy in runoff calculations and plant-specific hydrological processes.

Table 3.8: Air quality removal in “Le Vallere” Park (i-Tree Eco).

	NO_2	O_3	PM2.5	SO_2
Removed quantity (kg/year)	89.3	305.6	8.9	32.2

i-Tree Hydro. In this section, the main findings regarding the water-related ES of the park are presented. The analysis begins with the examination of the current hydrological state of the region, referred to as the Present Scenario (PS), which is then contrasted with two possible Future Scenarios (FS.1, FS.2). In these scenarios, modifications in temperature and precipitation are based on the COSMO-CLM climate model, and a planting program for new trees is implemented at specified intervals. Using i-Tree, changes in stream flow and water quality are measured and displayed, both hourly and cumulatively. Present Scenario (PS) involves the 2019 input data. Hydro, a particular hydrological model for vegetation, is employed in the “Le Vallere” park project to analyze the overall influence of flora on water quantity and quality in the area. This study allows for an assessment of how land use can impact hydrological response, leading to better resource management and pollution control in the urban context. Results are organized into categories of water quality, water quantity, and comprehensive assessments of vegetation and substrate hydrology, referred to as advanced outputs.

In terms of **Water Quantity** calculated the Total Flow and its distribution into: (i) Pervious Flow, which is runoff on permeable soil caused by rainfall intensity surpassing the soil's filtration rate or when the soil is fully saturated; (ii) Impervious Flow, which originates when rain exceeds the maximum level of containment on impermeable surfaces; and (iii) Base Flow, which results from soil porosity filtration dependent on soil transmissivity, average slope, and water content when not saturated. According to Table 3.9, almost 99% of the runoff generated is permeable flow, resulting from excess saturation and infiltration due to the specific area and land cover distribution. Only slightly over 1,500 cubic meters per year are classified as impermeable runoff, associated with small portions of surface used for parking or built-up areas. Furthermore, the quantity of Base Flow infiltrating into the aquifer is less than 1,000 cubic meters, due to the characteristic slow flow response.

Table 3.9: Water Quantity outputs for PS, FS.1 and FS.2 (see Sub-sub-chapter 3.3.3), where Δx terms, for each FS.x, highlight differences compared with PS (i-Tree Hydro).

		PS	**FS.1**		**FS.2**	
	UM	**Yearly Amount**	**Yearly Amount**	**Δ1**	**Yearly Amount**	**Δ2**
Rainfall	mm	914.50	900.00	-14.50	774.00	-140.50
Total flow	m^3/yr	217,763.21	208,457.21	-9306.00	183,280.91	-34,482.30
Base flow	m^3/yr	852.46	852.46	0.00	852.46	0.00
Pervious runoff	m^3/yr	215,393.35	206,630.09	-8763.26	181,145.98	-34,241.84
Impervious runoff	m^3/yr	1517.40	974.65	-542.75	1282.47	+234.93

The **Water Quality** of surface runoff of the park was assessed (Table 3.10) by calculating the 10 characteristic pollutant loads, with respective coefficients (Table 3.7). These indicators provide a reliable estimate of the water pollution state. It should be highlighted that TSS, BOD and COD are prevalent, with values at least two orders of magnitude greater than the secondary pollutants. These results will be revisited and compared to the water pollution state of FS.1 and FS.2.

Table 3.10: Water quality outputs (i-Tree Hydro).

Scenario	**Water pollutants [kg/year]**									
	TSS	**BOD**	**COD**	**tP**	**sP**	**TKN**	**$NO_2 + NO_3$**	**Cu**	**Pb**	**Zn**
PS	47,176.22	6532.90	27,858.45	68.60	28.09	500.86	143.29	9.80	12.63	102.78
FS.1	42,902.16	6253.72	26,667.93	59.09	24.20	431.51	123.45	8.44	10.88	88.55
FS.2	39,705.98	5498.43	23,447.13	57.74	23.64	421.55	120.60	8.25	10.63	86.51

As i-Tree Hydro is a hydrological model specifically designed for vegetation, it has an advanced output section that focuses on the hydrology of the vegetation and subsurface, operating on a tree-scale water balance. **Vegetation Hydrology** encompasses all the processes that prevent the formation of surface runoff at the onset of the meteoric event, including interception by leaf cover (*Interception by vegetation*) and accumulation by leaves and barks (*Storage on vegetation surface*), evaporation from the leaf apparatus of the tree (*Evaporation from vegetation*), and throughfall of water onto the ground once the canopy's maximum storage capacity has been reached (*Throughfall from Vegetation*).

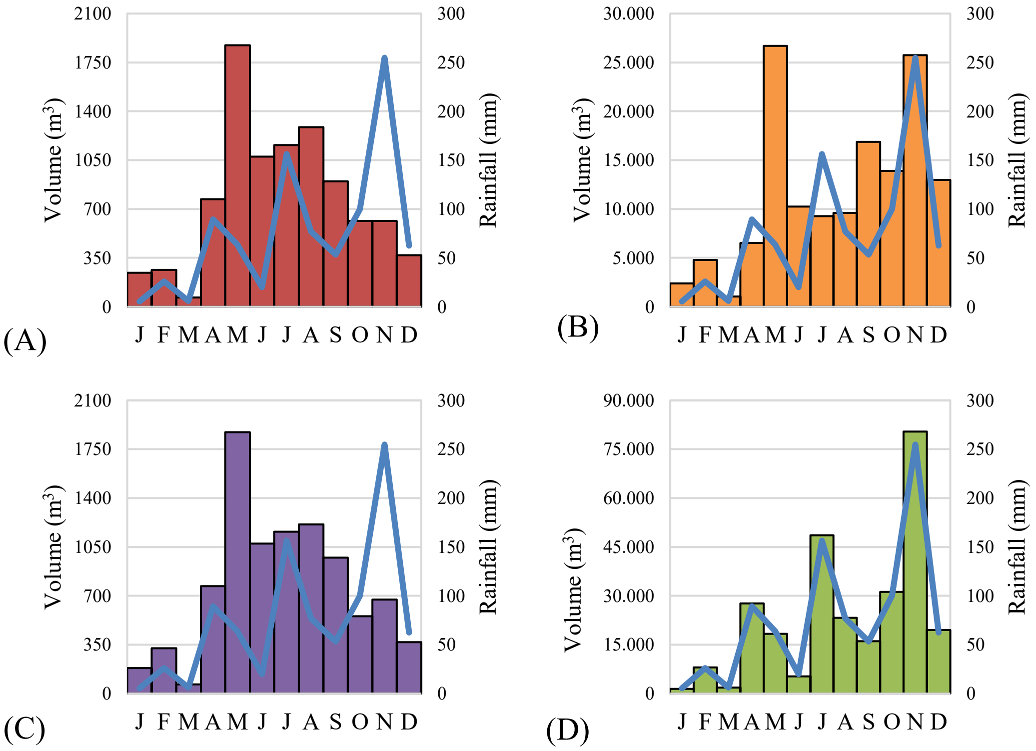

Figure 3.6: Trend of Hydrological components (bar charts) and cumulative rainfall on monthly basis (line chart) for PS: (A) Interception by vegetation; (B) Evaporation from vegetation; (C) Storage on vegetation surface; (D) Throughfall from vegetation [adapted from Busca & Revelli, 2022].

Figure 3.6 displays the monthly trend of these components (in a bar chart), relative to the accumulated monthly rainfall (in a line chart) for the year 2019 (PS). The impact of the monthly distribution of rainfall was most noticeable on two elements (Figure 3.6-C, and Figure 3.6-D). There appeared to be no consistent correlation with the aspects of Figure a and Figure 3.6-B, particularly during fall months near October and November. The intercepted water volumes were evidently smaller in the fall months of October and November (approximately 600 cubic meters) and December (about 350 cubic meters) compared to the spring and summer months, despite greater precipitation (with a peak in November exceeding 250 millimeters). This phenomenon is linked to seasonal characteristics of trees, where leaves, except for evergreen plants, act as the primary accumulator of intercepted rain. The monthly trend in Figure 3.6-B can be explained by the relation between the evaporative process and climatic conditions of the region (temperature, relative humidity). The evaporated volumes in the last quarter of the year (roughly 1,600 cubic meters) were significantly lower than the third quarter (3,250 cubic meters from July to September), even though quarterly rainfall was greater (approximately 420 millimeters in the last quarter versus 290 millimeters in the third quarter).

Regarding the absolute values, throughfall is the element with the largest annual volume (about 280,000 cubic meters), followed by the storage on vegetation surface (about 140,000 cubic meters), with peaks occurring in high rainfall months. The simulation demonstrated the strong interrelation between canopy-level processes, rainfall event characteristics, and seasonal period, without direct correlation to the peak of monthly rainfall with the analyzed components' peaks.

3.3.3 Definition of future scenarios and mitigation actions

Two future scenarios were selected due to the impact of future climate change on the planet and the study area. Specifically, the Representative Concentration Pathways (RCP) 4.5 and 8.5 were used as reference, as they represent different conditions adopted by the Intergovernmental Panel on Climate Change (IPCC) based on the potential range of radiative forcing values. RCP 4.5 reflects mitigation actions that could lead to dioxide carbon stabilization in the atmosphere by the middle of the current century (4.5 watt per square meter, intermediate case), while RCP 8.5 represents the worst-case scenario where no action is taken to reduce the effects of climate change (8.5 watt per square meter). The study focused on two indicators identified by the IPCC as significant for climate projections in the Mediterranean area: temperatures and annual rainfall reduction. The work was based on data reported in some reports (Arpa Piemonte, 2018; Ispra, 2015) and used the high-resolution simulations of the regional climatic model COSMO-CLM (Bucchignani et al., 2016) produced by the Euro-Mediterranean Center on Climate Change (CMCC) for the thirty-year period 2071–2100. For FS.1 (associated to RCP 4.5), a future planting program was taken into account, which has been developed in agreement with park management technicians and based on growth and mortality rates of trees while no mitigation action was considered in FS.2 (associated to RCP 8.5). The program was designed to adapt to future changes, and its implementation was made possible with the use of Forecast, an i-Tree Eco component that will be further in the following part of the thesis.

The future **temperature** projections for Turin have been determined by considering the seasonal average temperature increases (national average) between the time periods of 1971-2000 and 2071-2100 (Ispra, 2015). These values have been adjusted to the Turin area, with an estimated increase of +3.3 °C for RCP4.5 and +6.0 °C for RCP8.5 over the thirty-year period (Arpa Piemonte, 2018). Based on the national seasonal average temperature increase and the projected annual average temperature increase for Turin, seasonal trends for the city have been forecasted for the 2071-2100 time period. Table 3.11 displays the national seasonal temperature trends for 2071-2100 (Ispra, 2015) and the anticipated average seasonal increase for Turin. The values indicate a more noticeable increase in all seasons for Turin compared to the rest of Italy, with an average annual increase of 2.47°C in Italy and 3.30°C in Turin projected for FS.1, and 4.45°C in Italy and 6.00°C in Turin for FS.2.

To implement i-Tree Hydro using a representative year between 2071-2100, data needed to be processed in hourly series based on previsions. The monthly values of the 2019 series were increased by amounts obtained for respective seasonal periods in Turin. Each month's hourly data in 2019, used as input data in PS, were increased with corresponding month quantities. Figure 3.7 compares the estimated trends of annual temperature for FS.1 and FS.2 with PS according to the two emission scenarios (more information in Appendix A, Table A.1).

Table 3.11: Expected increase of temperature for 2071–2100 relating to the national and Turin context.

Season	**Average Expected Increase (°C)—FS.1**		**Average Expected Increase (°C)—FS.2**	
	Italy	**Turin**	**Italy**	**Turin**
Winter	+2.20	+2.93	+4.00	+5.39
Spring	+2.10	+2.80	+3.80	+5.12
Summer	+3.10	+4.13	+5.60	+7.55
Autumn	+2.50	+3.33	+4.40	+5.93
Average	+2.47	+3.30	+4.45	+6.00

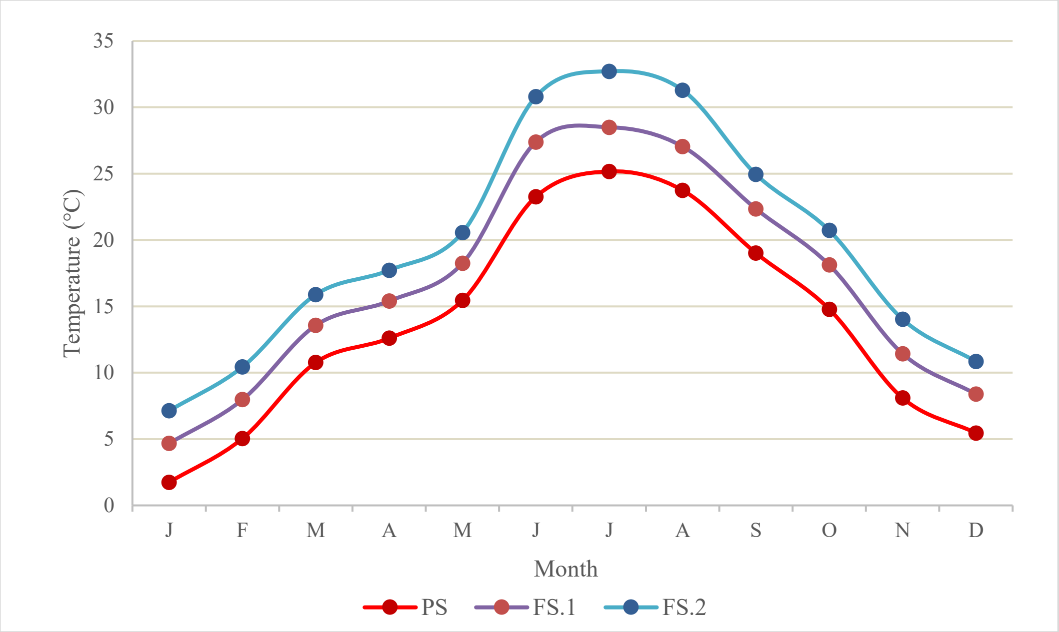

Figure 3.7: Monthly temperature trend of recorded for PS and those estimated for FS.1 and FS.2 [adapted from Busca & Revelli, 2022].

By considering the annual and monthly cumulative value estimates for 2071-2100 (Arpa Piemonte, 2018) for both future scenarios, the future projections for **rainfall** have been assessed. Alongside a decrease in the total annual rainfall amount, the simulation has factored in a reduction in the number of rainy days. Conventionally, a rainy day is defined as a day where the rain gauge records a value greater than 1 millimeter. Table 3.12 provides a summary of the estimated values that have been used to derive the trend of future rainfall in the two different scenarios for the reference time period.

Table 3.12: Precipitation and rainy days for PS ("Torino-Vallere" weather station) and estimates for FS.1 and FS.2.

Scenario	**Annual Precipitation (mm)**	**Rainy Days**
PS	914.50	79
FS.1	900.00	67
FS.2	774.00	53

The following methodology has been utilized to achieve the estimated hourly distribution of rainfall for each Future Scenario FS.x for a reference year between 2071-2100: (i) The daily grouping of the hourly rainfall data from the "Torino-Vallere" weather station for 2019 has been done, (ii) based on the daily values, the number of days with rain has been reduced. Among the days with less than 5 millimeters of rain, the days with zero precipitation were randomly selected to be eliminated. The decision to eliminate rainy days with precipitation between 1 and 5 millimeters is in accordance with future predictions about the tendency of meteoric events to increase in intensity while reducing in number; (iii) the cumulative new rainfall for the entire year was obtained by adding the new daily rainfall values, known as $P_{newPS,x}$; (iv) furthermore, as the annual precipitation value registered for PS is 914.5 millimeters, the remaining rainy days, i.e., those that have not been eliminated, were multiplied by the index $i_{PS,x}$ (Equation 17).

$$i_{PS,x} = \frac{P_{PS}}{P_{newPS,x}} \qquad (17)$$

The above approach has resulted in corrected hourly series, based on the expected decline in the number of wet days for every FS.x. After obtaining the monthly precipitation estimates for FS.x (Ispra, 2015), the final estimate for the hourly rainfall distribution was calculated.

Table 3.13: Monthly rainfall for PS ("Torino-Vallere" weather station) and estimates for FS.1 and FS.2.

Month	**PS**	**FS.1**	**FS.2**
January	5.4	44.0	58.0
February	26.0	46.0	45.0
March	6.0	84.0	77.0
April	89.4	108.0	93.0
May	63.6	134.0	109.0
June	20.0	63.0	43.0
July	156.4	34.0	13.0
August	77.0	54.0	26.0
September	53.3	88.0	56.0
October	100.0	101.0	106.0
November	254.8	101.0	87.0
December	62.6	43.0	61.0

(v) Monthly groupings were made for rainfall values of "new PS.x"; (vi) to adjust "new PS.x" rainfall values to the monthly amounts of FS.x (Table 3.13) for each n-month, a new index (Equation 18) was created; (vii) lastly, for each n-month, the hourly rainfall amounts for "PS" were multiplied by the corresponding index in FS.x

$$\mathrm{i}_{\mathrm{n,FS.x}} = \frac{\mathrm{P}_{\mathrm{n,FS.x}}}{\mathrm{P}_{\mathrm{n,new\ PS.x}}} \qquad (18)$$

As a result, new series of hourly rainfall data were obtained for the 2071-2100 period that were representative of a complete year for both FS.1 (x=1) and FS.2 (x=2), and ready to be processed in i-Tree Hydro. The parameters related to land cover remained the same, while the *Annual Average Flow of Project Area* (Table 3.6) has been altered based on the forecasts of annual rainfall for the two future scenarios. Specifically, 9.821 x 10^{-3} cubic meters per second and 8.446 x 10^{-3} cubic meters per second for FS.1 and FS.2 respectively, compared to 9.986 x 10^{-3} cubic meters per second for PS.

To adhere to the definition of the RCP4.5 scenario, a meticulous arboreal management plan has been developed as **mitigation action**, in accordance with the on management institution of the park. This program includes the maintenance of existing tree populations and the implementation of a new planting initiative, utilizing Forecast, an i-Tree Eco supplement that allows for future projections on urban forest structure composition and pollutant reduction. This tool requires the specification of certain variables, such as the number of forecasted years, the amount of days each year with temperatures above 0 °C, and the annual death rate of plants based on their health condition. The forecast period has been set to 65 years, beginning in 2020 and referencing the years 2071-2100. The total number of days with temperatures above 0 °C was determined by subtracting the number of frost days (Arpa Piemonte, 2018). To determine mortality rates, a value of 0.50% was assigned for healthy trees (0-49% dieback), 10.30% for trees in poor health (50-74% dieback), and 50% for trees with severe dieback (75-99%). These values were confirmed by literature data (Dobbertin et al., 2009) and the park management institution. The Planting Program (PP) detailed in FS.1 includes: (i) planting 170 trees during the second year of simulation to compensate for the removal of existing trees as part of the bank defenses and recalibration project of the Po River; (ii) planting 33 trees during the third year to replace those lost on the tree-lined path within the same area; (iii) planting 20 trees per year for 61 years, with a focus on preserving the current structure of the park over time.

Scenario FS.1b has been created to make a comparison with FS.1 and it considers only temperature and precipitation variations in RCP 4.5 without accounting for PP. FS.1b includes land cover parameters from PS. The number of trees expected for FS.1 was used to estimate new land cover and LAI, reported in

Table 3.14. *Tree-Pervious* percentage has increased by almost double, resulting in decreased *Grass-Herbaceous* cover and 2% reduction in *Soil-Bare Ground* cover due to embankment grassing. *Impervious Ground* decreased by 1%, causing a variation in DCIA.

Table 3.14: Main land cover input data for FS.1 and FS.1b.

Input Data	**FS.1**	**FS.1b**
Tree—Pervious (%)	64.30	33.92
Tree—Impervious (%)	1.62	1.62
Grass—Herbaceous (%)	29.80	57.15
Impervious Ground (%)	2.77	3.77
Water (%)	0.00	0.00
Soil—Bare Ground (%)	1.54	3.54
DCIA (%)	8.16	10.13
LAI	1.79	1.74

In Sub-sub-chapter 3.3.4, the discussion about comparison among current and future scenarios considered FS.1.

3.3.4 Scenario comparison

This sub-sub-chapter examines the comparison of water exits created in the “Le Vallere” park over one year for the three different scenarios, both totally and subdivided by the components (*Base flow*, *Pervious runoff*, and *Impervious runoff*). **Water Quantity** comparison is shown in Table 3.9, highlighting the differences (Δ) in absolute terms of FS.1 and FS.2 with respect to the original scenario PS. The comparison for emphasized a common decrease in the *Total flow* amounts as the rainfall decreased, with a more pronounced reduction for the FS.2, characterized by lower annual precipitation values. The major differences between the two upcoming scenarios concern the allocation of the entire outflow into its three components: for FS.2, the percentages of the three components almost remained the same compared to PS, while in FS.1 *Pervious runoff* and *Impervious runoff* components shifted respectively from 98.9% and 0.7% for PS to 99.1% and 0.5%. The alteration of permeable and impermeable ground outflow is due to the amendment of land cover parameters entailed in FS.1, which depends on the planting plan adopted.

Water Quality results have displayed an overall decrease trend for all assessed pollutants in both future scenarios, with a greater reduction observed in FS.2 (16% reduction) compared to FS.1 (7% reduction). The reduction in FS.2 can be attributed to the decrease in annual rainfall estimates, which has resulted in a reduction of surface water runoff (183,000 cubic meters for FS.2) compared to PS (218,000 cubic meters). However, in FS.1, the reduction in the polluting load (6%) was not directly proportional to the decrease in the total flow generated annually (208,000 cubic meters), which only decreased by about 4% compared to PS. In FS.1, TSS and secondary pollutant coefficients were reduced by 5% and 10%, respectively, due to the implementation of various climate change mitigation actions. The reduction in TSS was attributed to human pollution and soil erosion, which were mitigated in the RCP4.5 scenario, whereas the reduction in secondary pollutant coefficients was due to the corresponding decrease in air pollutants. Figure 3.8 presents estimates of pollutants categorized into primary (Figure 3.8-A) and secondary pollutants (Figure 3.8-B) based on their respective magnitudes of concentration.

Following the examination of the monthly patterns of the four elements of **Vegetation Hydrology** (Figure 3.6) for PS, a comparison with FS.1 and FS.2 was presented in terms of overall annual values, as illustrated in Figure 3.9. It should be noted that the distribution of rainfall throughout the year varies for each examined scenario, thus affecting the monthly trends.

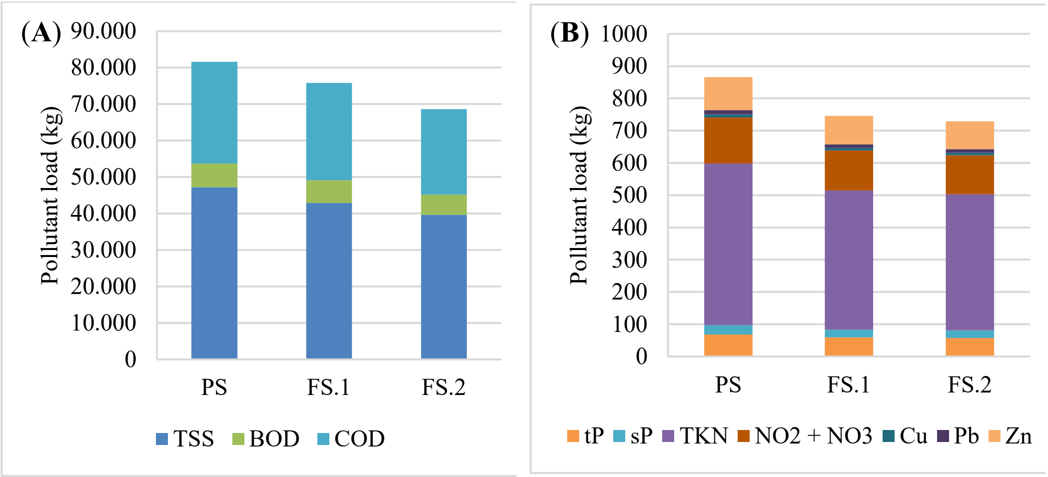

Figure 3.8: Water Quality outputs for PS, FS.1, and FS.2: (A) main pollutants; (B) secondary pollutants [adapted from Busca & Revelli, 2022].

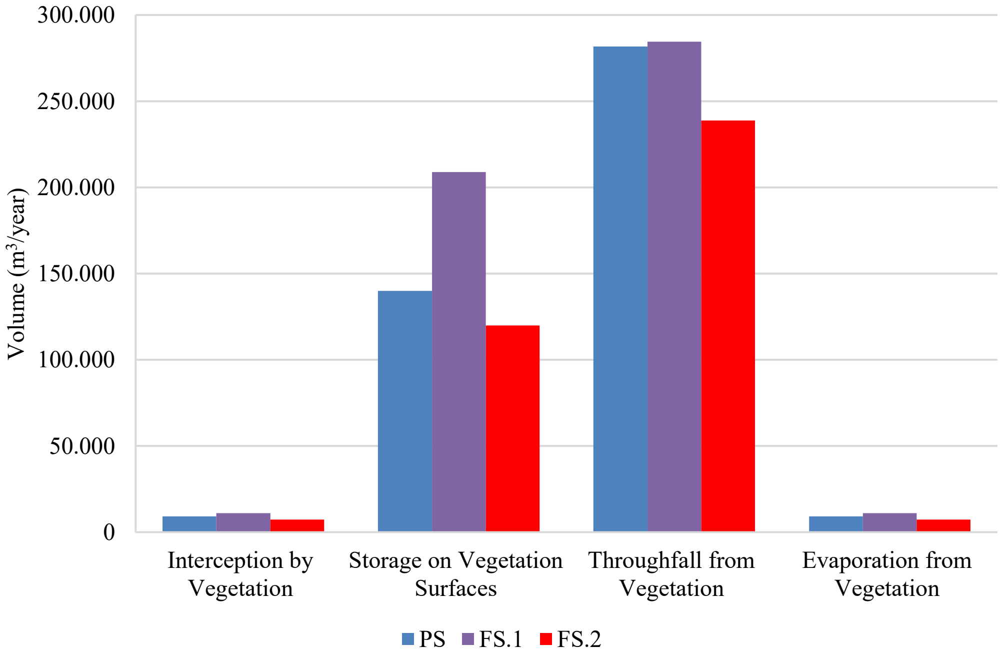

Figure 3.9: Vegetation Hydrology outputs for PS, FS.1 and FS.2 [adapted from Busca & Revelli, 2022].

It comes out the two future scenarios have exhibited opposite variations with regards to PS concerning hydrological components. FS.1 has revealed an increasing trend in all the components while FS.2 has shown a general decrease. While this outcome was expected for FS.2 due to an annual predicted precipitation value of less than 15% (compared to PS, more investigation is needed for FS.1. Despite experiencing a 1.5% decrease in annual rainfall, all the hydrological components considered in FS.1 have shown to be greater than those for PS. The reason for this phenomenon is the predominant influence of the planting program implemented in FS.1 as a climate change mitigation measure, which has significantly affected the hydrological mechanisms associated with vegetation. *Storage on Vegetation Surfaces*, in particular, has seen the largest increase in percentage terms (about 50%) due to the rise in tree cover which corresponded to a considerable increase in the total leaf surface (Table 3.14).

3.3.5 Discussion

This sub-sub-chapter discusses the findings of a study on water runoff generated by a green area and its implications for water-related ecosystem services management. The study examines both quantitative and qualitative characteristics of the runoff and highlights the significant contribution of surface runoff from permeable surfaces due to soil saturation or excess filtration rate. This runoff carries pollutants such as TSS, BOD, and COD, mainly derived from the organic composition of the soil. The study also explores advanced hydrology outputs related to vegetation, which reveal the volume and distribution of hydrological components within a year. These outputs indicate that vegetation interception, absorption, and evaporation are complex processes influenced by climatic conditions and do not always align with the distribution of rainfall.

The results show that vegetation plays a crucial role in mitigating surface runoff and reducing the risk of flooding in urban areas. The study also utilizes the Eco software, a part of the i-Tree suite, to quantify the avoided runoff thanks to vegetation, measuring the volume of surface water runoff intercepted, infiltrated, and stored by the park. However, it is noted that the estimated avoided runoff is relatively small compared to the overall outflow rates in the area.

To assess the impact of climate change on water-related ecosystem services management, the study compares the current situation with two future scenarios (FS.1 and FS.2) based on the COSMO-CLM regional climate model and emission scenarios (RCP4.5 and RCP8.5). FS.1, which includes mitigating actions like a planting program, leads to improvements in tree cover, leaf area, and hydrological components, resulting in a reduction of surface water outflows. However, FS.2 shows a decrease in water flow due to lower precipitation and a limited contribution from vegetation. The study's findings have implications for territorial planning in the Piedmont Po Protected Areas and can inform future plans to adapt to climate change in Moncalieri and Turin. Moreover, it emphasizes the need for greater attention to solutions that minimize water stress and hydrogeological risks in urban settings. The economic estimate associated with this ecosystem service underscores the challenges in assigning an economic value to ecosystem services, despite the significant harm caused by frequent extreme flood events. However, the study acknowledges limitations, such as relying on a single climate model, and suggests considering multiple models for more robust results. Additionally, further investigation is needed to understand the park's ability to mitigate the Urban Heat Island effect in the urban context, in addition to the need of a more specific economic study to quantify the monetary benefits of saved water runoff and its impact on the municipality, neighboring activities, and residents.

3.4 “Colonnetti” Park: a story from future possible scenarios

3.4.1 Study area and input data

The sustainability offered by the "Colonnetti" park, a green area of approximately 38 hectares located in the Municipality of Turin was analyzed. The study focuses on evaluating the main environmental benefits that the green space is capable of generating in the surrounding urban area, from carbon sequestration and storage to the reduction of atmospheric pollutants, without neglecting the park's role in surface water runoff. The implemented tool, i-Tree Eco, allowed for an analysis from an economic point of view as well, giving a general assessment of the monetary benefit generated quietly by the "Colonnetti" park. Finally, the study concludes by focusing on future configurations, comparing the current scenario with different configurations in the perspective of future territorial planning.

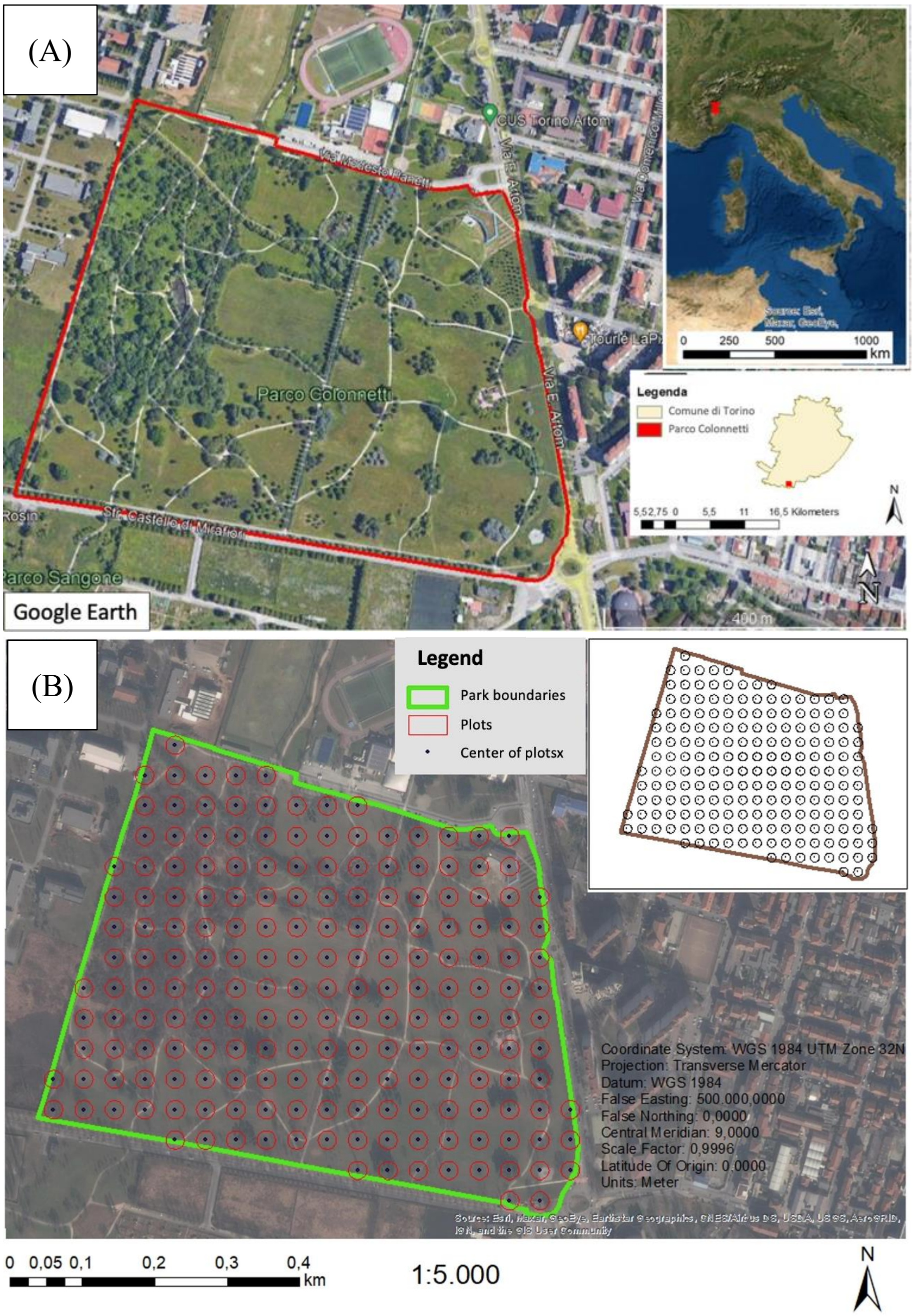

Figure 3.10: Geographical framework of “Colonnetti” park (A). Plot distribution for the plot-based sample inventory in i-Tree Eco (B).

"Colonnetti," urban park extends into the suburban neighborhood of Mirafiori Sud in the metropolitan city of Turin (Figure 3.10-A). The park, named after mathematician Gustavo Colonnetti, is now an urban green area that spans 385 thousand square meters, but it was once part of the Mirafiori airport, which remained operational until the end of World War II. The green area is equipped with internal paths, playgrounds for children, sports facilities, socio-cultural gathering spaces in an environment suitable for the naturalistic development of flora and fauna, in addition to a social gathering structure and some branches and after-school activities for children.

In-situ data were gathered through a "Plot-based sample inventory" during a 5-day inspection conducted in September 2021, together with Dr. Ivano Lagonigro (Figure 3.11). The preparation of the project involved the definition of the area of interest (AOI) by drawing the relative polygon using ArcMap with the WGS 1981984 UTM Zone 32 N. Then the definition of the sampling areas led to the identification of 193 plots with a fixed grid arrangement (Figure 3.10-B) with an distance between centers of 42 meters, given the irregular distribution of the trees, as evident from Figure 3.10-A. The grid was generated using ESRI ArcGis and the plots were defined with ArcToolbox as circular areas of 500 square meters (corresponding to a radius of 12.62 meters). The data was subsequently imported into i-Tree Eco on the area of interest. The accuracy of the in-situ data, many of which are not mandatory, is dependent on the precision of the fieldwork, utilizing a metric tape, a dendrometric stand for measuring distances from the plot center, tree circumferences and canopy width, in addition to a range of mobile applications: (i) *Coordinates*, to find the position of plot's center; (ii) *PlantNet*, for the species identification; (iii) *Arboreal*, for the tree height estimates. In addition to the mandatory information about trees (species, DBH) and about plots (percentage of plot covered by trees, percentage of plot accessible), the following data were retrieved: ground cover, land use, total tree height and canopy height, distance and direction of tree from the center of the plot, canopy health, N-S and W-E canopy width, percentage of missing canopy. crown light exposure, percentage of impermeable surface on tree cover.

Figure 3.11: Some photos from the site inspection (September 2021).

The data retrieved on site were entered manually in i-Tree Eco, together with the mandatory data (location information, meteorological data, benefit prices). The total number of sampled trees was 232 referring to 42 different species and a sampled area of 96,500 square meters. About the economic estimation, benefit prices refer to the previous studies in the Turin metropolitan area (Sub-sub-chapter 3.3.1), considering a euro/dollar exchange rate equal to 0.862 (October 2021).

3.4.2 Greenery structure and future scenarios

The first result provided by the program is an evaluation of the composition of the urban forest, based on field data. The "Colonnetti" park has an estimated number of 1124 (±72) trees belonging to 42 different species, covering approximately 33% of the park's surface. As shown in Table 3.15, the most common species are: (i) *Tilia platyphyllos* (18.5%), (ii) *Celtis australis* (8.6%), and (iii) *Cedrus atlantica* (6.9%). Based on the regression equations of the UFORE model (Nowak, 1996), i-Tree Eco estimates the leaf area and biomass of the park, with a total value of 85.7 ± 7.8 hectares and 72.2 ± 7.6 tons, respectively. It is worth noting that the total leaf area value is more than double the park's walkable surface area (about 38 hectares), highlighting the massive presence of shrubs and trees within the area.

Table 3.15: Composition of the urban tree population for “Colonnetti” park.

Species	**Trees**	**%**	**Species**	**Trees**	**%**
Tilia platyphyllos	208	18.5	*Prunus avium*	15	1.3
Celtis australis	97	8.6	*Fagus sylvatica*	10	0.9
Cedrus atlantica	78	6.9	*Pinus resinosa*	10	0.9
Ulmus minor	63	5.6	*Pinus wallichiana*	10	0.9
Acer saccharinum	58	5.2	*Platanus occidentalis*	10	0.9
Fraxinus excelsior	58	5.2	*Populus alba*	10	0.9
Cedrus deodara	48	4.3	*Prunus cerasifera*	10	0.9
Quercus rubra	39	3.4	*Salix alba*	10	0.9
Populus nigra	39	3.4	*Acer negundo*	5	0.4
Prunus serotina	39	3.4	*Pterocarya fraxinifolia*	5	0.4
Pinus nigra	34	3.0	*Prunus domestica*	5	0.4
Aesculus hippocastanum	29	2.6	*Morus nigra*	5	0.4
Salix babylonica	29	2.6	*Liriodendron tulipifera*	5	0.4
Acer platanoides	29	2.6	*Liquidambar styraciflua*	5	0.4
Acer campestre	24	2.2	*Fraxinus ornus*	5	0.4
Pinus strobus	24	2.2	*Celtis occidentalis*	5	0.4
Tilia tomentosa	24	2.2	*Carpinus betulus*	5	0.4
Tilia cordata	15	1.3	*Acer saccharum*	5	0.4
Juglans nigra	15	1.3	*Quercus robur*	5	0.4
Ostrya carpinifolia	15	1.3	*Acer buergerianum*	5	0.4
Ulmus pumila	15	1.3	*Acer tataricum*	5	0.4

The leaf area of a tree is obtained by summing the surfaces of only those leaves that are reached by sunlight. This area is proportional to the tree's capacity to capture carbon dioxide, produce oxygen, and reduce air pollutants. For both deciduous broadleaf trees and evergreen conifers, the i-Tree model can calculate the leaf surface area. For deciduous trees, it utilizes regression equations (Nowak, 1996), while for other species (such as evergreens), it incorporates correction coefficients, as shown in Sub-chapter 2.4. *Tilia Platyphyllos*, the species with the highest number of individuals in the park (18.5%), does not have the largest leaf surface area: it is slightly smaller than the surface area of *Quercus Rubra*, which represents 3.4% of the population (tenth in terms of individuals). Instead, the biomass produced by trees, which refers to the organic matter contained within them, is valuable data for calculating carbon absorption and sequestration. The estimation of leaf biomass used field data (DBH, height) and modified allometric equations (Nowak et al., 2002) based on tree characteristics, that differs from those used for leaf area calculations. As shown in Figure 3.12, there is not a direct correlation among tree population leaf area and leaf biomass: *Cedrus deodara* comes out to be the species with the highest impact on total leaf biomass (21%), followed by *Cedrus atlantica* (16%) and *Quercus rubra* (11%).

i-Tree Eco's mathematical model uses mandatory DBH data to calculate various parameters, including leaf biomass and stored carbon. The distribution that emerges from the analysis of the 10 most populous species of the park presents a higher concentration in the diameter classes 15.2-30.5, 30.5-45.7 and 45.7-61 centimeters, with the exception of some particular species such as *Tilia Platyphyllos* (7.6-15.2 centimeters) or *Ulmus Minor, Cedrus Deodara, Quercus Rubra* and *Populus Nigra* which fall in the class of 61-76.2 centimeters and *Acer Saccharinum* and *Quercus Rubra* in the class of 76.2-91.4 centimeters.

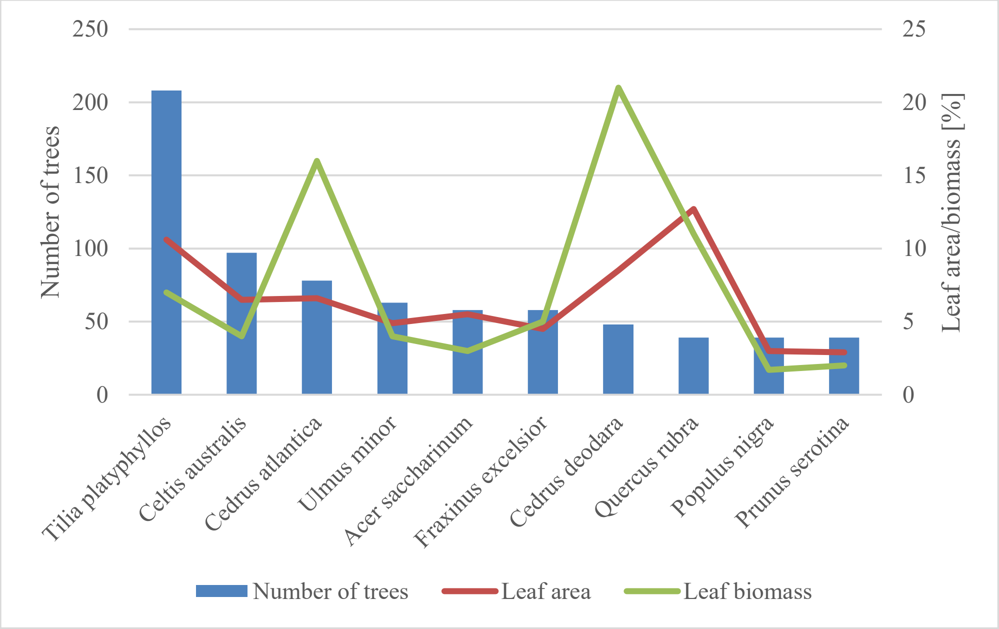

Figure 3.12: Leaf area and leaf biomass compared to tree population for the 10 most populous tree species.

During the field activity, it was observed that the park has a diverse tree population. The overall condition of the trees is very good, although there are some dead trunks in the less maintained and shrub-rich portion of the park (west zone of the park). This aspect should not be considered negative since the dry plants and shrubs serve as a refuge for many animal species such as squirrels, rabbits, various bird species, etc., and they are also important for biodiversity conservation. Specifically, from the i-Tree Eco report it can be deduced that about 80% of the trees are in good/excellent condition, 11% in a moderate state of health and only 6% in critical condition (intervention required) while 2% trees are dead.

Along with quantifying the environmental benefits associated with the "Colonnetti" park in the Mirafiori Sud neighborhood at the current time of the analysis (Present Scenario, PS), the work continued with a focus on the future. Two particularly interesting scenarios were chosen and a comparison analysis was carried out with PS:

(i) Future Scenario FS.1, characterized by the extinction of the *Cedrus Atlantica* species; it was chosen as it represents a potential situation in which the park will be in the future, given the danger of the aforementioned species' extinction (which is third in prevalence).

(ii) Future Scenario FS.2, characterized by the total absence of shrubs; FS.2 hypothesized the complete removal of shrubs from the analysis for aesthetic purposes, as a significant portion of the western area of the park is difficult to access because of them.

3.4.3 Results and comparison

Table 3.16 provides a summary of the ES quantification by i-Tree Eco for PS. The economic value associated with the storage of 614 tons of carbon in the park amounts to over 134 thousand euros, while the total annual economic estimate related to the atmospheric pollutant removal, net carbon sequestration, and avoided surface runoff exceeds 100 thousand euros. As mentioned previously, the economic quantification of oxygen production has not been conducted. Specifically, the highest contribution is attributed to the quantity of PM2.5 particles removed (approximately 43 thousand euros for the removal of just 36 kilograms), which is characterized by a significant unit benefit due to its hazardous impact on human health. Additionally, the removal of ozone (earning almost 20 thousand euros for the removal of over 500 kilograms) represents the primary pollutant removed in terms of quantity. In terms of volatile organic compounds (VOCs), the park contributes to the production of 116 kilograms of isoprene and 209 kilograms of monoterpene, totaling 325 kilograms.

For an easier interpretation of the results, the software produces interesting comparisons in terms of the average annual emissions of cars and households. For example, the fixation of C in vegetation biomass corresponds to an emission saving of about 480 cars and 196 single-family units. From Table 3.16, it is clear that the greatest economic benefit comes from the removal of atmospheric pollutants by vegetation (about 60% of the total monetary value), primarily attributed to PM2.5 particulate matter, also known as "fine dust", which is largely responsible for the high levels of urban pollution during long winters in Turin.

Table 3.16: Ecosystem services quantification for Colonnetti Park.

Ecosystem Service		**Amount**	**UM**	**Economic value [€]**
Annual air pollutant removal	O_3	556.6	kg	19,330
	NO_2	246.5	kg	1,278
	SO_2	60.5	kg	114
	CO	78.5	kg	86
	PM2.5	36.1	kg	43,569
Carbon storage		614	t	134,834
Annual net carbon sequestration		19.55	t	4,293
Annual avoided surface runoff		1,080	m^3	2,100
Annual oxygen production		52.12	t	-

Summarizing the results for air quality, it has been estimated that trees remove 0.978 metric tons of air pollution: specifically, 556.6 kg of ozone (O_3), 78.5 kg of carbon monoxide (CO), 246.5 kg of nitrogen dioxide (NO_2), 36.1 kg of particulate matter less than 2.5 microns (PM2.5) and finally 60.5 kg of sulfur dioxide (SO_2) per year. Figure 3.13 shows the monthly removal trend in "Colonnetti" park for each single air pollutant. Trees remove PM2.5 by capturing it on the surfaces of their leaves (Nowak et al. 2013). Particles of particulate matter can be re-entrained into the atmosphere, washed away by rainfall, dissolved, or deposited onto the soil. These mechanisms can result in either positive or negative values for pollution removal, depending on different atmospheric factors, as observed in Figure 3.13 for PM2.5.

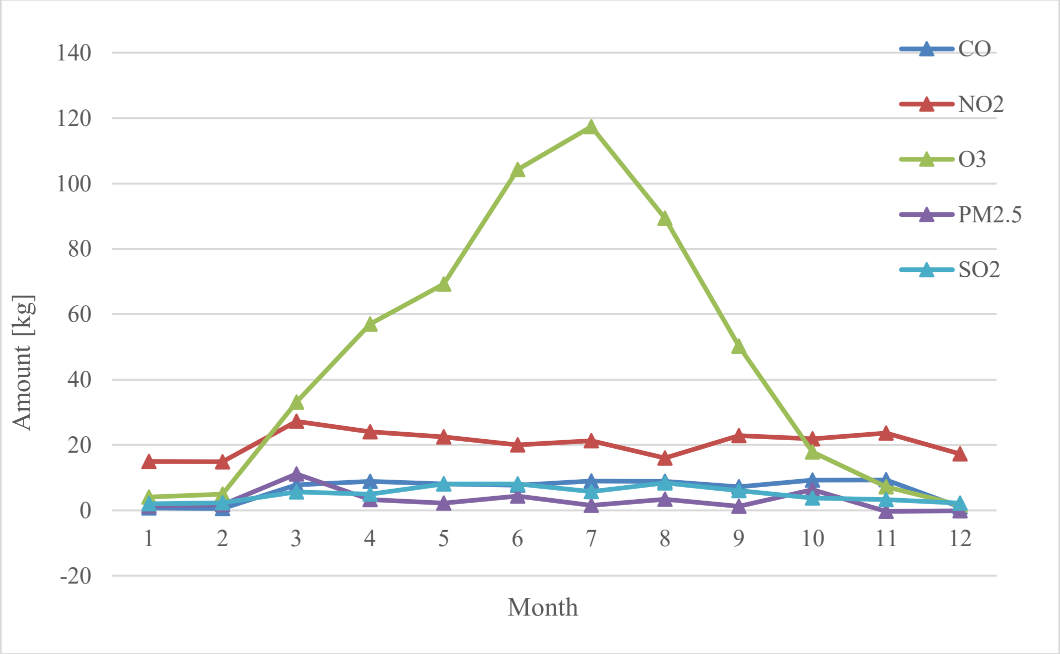

Figure 3.13: Monthly air pollutant removal trend for “Colonnetti” park.

In terms of hydrological effects, the tree population of the park was found to reduce the amount of surface runoff by over 1,080 cubic meters per year, with an estimated monetary value of about 2,100 euros, based on the total annual precipitation in the study area. As described in Sub-subchapter 2.4.2, the avoided surface runoff depends on the vegetation and, in particular, on the presence of trees, which activate different hydrological processes through which they retain rainwater. Not all trees act in the same way: depending on the type of species and the specific characteristics of each tree (height, diameter, state of health, etc.), the quantity of avoided runoff varies. Figure 3.14 displays an exported graph from i-Tree Eco outputs, presenting the ES breakdown by species, incorporating the ten species with greatest overall impact on the ES. Comparing Figure 3.14 with Figure 3.12, it is important to highlight the direct relationship between the species with a greater impact on reducing surface water runoff and the quantitative estimates of their total leaf area, while no proportionality is observed with the tree population (e.g., *Tilia platyphyllos*). Such analysis serves as a valuable tool for territorial planning, examining factors associated with the effectiveness of species distribution within the park.

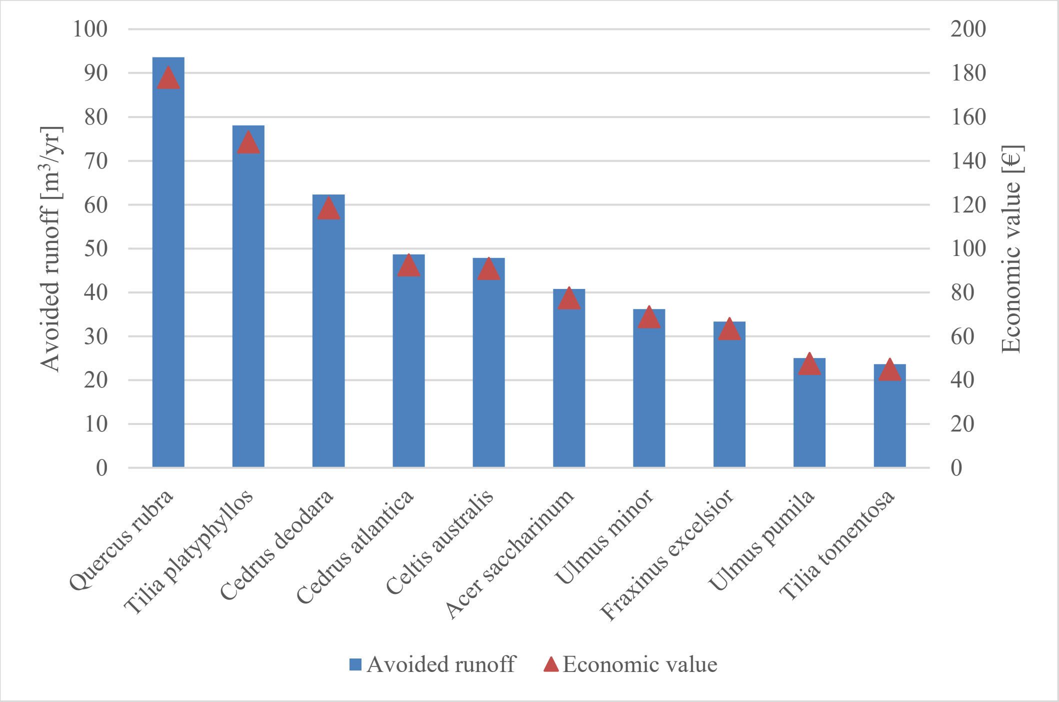

Figure 3.14: Avoided runoff (bars) and monetary value (points) for the ten species with greatest impact, from i-Tree Eco report.

In considering the comparison with the hypothetical future scenarios, Figure 3.15 focuses on the main results. Firstly, the graphs related to leaf area and leaf biomass were presented, which show a more pronounced overall decrease for FS.2 (absence of shrubs). For FS.1, the decrease is less evident, although it should be noted a different magnitude for leaf area (approximately -7%, Figure 3.15-A) and leaf biomass (-15%, Figure 3.15-B), demonstrating that the presence of shrubs within the park leads to a greater enrichment in terms of biomass compared to the leaf surface provided.

At the ES level, the most noticeable differences concerns FS.2, as the absence of shrubs has led to a significant decrease in each analyzed benefit, with reductions ranging from 27% (air pollutant removal, Figure 3.15-C) to 32% (avoided surface runoff, Figure 3.15-D). Imagining a park characterized by the presence of only tree species within large expanses of grass would drastically reduce the benefits compared to the current status. The extinction of *Cedrus Atlantica* (FS.1), on the other hand, shows reductions in quantities of modest size compared to SP, although it should be emphasized a general reduction of about 7.5%.

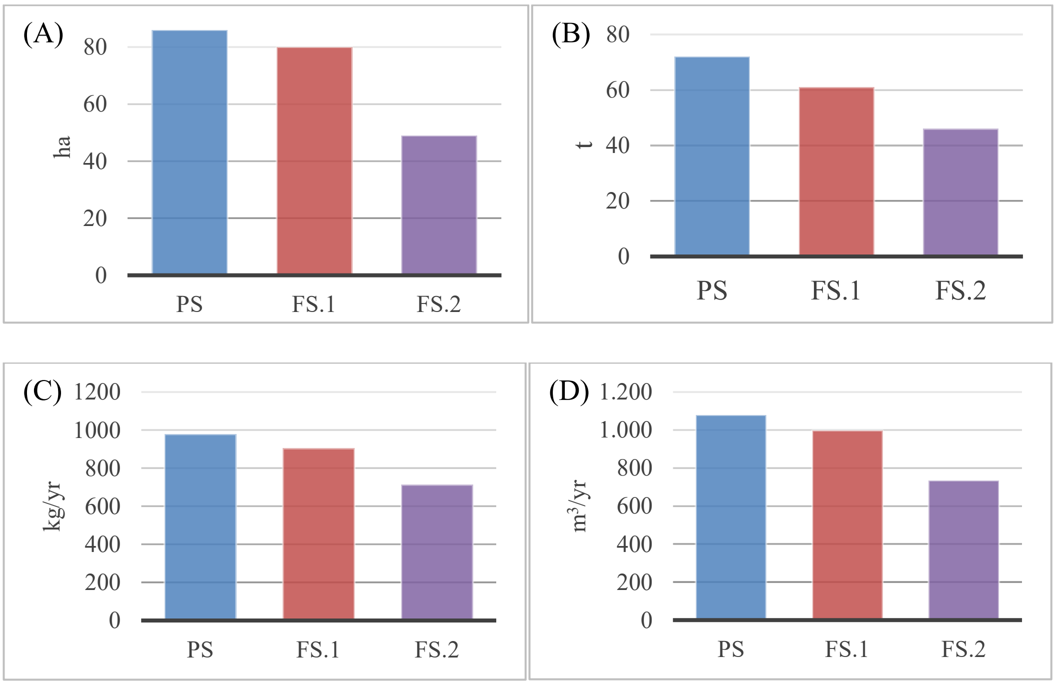

Figure 3.15: Comparison between FS.1 (orange), FS.2 (yellow) and PS (blue) for: (A) leaf area, (B) leaf biomass, (C) air pollutant removal, (D) avoided surface runoff.

From the comparison with the present scenario PS, it emerges that the hypothesis of eliminating the shrub presence, aimed at improving the aesthetic of the park, has produced significant reductions in the environmental services while the hypothetical extinction of the aforementioned species would cause a negligible decrease. For the future, a specific integrated study is planned for the park's hydrological balances, through the use of certain tools provided by the i-Tree suite, including Hydro and Canopy, with the aim of improving the quantity and quality of knowledge about the flows that concern the park and consequently, the surrounding urban water network, only partially treated through the i-Tree Eco tool. The quantitative analysis of the benefits provided by “Colonnetti” park is part of a project related to the metropolitan city of Turin and specifically focuses on its influence on certain environmental aspects within the urban neighborhood of South Mirafiori where it is located. By providing outputs related to various ES, the study aims to scientifically demonstrate, incorporating economic considerations, the necessity of including green spaces and infrastructure within cities, particularly large ones. Through a comparison with reasonably identified future scenarios, the study aims to provide valuable insights for the future planning of the area.

3.5 Concluding remarks of Part I

In collaboration with various public entities (Municipality of Turin, “Ente di Gestione delle Aree Protette del Po Torinese”), we conducted a series of quantitative analyses in the Turin metropolitan area that highlighted several aspects related to urban ecosystem services, including:

(i) The strong link with land cover distribution and the shared co-design experience between public entities and residents ("Via Revello").
(ii) The interconnection with ongoing climate change and the adaptability of the approach used to manage future data projections ("Le Vallere").
(iii) The variability in the presence of future scenarios, providing an opportunity to consolidate the versatility of the tool even in reasonably plausible hypothetical contexts ("Colonnetti").

Various information was extracted from an urban territorial planning perspective. Moreover, the conducted project allowed us to characterize an evaluation method that demonstrated its versatility in relation to different scenarios. This represents a significant advantage in an urban context, which is inherently dynamic. On the other hand, it should be underlined that the weather station (Torino-Bric della Croce), chosen as reference station for its data completeness, is positioned at a higher altitude than the urban area in which the study was conducted: almost certainly an underestimation of the air pollutant removal of green areas was produced. Furthermore, a doubt emerged regarding the unit price data linked to the avoided water flow, based on bibliographic references linked to the US context: a future update may be necessary to estimate the economic benefit in a realistic way. The project in the Turin area paved the way for the subsequent development of the project, namely expanding the assessment both spatially (urban scale) and in terms of component transversality, which is fully addressed in Chapter 4.

Chapter 4

Part II – ES in the urban area of Boadilla del Monte

The work described in this chapter is partially derived from [Busca et al., 2023a] and from [Busca et al., 2023b].

4.1 Introduction

This study examines the ecological advantages provided by urban trees in a mid-sized city (approximately 60,000 inhabitants) for both the environment and the local population. The benefits, including carbon storage and sequestration, air pollution reduction, decreased surface runoff, and oxygen production, was evaluated through i-Tree Eco. Additionally, the social impact of the city's green spaces, many of which contain the aforementioned trees, is considered. This research has been previously explored in scientific studies such as Bratman et al. (2019) and Fagarazzi et al. (2021), as well as reviews such as Pinto et al. (2022). The main objective of this project, aligned with Goal 11 (Sustainable Cities and Communities) in the United Nations' Agenda 2030, is to prove the positive role of urban trees in the design of an environmentally sustainable and resilient Boadilla del Monte (Spain) for the future. This includes an economic estimation of the environmental benefits provided by the tree population of over 33,000 trees located in 28 neighborhoods of the city. The specific goals of this project include: (i) quantifying the ecosystem services provided by the urban trees, (ii) comparing the sustainability and efficacy of the different districts, and (iii) conducting a cost-benefit analysis of the city's public green spaces according to the Municipality of Boadilla del Monte. This chapter is divided into different components, including this introduction (Sub-chapter 4.1), a deepening about the project, a description of the study area, input data and site inspection (Sub-chapter 4.2), an overview of the structure of Boadilla del Monte's urban greenery, ES quantification and monetary analysis (Sub-chapter 4.3), a discussion about the outputs, by species and urban districts (Sub-chapter 4.4), and concluding with Sub-chapter 4.5 with an in-depth focus on the cultural category of ES, through the citizen participation.

4.2 Project, study area and tree’s inventory

The project was conducted in the urban area of Boadilla del Monte (40°24′18″ N, -03°52′42″ W), in the “Comunidad Autonóma de Madrid” (Spain). According to the Instituto Nacional de Estadística (2022), Boadilla del Monte has an area of 47.2 square kilometers and a population of 62,627 inhabitants, and it has an altitude of 689 meters above sea level.

As per the Köppen and Geiger classification, Boadilla del Monte experiences a hot-summer Mediterranean climate (Csa). The area is characterized by limestone, marl, and gypsum; various torrents such as Nacedero, Valenoso, and Los Pastores cut across the urban territory. The study area in consideration is distributed among 28 districts (Área Sur 4.1, Área Sur 4.2, Bonanza, Casco urbano, Club las Encinas, Complejo Deportivo Angel Nieto, Cortijo Norte, Cortijo Sur, El Pastel, La Cárcava, Las Lomas, Los Fresnos, Los Fresnos 2, Monte de las Encinas, Montepríncipe, Norte Encinar, Olivar Fase 3, Olivar de Mirabal, Parque de Boadilla, Prado del Espino, Pino Centinela, Sector 2,3 y 4, Sector 11, Sector B, Valdecabañas, Valdepastores, Valenoso, and Viñas Viejas) covering 2.813 square kilometers, as illustrated in Figure 4.1.

For the conducted research activity, numerous factors have been taken into consideration to choose the meteorological station that represents the climate of Boadilla. A comprehensive analysis of the data has been conducted, considering factors such as geographical location, record duration, data quality, climate variability, and topographic characteristics. Based on these factors, the meteorological station selected as the reference for hourly weather and precipitation data is Barajas (Fig.1).

In terms of pollutant concentration, the Air Quality Network of the Community of Madrid comprises 24 fixed measurement stations. To determine the representative air quality stations for Boadilla, the following factors were considered: strategic location, geographic coverage, demographic and industrial characteristics, validation and calibration, consistency, and continuity. Taking these factors into account, the representative stations for air quality in the specific area of Boadilla del Monte were identified as Móstoles (for CO, O_3, NO_2, and SO_2) and Alcorcón (for PM2.5). These stations are indicated in the map of Figure 4.1.

Model simulation was conducted for the year 2015, which is the most recent year in i-Tree Eco for which both weather and pollution hourly data were fully available from the aforementioned stations. Additionally, the compatibility with the reference year of the inventory has been verified.

The functioning of the software is based on the UFORE model, and it analyzes the various ecosystem services of urban trees in Boadilla del Monte. Project metadata can be found in Appendix B (Table B.1). The model was run for 2015, which is the most recent year for which weather and pollution data were available from the aforementioned stations. For the case study, the "Complete Inventory" method was used to create a detailed catalog of tree and shrub species and define land use and cover.

Table B.2 in Appendix B reports reference benefit unit prices used in the analysis for the monetary evaluation of ecosystem services. Default values provided by the software were used for surface runoff (USD context) and air pollutants, while a more current and appropriate unit price for the European context, 85.30 euros per metric ton, was used for carbon dioxide, equivalent to 313.05 euros per metric ton for carbon (reference: site-inspection in May 2022). For air pollutants (CO, NO_2, O_3, PM2.5, SO_2), calculations were based on European average externality values (van Essen et al., 2011) or Ben MAP regression equations (Nowak et al., 2014) that included user-defined population calculations.

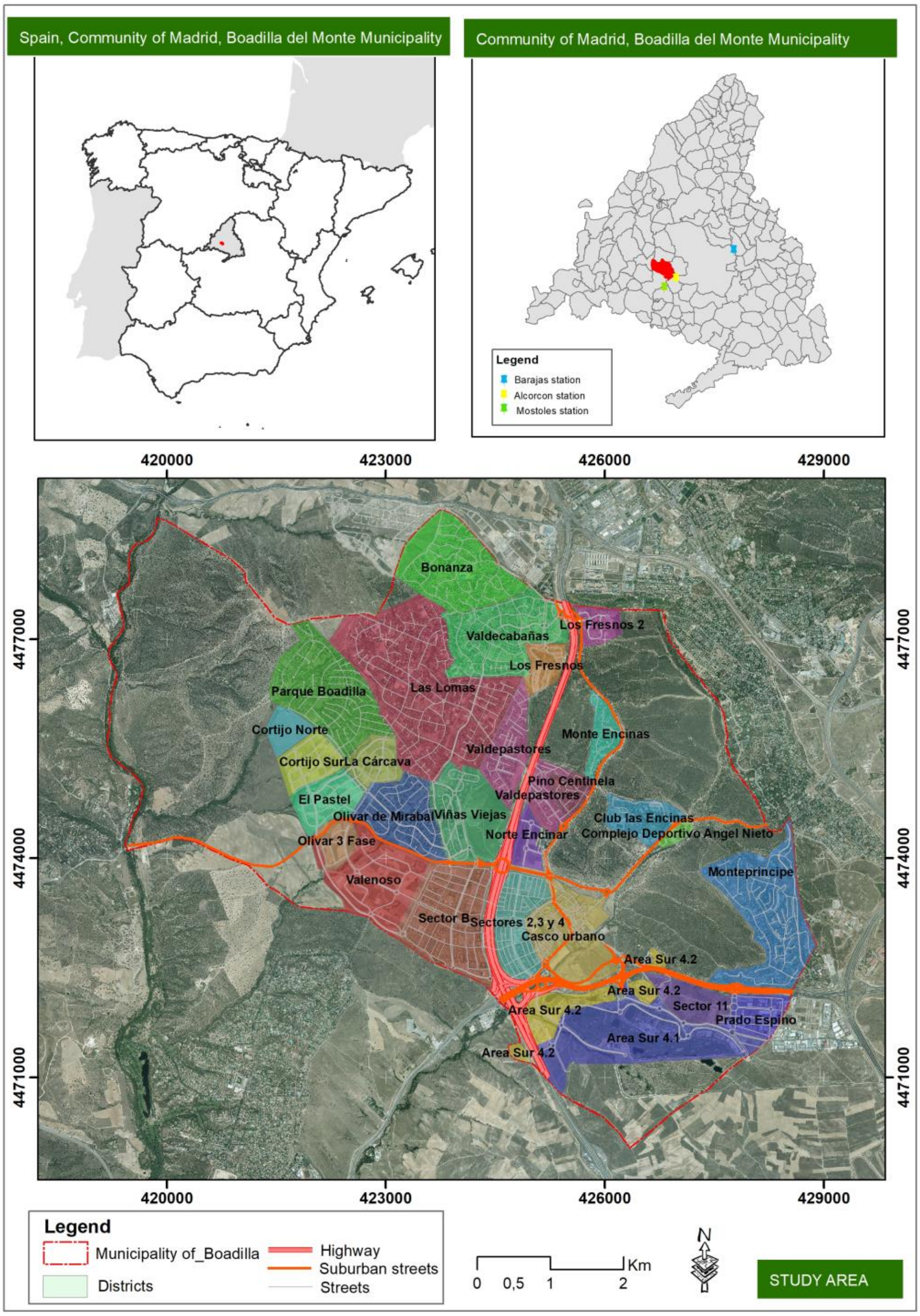

Figure 4.1: Geographical framework and district distribution of Boadilla del Monte.

The collaborative project with the "Ayuntamiento de Boadilla del Monte," particularly with the "Concejalía de Medio Ambiente, Deportes y Festejos," was carried out with the valuable assistance of "Jardines Boadilla UTE" in managing municipal green spaces (Ayuntamiento de Boadilla del Monte, 2015). Information for the study was kindly provided by the aforementioned network, which had recently conducted a complete inventory of 34,203 trees and shrubs in the area. The inventory included known characteristics such as species, Diameter at Breast Height (DBH), district, street, x and y coordinates, age, height, perimeter, health, possible interference, and date of detection. A total of 2,000 individuals were excluded from analysis due to uprooted trees or missing data, resulting in a total of 33,255 urban trees surveyed.

The mapped inventory was conducted in three steps (Ayuntamiento de Boadilla del Monte, 2015):

i. The field survey was conducted using a vehicle equipped with IMAJBOX field survey equipment. The equipment includes a 5 MP camera, a 50-channel differential GPS, an inertial station (IMU) to correct positioning in areas of low GPS coverage, and a barometric sensor to obtain a high-precision position. Correlative images were obtained and used to extract geographic information through photogrammetry in a GIS.
ii. The survey data undergoes post-processing and quality control to ensure no low image quality or positioning errors exist.
iii. The GIS IMAJVIEW production software was used to carry out inventory production by positioning and categorizing trees in a standardized manner. The software allows for positioning points, lines, and polygons through photogrammetry with a DRMS precision of 50 centimeters and allows for 3D measurements of any object visible in the image.

The urban inventory was conducted in 2015, then updated annually by the City Council and its last version was used in this analysis. To supplement the inventory, an inspection of urban green areas in Boadilla del Monte was conducted in May 2022 (Figure 4.2) to gather missing information regarding the characteristics of urban trees. The inspection data was integrated into the existing database, and subsequent data processing was performed to ensure compatibility with i-Tree Eco requirements.

Figure 4.2: Site-inspection conducted in May 2022: (A) gardens of Palacio del Infante don Luis; (B) example of urban street tree-lined (photos: Francesco Busca).

Weather and Pollution Data. Figure 4.3 details the daily weather distribution data for model simulation in Boadilla del Monte in 2015. The yearly rainfall total was 278 millimeters with a distinct concentration during autumn (a peak of 43 millimeters in October) and the lowest levels in summer, with only 15 millimeters of precipitation between July and August. The average daily temperature was 15.9 °C, with the coldest temperatures in January and early February (-4 °C) and the warmest in July (40°C). While i-Tree Eco has provided information on Photosynthetically Active Radiation (PAR) and UV index, these factors were not analyzed in this study.

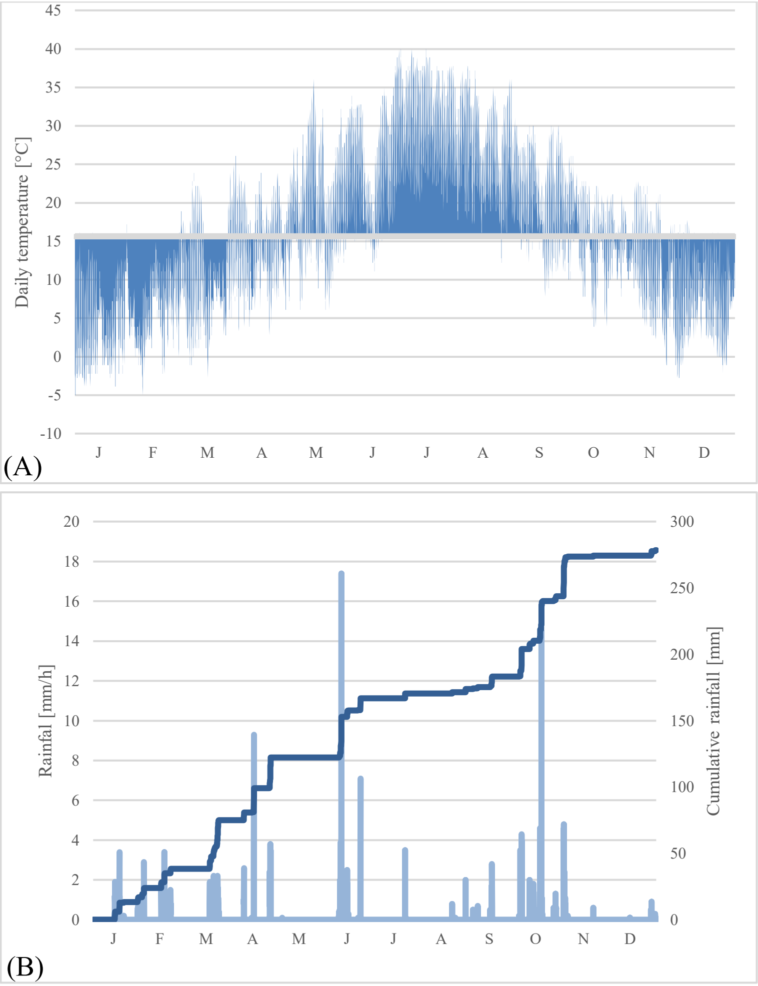

Figure 4.3: Weather Data in 2015: (A) daily temperature with respect to the average daily temperature; (B) daily precipitation and cumulative daily precipitation.

Figure 4.4 delves into air pollutant concentrations in 2015 through daily concentration trends for each pollutant. Mostly fluctuating trends can be observed throughout the various seasons, with higher average values observed during fall and winter for CO and PM2.5, and a more constant trend throughout the year for SO_2.

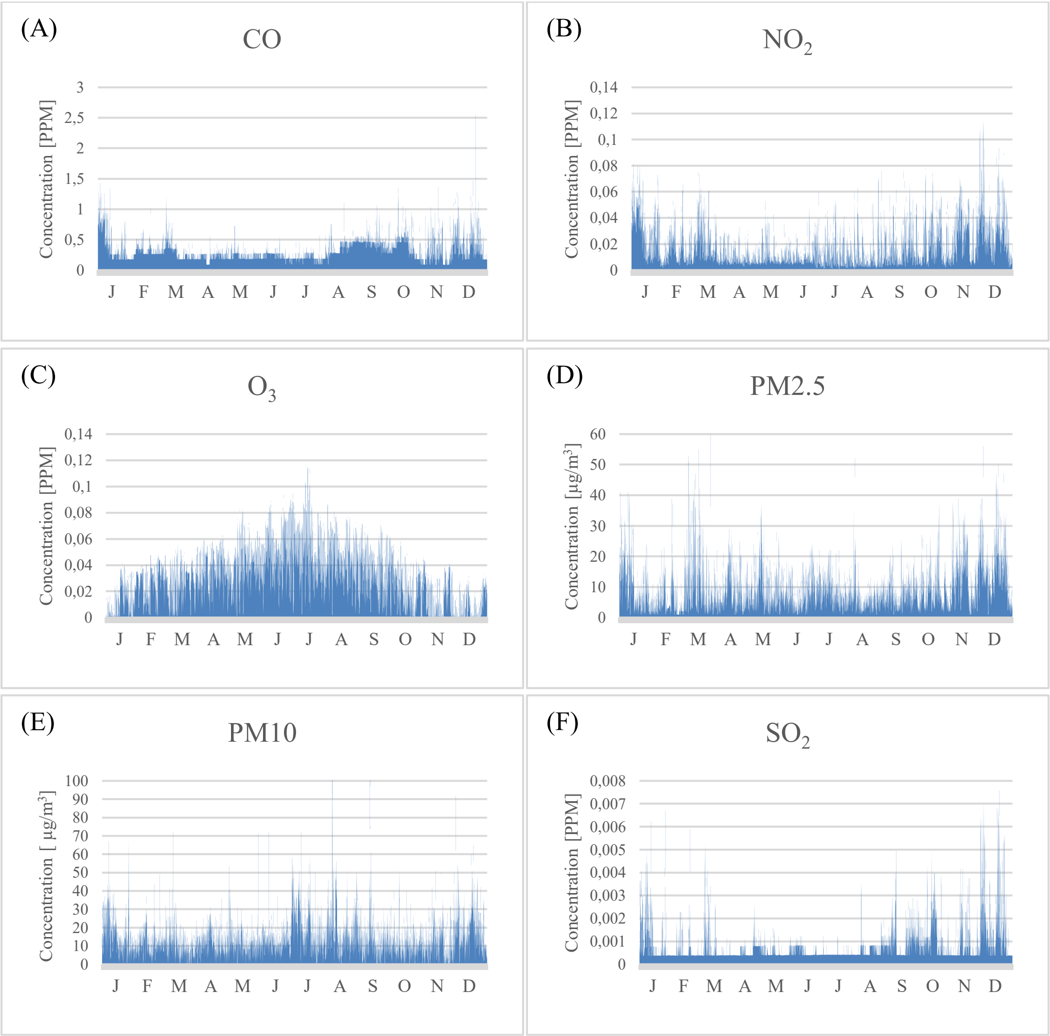

Figure 4.4: Pollution Data in 2015: air pollutant daily concentration for (A) CO; (B) NO_2; (C) O_3; (D) PM2.5; (E) PM10 and (F) SO_2.

4.3 Results

4.3.1 General overview on the greenery structure

An evaluation of the vegetation structure, function, and value of the urban forest in Boadilla del Monte has been undertaken. The Boadilla del Monte urban forest consists of 33,255 trees with a tree coverage of 30.8 percent (see Figure 4.6 for the distribution of tree population by district). The three most prevalent species are *Platanus orientalis* (19.3%), *Pinus pinea* (17.7%), and *Pinus halepensis* (9.3%). Table 4.1 outlines the key characteristics of the ten most populous species in the urban greenery, while refer to Appendix B (Table B.3) for the complete list of species data.

Table 4.1: Population Summary by DBH class for the top 10 most populated species.

Species	**Percent of population**	**Leaf Area (m^2)**	**Leaf Biomass (metric ton)**
Platanus orientalis	19.3 %	981,110	45.067
Pinus pinea	17.7 %	1,313,810	126.633
Pinus halepensis	9.3 %	1,046,390	100.856
Acer negundo	8.1 %	228,070	20.864
Cupressus sempervirens	3.6 %	83,510	19.577
Tilia cordata	3.1 %	48,640	3.644
Pyrus communis	3.0 %	30,030	2.259
Platanus x hybrida	2.8 %	79,450	3.469
Prunus cerasifera	2.5 %	31,680	1.925
Iva sp.	1.9 %	46,480	10.111

Regarding DBH, it varies from a minimum of 3 centimeters to a maximum of 159 centimeters with a 37% of urban trees have a diameter less than 15.2 centimeters (6 inches), demonstrating the youthfulness of a significant portion of the tree population. Figure 4.5 shows the distribution of the ten most populated species according to their DBH: while some differences can be observed, all species exhibit peaks situated within the low-medium DBH range, between 7.6-15.2 cm and 45.7-61.0 cm.

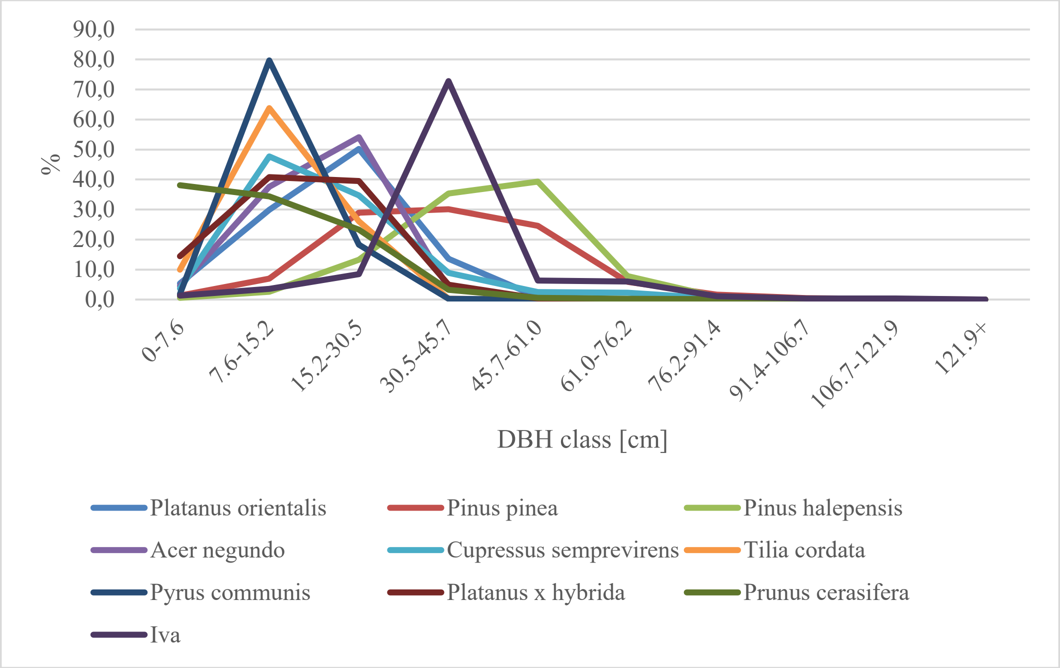

Figure 4.5: Population Summary by DBH class for the top 10 most populated species in the project area.

Nowak (1996) argues that estimating the leaf area and biomass of trees in both urban and natural areas is crucial for evaluating the processes of evapotranspiration, atmospheric deposition, biogenic volatile organic emissions, light interception, and other ecosystem services. It is therefore vital to quantify these values and assess the urban tree population's ecosystem services, using the regression equations upon which the i-Tree Eco's model is based (see Nowak, 1996 for further investigation and Nowak, 2021 for an in-depth analysis about the i-Tree Eco functioning).

In Boadilla del Monte, the leaf area covers 4.71 square kilometers, with the highest values in *Las Lomas* (1.49 square kilometers), followed by *Sector B* (0.47 square kilometers) and *Sectors 2, 3, y 4* (0.39 square kilometers). However, the distribution of leaf area per tree differs significantly from its absolute distribution by district. As shown in Figure 4.6, *Las Lomas* (348 square meters per tree), *Montepríncipe* (274 square meters per tree), and *Monte de las Encinas* (233 square meters per tree) have the three highest values. *Pinus pinea*, *Pinus halepensis*, and *Platanus orientalis* are the dominant species in terms of leaf area, representing over 70% of the total, as shown in Table 4.1.

Moreover, the total leaf biomass stored in Boadilla del Monte is 408.89 metric tons, with 12.26 thousand metric tons of tree dry weight biomass. *Pinus pinea* and *Pinus halepensis* together account for more than 50% of the total, as evidenced by Table 4.1. For the results by species and by district, please consult Appendix B (Tables B.4 and B.5).

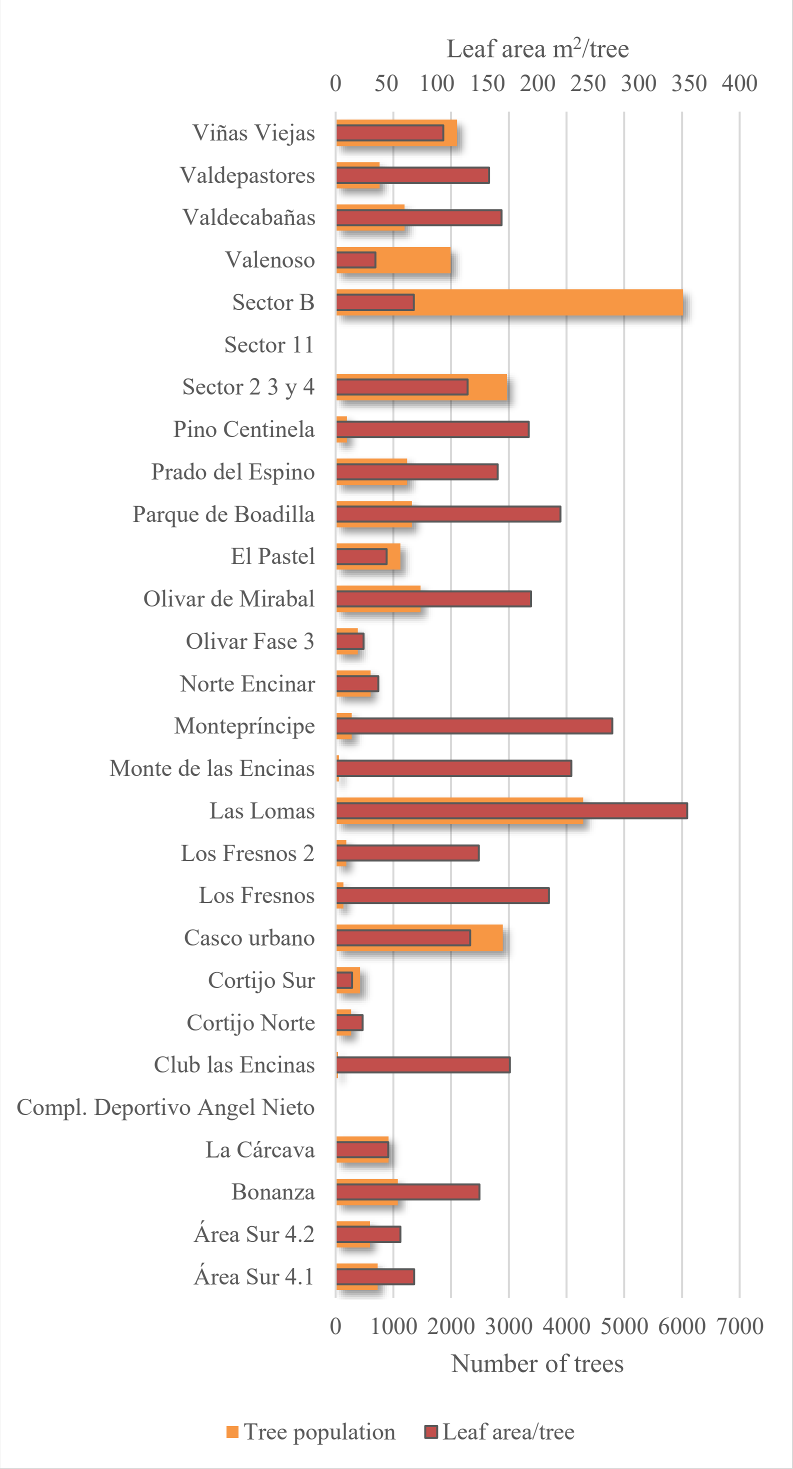

Figure 4.6: Population Summary by district.

4.3.2 General of Ecosystem Services

Table 4.2 summarizes the results about ES provision by the urban trees of Boadilla del Monte in 2015, for each of which a specific focus is dedicated.

Table 4.2: Ecosystem Services summary for Boadilla del Monte.

Ecosystem Service	Amount	Monetary value
Air Pollution Removal	7.408 t/yr	39,000 €/yr
Carbon Storage	6,131 t	1,919,310 €
Carbon Sequestration	278.11 t/yr	87,062 €/yr
Avoided Surface Runoff	7,557 m^3/yr	14,373 €/yr
Oxygen Production	741.60 t/yr	-
Replacement value		$43.75 \cdot 10^6$ €

Air pollution removal by urban trees. The effectiveness of urban trees in removing pollution in Boadilla del Monte was determined using field data and available pollution and weather data. The study revealed that trees remove 7.41 metric tons of air pollution annually, particularly 4176.02 kilograms of ozone (O_3), 122.918 kilograms of carbon monoxide (CO), 1197.03 kilograms of nitrogen dioxide (NO_2), 92.06 kilograms of particulate matter less than 2.5 microns (PM2.5), 1710.14 kilograms of particulate matter less than 10 microns and greater than 2.5 microns (PM10), and finally 109.43 kilograms of sulfur dioxide (SO_2). Figure 4.7 portrays the monthly pattern of pollution removal in Boadilla del Monte for each air pollutant, while additional information regarding the dry deposition flux per unit tree cover can be found in Appendix B (Figure B.1). For ease of reference, the pollutants have been categorized into two separate graphs based on their values' order of magnitude. Fig. 8-A reveals a nearly consistent pattern of monthly values for PM10 and NO_2 throughout the entire year, whereas O_3 reduction was primarily concentrated in the middle portion, peaking at around 600 kilograms during the summer months. Conversely, Fig. 8-B illustrates a fluctuating distribution for all three pollutants, with a more pronounced effect observed for PM2.5 and a less noticeable impact for SO_2, spanning across the entire year.

Trees remove PM2.5 and PM10 when the particles are deposited on leaf surfaces (Nowak et al., 2013). The particles can be washed off by precipitation, resuspended into the atmosphere or dissolved or dropped to the soil, which can result in diverse pollution removal values depending on the atmospheric factors, as seen in 2015 in Boadilla del Monte (Figure 4.7).

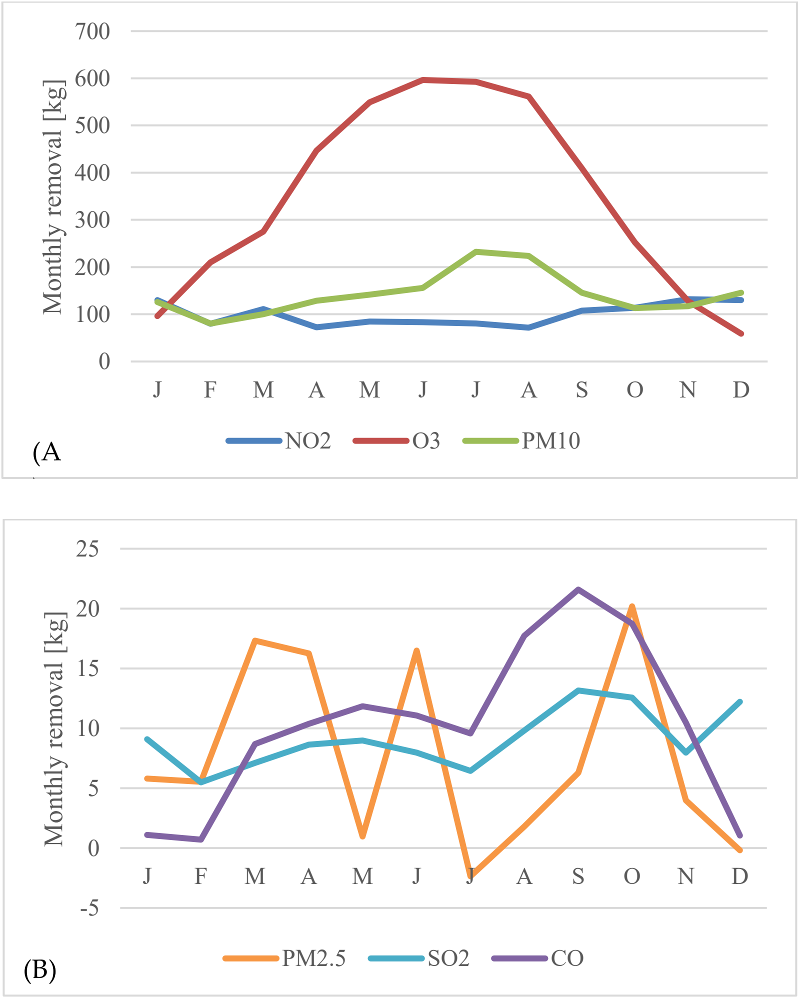

Figure 4.7: Monthly air pollutant removal trend in Boadilla del Monte for (A) NO_2, O_3, PM10; (B) PM2.5, SO_2, CO.

In the year 2015, trees within the Boadilla del Monte area released an estimated 5.262 metric tons of volatile organic compounds (VOCs). Specifically, this comprised 3.869 metric tons of monoterpene and 1.393 metric tons of isoprene, as depicted in Figure 4.8. Notably, during the summer months, these emissions reached peak levels exceeding 2,500 grams per hour for monoterpene and 2,000 grams per hour for isoprene. The emission levels of VOCs vary depending on various environmental factors, including tree species and the biomass of dry leaves (as detailed in Table B.4 in Appendix B for each species).

Consequently, it was found that 59 percent of the urban forest's VOC emissions originated from *Pinus pinea* (amounting to 1.734 metric tons per year) and *Pinus halepensis* (equating to 1.381 metric tons per year). Remarkably, these two tree species accounted for over 50 percent of the total leaf dry weight biomass within the urban tree inventory. It is important to note that these VOCs serve as precursor chemicals for ozone formation.

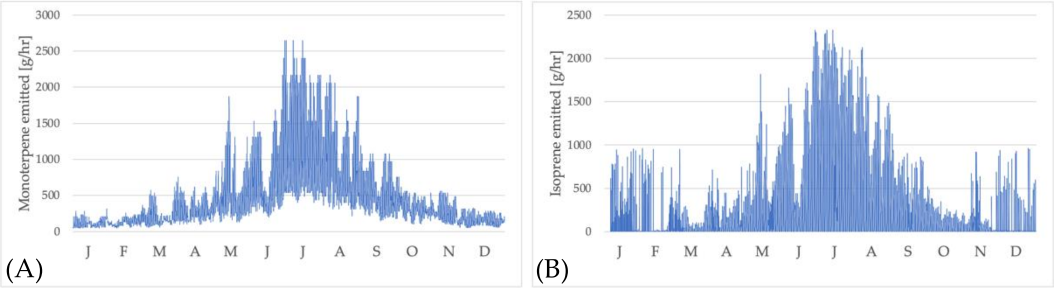

Figure 4.8: Monoterpene (A) and Isoprene (B) emitted by trees during 2015.

The determination of air pollution mitigation using the i-Tree model relies on deposition velocities and flux patterns, which have been validated to align with actual field measurements (Nowak, 2021). Consequently, it provides accurate estimations. However, it is important to note that the model does not consider local-scale tree interactions, and the level of certainty regarding health effects remains uncertain. Regarding VOC emissions, the calculation method is deemed reliable, although there is room for improvement in estimating ozone formation.

Carbon storage and sequestration. Urban trees have the potential to mitigate climate change by sequestering atmospheric carbon through the uptake of carbon dioxide (Safford et al., 2013) and it can affect energy consumption in buildings, thus impacting carbon dioxide emissions from fossil-fuel powered sources (Abdollahi et al., 2000). Trees are capable of reducing the amount of carbon in the atmosphere by sequestering carbon during each year of growth, depending on different features, such as projected tree growth, leaf area and meteorological data. In Boadilla del Monte, the estimated gross sequestration of carbon by trees is approximately 278.1 metric tons per year, distributed per urban district and per species as in Appendix B (Tables B.9 and B.13 respectively).

Furthermore, carbon storage in trees can also contribute to mitigating the effects of climate change (Kauppi et al., 2022). As trees grow, they store carbon in their tissues. When a tree dies and decays, the stored carbon is released back into the atmosphere. Therefore, the amount of carbon stored in a tree can be used as an indication of the amount that will be released if the tree dies. Proper tree maintenance can help to maintain carbon storage and reduce the amount of carbon emitted, as discussed in Nowak et al. (2002). In Boadilla del Monte, trees are estimated to store 6,130 metric tons of carbon, with *Pinus pinea* being the species that stores and sequesters the most carbon (32.5% of the total carbon stored and 23.5% of the sequestered carbon) (Boadilla del Monte City Hall, 2016). Refer to Appendix B (Table B.13) for additional information regarding the carbon storage and sequestration by species.

The use of the i-Tree framework is appropriate for determining carbon storage as it is linked to estimations of tree biomass, which are directly derived from tree measurements. In terms of total carbon sequestration, its dependability also hinges on estimations of tree growth, which are believed to fall within the range of measured values (Nowak, 2021). Moreover, the estimation of net sequestration, in addition to total sequestration, considers decomposition estimates. These estimates, in turn, rely on assumptions regarding mortality rates, which have been adopted as the default values provided by i-Tree for this particular analysis.

Avoided Surface Runoff. Surface runoff can be a source of concern in many urban areas, as it can lead to pollution of streams, wetlands, rivers, lakes, and oceans. When it rains, some of the precipitation is intercepted by vegetation such as trees and shrubs, while the rest reaches the ground. This portion that reaches the ground and does not infiltrate into the soil is known as surface runoff (Hirabayashi, 2013), and the amount of it is increased in urban areas due to the large extent of impermeable surfaces. Urban trees and shrubs play a vital role in reducing surface runoff through processes such as interception, evaporation, and transpiration, and their root systems facilitate infiltration and storage in the soil.

The 33,255 urban trees in Boadilla del Monte contribute to avoiding 7,557 cubic meters of surface runoff per year, comparable to over 3 Olympic-size swimming pools. This estimate is based on the sampled tree population's ability to reduce the amount of rainwater flowing superficially in the city. The methodology incorporates meteorological data from the reference year, which includes almost 9,000 annual precipitation values, with hourly frequency, spanning from 1 January to 31 December, for a total rainfall of 278 millimeters. i-Tree Eco enables the direct selection of meteorological stations based on proximity to the study area.

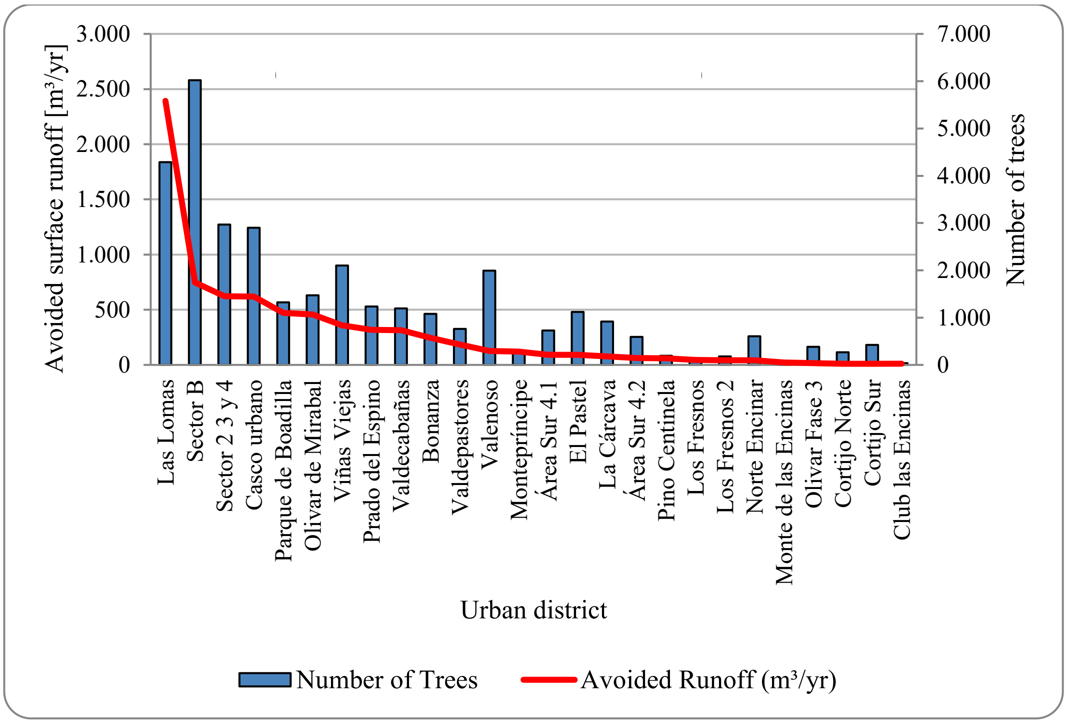

Figure 4.9: Avoided surface runoff and tree population by urban district of Boadilla del Monte.

At the local level (Figure 4.9), *Las Lomas* displayed the highest yearly contribution to the examined ecosystem services (2,393 cubic meters) and possessed the most significant values for all hydrological elements considered, despite not having the largest tree population (4,288 trees). *Sector B* had the most densely populated area (6,020 trees) despite having a surface water runoff that was less than one-third of the corresponding value for *Las Lomas* (748 cubic meters). The most influential parameter of ecosystem services was identified as leaf area, as the various hydrological components related to retained water value relied on the overall surface area of leaves. The lack of correlation between the number of trees and the total leaf area was attributed to the diverse configurations and sizes of tree leaves, as well as the impact of tree age on the leaf area measurement.

The tree population sample in Boadilla del Monte encompasses more than 110 distinct species, with approximately 40 of them having fewer than 10 individual trees. This particular section investigates the behavior of the top 10 species that have a notable influence on preventing surface runoff, and the primary findings are summarized in Table 4.3. Each species is linked to specific values regarding tree population, overall leaf area, avoided surface runoff, and the elements of potential evapotranspiration, evaporation, transpiration, and water interception. Potential evapotranspiration refers to the amount of water released from the soil and trees under optimal water supply, transpiration represents the release of water vapor influenced by leaf resistance, rainfall interception denotes the capture of water by tree leaves, and tree evaporation represents a portion of the intercepted precipitation vapor released back into the atmosphere (Hiirabayashi, 2015). It is evident that the number of trees does not directly impact the hydrological elements that determine retained surface runoff, but rather the emphasis lies on the leaf area. i-Tree Eco estimates this value for each individual tree in the sampled population by considering DBH (diameter at breast height), crown height and dimensions, health condition, light exposure, and other factors during the data input phase. Providing these input data ensures accuracy, and the average leaf area value for a single tree depends on the species and the aforementioned characteristics. For example, young trees tend to have smaller leaves, and this factor affects the overall value associated with the species.

Platanus orientalis, despite having the highest tree count (6,416), exhibits a smaller overall leaf area compared to trees of the *Pinus* genus, resulting in lower values of avoided surface runoff. Among the urban trees in Boadilla del Monte, the species with the greatest individual contribution to avoided surface runoff is *Pinus pinea* (5,884 trees), with a value of 2,106 cubic meters. *Pinus halepensis* (3,084 trees) demonstrates the best performance per tree, with an associated value of 1,677 cubic meters. *Populus alba* achieves the highest efficiency per individual tree due to its above-average leaf area values. Among the 10 reported species, *Cupressus sempervirens* is the least effective in reducing surface runoff.

Table 4.3: Hydrological effects compared to urban canopy structure for the 10 species with greatest overall impact on runoff.

Species	**Trees** [-]	**Leaf Area** [m^2]	**Potential evapotransp.** [m^3/yr]	**Evaporation** [m^3/yr]	**Transpiration** [m^3/yr]	**Avoided runoff** [m^3/yr]
Pinus pinea	5,884	1,313,810	124,180	10,061	37,485	2,106
Pinus halepensis	3,084	1,046,390	98,903	8,013	29,855	1,677
Platanus orientalis	6,416	981,110	92,733	7,513	27,992	1,573
Acer negundo	2,688	228,070	21,557	1,747	6,507	366
Pinus pinaster	508	113,980	10,774	873	3,252	183
Populus alba	248	89,100	8,421	682	2,542	143
Ulmus pumila	423	86,320	8,158	661	2,463	138
Cupressus sempervirens	1,183	83,510	7,894	640	2,383	134
Platanus x hybrida	926	79,450	7,509	608	2,267	127
Quercus ilex	432	51,020	4,822	391	1,456	82

The estimation of hydrological effects, including the reduction in surface runoff, carries an unknown level of uncertainty. However, this uncertainty is considered moderate, as i-Tree Eco simplifies certain assumptions from the i-Tree

Hydro model, which is a tool specifically designed for hydrological modeling of vegetation at the urban scale.

Oxygen Production. It is a well-known benefit of urban trees, with the amount produced annually being dependent on the level of carbon sequestered by the tree and the accumulation of tree biomass (Sharma et al., 2019).

In Boadilla del Monte, trees are estimated to produce 741.6 metric tons of oxygen per year, with distribution among urban districts shown in Figure 4.10 and compared to annual gross carbon sequestered. From the graph, it is evident that the highest oxygen supplier is *Las Lomas* (almost 170 metric tons per year), followed by *Sector B* (more than 100 metric tons per year) and *Casco urbano* (about 74 metric tons per year). Additional details about oxygen production by district with corresponding relative values are shown in Appendix B (Table B.12).

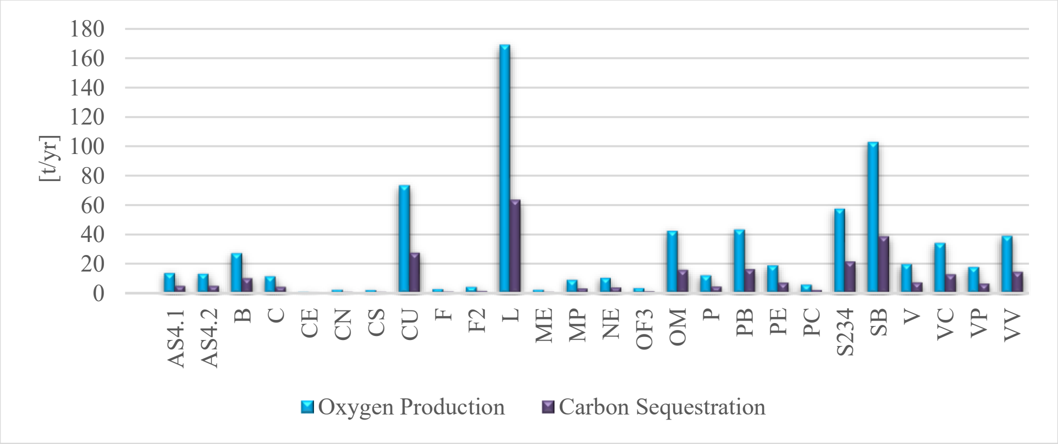

Figure 4.10: Oxygen Production and gross carbon sequestration by urban district.

4.3.3 Monetary evaluation and Cost vs Benefit analysis

Following the Materials and Methods chapter, the environmental services (ES) measured by i-Tree Eco were converted into economic values (see Sub-sub-chapter 2.3.2) by using the benefit unit prices listed in Appendix B (Table B.2): (i) 85.30 euros per CO_2 metric ton (carbon storage and gross carbon sequestration), based on the European Union Emissions Trading System (EU ETS) updated as of May

2022; (ii) 1.902 euros per cubic meter for avoided surface runoff; (iii) for pollution removal: 1,095.27 euros per metric ton (CO), 3,918.42 euros per metric ton (O_3), 584.69 euros per metric ton (NO_2), 212.92 euros per metric ton (SO_2), 136,099.27 euros per metric ton (PM2.5), and 2,974.64 euros per metric ton (PM10); (iv) no monetary value was assigned to oxygen production due to its relatively insignificant contribution to the atmosphere and extensive production by aquatic systems. Instead, the replacement value of a tree was estimated as the local cost of replacing a similar tree, and the total value represents the estimated cost of replacing all urban trees.

There is a tendency to combine positive estimates of ozone removal effects with negative values of VOC emission effects to determine the overall effect of trees on ozone. However, this should not be done. Instead, estimates of VOC effects on ozone formation should be directly contrasted with ozone removal by trees.

It has also been proven that trees lower ozone concentrations by reducing air temperature (Cardelino & Chameides, 1990), but this effect has not been examined in this analysis. The i-Tree report suggests further modeling to combine tree effects on air temperature, pollution removal, and VOC emissions to better understand the overall effect of trees on ozone concentrations.

The final results are presented in Table 4.2 and Table 4.4. Carbon storage has a total value of almost 2 million euros, depending on the total biomass available in the urban greenery during the analysis. The annual monetary estimate is about 140 thousand euros, with carbon sequestration contributing the largest amount (about 62%). Figure 4.11 shows that O_3 reduction contributes almost 50% to the total air pollutant removal value, followed closely by PM2.5 at about 37%. The analysis also estimated a replacement value of over 43 million euros.

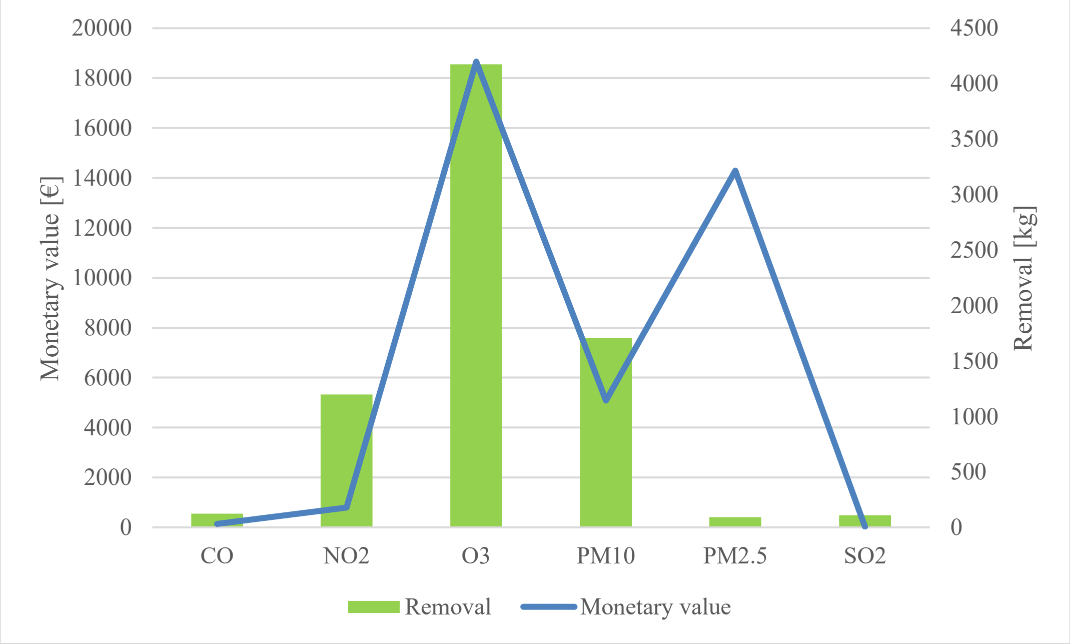

Figure 4.11: Monetary estimation of air pollutants removal according to the related removal in Boadilla del Monte in 2015.

Subsequently, in collaboration with the Municipality of Boadilla del Monte, the average costs incurred annually by the public administration for ordinary and extraordinary maintenance of urban trees were estimated. Cost assumptions were based on tree macro-categories: new tree plantation, tree maintenance, and dead tree removal. An average annual number of affected trees for each category was considered, and an economic evaluation updated to November 2022 was obtained from Base de Precios Paisajismo (BPP), a Spanish price base specialized in urban public space, garden, and park projects (Paisajismo, 2022). The annual estimates included 500 planted trees (23.24 euros per tree), 1000 maintained trees (36.31 euros per tree), and 500 removed trees (38.47 euros per tree); further information can be found in Appendix B (Table B.6).

Table 4.4 summarizes the annual environmental estimates of benefits and costs relating to urban trees in Boadilla del Monte. The corresponding value in euros per single average tree and euros per single average capita are reported for each item of both categories considering a total population of 33,255 trees and a city population of 62,627 inhabitants.

Table 4.4: Net annual benefits for urban trees of Boadilla del Monte, considering the annual ES evaluated with i-Tree Eco.

Benefits	**Total (€)**	**€/tree**	**€/capita**
Avoided Runoff	14,373	0.43	0.24
Carbon Sequestration	87,062	2.62	1.39
Pollution Removal	39,000	1.17	0.65
Total Benefits	**140,435**	**4.22**	**2.24**
Costs			
Purchasing trees and planting	11,620	0.35	0.19
Contract pruning	36,310	1.09	0.58
Removal	19,235	0.58	0.31
Total Costs	**67,165**	**2.02**	**1.07**
Net Benefits	73,270	2.20	1.12
Benefit-cost ratio	2.09	2.09	2.09

The most significant findings of the "Costs vs Benefits" analysis are presented in the last two rows of Table 4.4. A net benefit of 73,270 euros emerges, with the benefit-cost ratio values greater than or equal to 2: the total benefit produced by urban trees doubles the costs for the reference year. It can be concluded that green spaces within urban areas are not just an expense, but the costs of maintaining them can be offset by the long-term benefits to the health and well-being of the citizens. Moreover, it is noteworthy that the urban tree population in Boadilla del Monte is relatively young and has an even higher potential for future SE productivity, as per some studies (Moody et al., 2021) that consider specific ecosystem services. Periodic analysis and comparison, for instance, every five years, could aid the Municipality of Boadilla del Monte in monitoring the tree population's growth and ES productivity progress.

4.4 Discussion

This chapter delves deeper into aspects related to the outputs just shown. Specifically, it focuses on the role of districts on the total production of ecosystem services (ES) in Boadilla del Monte, the efficiency of the tree species, and a comparison with other cities. Differentiating tree cataloging by district when entering input data allows for comparisons between different urban areas. However, the influence of each district's peculiarities on the comparison, which were not considered in this study, should be noted (refer to Tables B.8, B.9, B.10, B.11 and B.12 in Appendix B for complete outputs by district).

Among the districts with urban trees cataloged, *Complejo Deportivo Angel Nieto* and *Sector 11* have zero values. *Las Lomas* appears to be the district with the best results in total terms, considering its 4,288 trees (about 13%) out of a total of 33,255. It produces 35% of urban carbon storage, 32% of avoided runoff (Figure 4.9) and pollution removal, and 23% of carbon sequestration (Figure 4.10) and oxygen production (Figure 4.10). *Sector B*, with 6,020 urban trees equal to 18%, is the second most productive district for all ES, except for carbon storage, where *Casco Urbano* (2,899 trees equal to 8.7%) prevails, contending for the third place with *Sector 234* (2,968 trees equal to 9% of total tree population). *Sector B* contributes 14% to the total carbon gross sequestration and oxygen production, and 10% to the total pollution removal and avoided runoff, while it produces 8.3% of the total carbon storage, overtaken by *Casco Urbano* which contributes with a 9.3%.

Despite their 0.368 square kilometers and 0.237 square kilometers respectively, which are equivalent to almost 22% of the total, *Montepríncipe* and *Parque de Boadilla* contribute little towards ES. *Club las Encinas*, *Cortijo Sur*, and *Cortijo Norte* are the worst districts in absolute terms, with general contributions of 0.2%, 0.3%, and 0.3% for all ES, with the exception of carbon storage in which *Olivar Fase 3* replaces *Club las Encinas*. *Monte de las Encinas* is also one of the least contributing districts, particularly for carbon gross sequestration and oxygen production (Figure 4.10) with less than 0.5%.

The primary discoveries mentioned earlier were presented in relation to the population of trees. However, it is important to highlight that the conducted analysis revealed that the number of trees does not directly impact the evaluation of ecosystem services (ES). This can be observed in Tables B.8 to B.12 provided in Appendix B, which specifically concentrate on the assessment of ES within each urban district. Therefore, within the Sub-sub-chapter 4.3.2, a thorough discussion has been anticipated to identify the key parameters and factors that predominantly influence each benefit provided by urban trees in Boadilla del Monte. The detailed analysis is presented below.

To optimize sustainable future planning of urban green areas, analyzing the species' effectiveness on ES production deserves more investigation. Table B.13 in Appendix B summarizes the species contribution to each ES in both environmental and economic terms. In terms of absolute values, *Pinus pinea* emerged as the species with the highest provision of ecosystem services (ES) furniture, surpassing *Platanus orientalis*, despite the latter being more abundant in the urban area of Boadilla del Monte. *Pinus halepensis* ranked third in ES productivity. It is noteworthy that trees belonging to the *Pinus* genus (*Pinus halepensis*, *Pinus pinaster*, *Pinus pinea*) accounted for 40 percent (carbon sequestration) to 55 percent (carbon storage) of the overall ES supply, depending on the specific ES considered. It is interesting to highlight that among the top ten most influential species in the urban area, *Pinus halepensis* exhibited the highest efficiency per individual tree. Specifically (Nowak, 2021): (i) the production of oxygen is directly linked to carbon sequestration, which primarily depends on leaf area, tree growth, light exposure, and the number of frost-free days in the area; (ii) carbon storage capacity is influenced by crown dimensions and tree health. Notably, *Pinus pinea* exhibited approximately four times greater dry weight biomass than *Platanus orientalis*, resulting in a similar disparity in carbon storage; (iii) both air pollution removal and avoided surface runoff are strongly influenced by leaf area. For instance, *Pinus pinea* possessed a leaf area that was 1.3 times larger than *Platanus orientalis*, resulting in similar rates of air pollutant removal and surface runoff reduction.

Furthermore, it is worth highlighting the exceptional efficiency of *Cupressus cashmeriana*, which holds the record for each ES on a per-tree basis, with an individual tree boasting a leaf area of 380 square meters and a dry weight biomass of 5.072 metric tons. Additionally, *Populus x canadensis* displayed notable performance in terms of carbon gross sequestration and pollution removal. For more details, refer to Appendix B (Table B.13).

About the monetary evaluation discussed in Sub-sub-chapter 4.3.3, it could be valuable to utilize a comparative analysis with other urban areas as a means of gaining a better understanding of the results (see Appendix B, Table B.7) but even more, it is should be highlighted a general lack of socio-political interest in addressing hydrogeological stress and risk, especially in urban: this neglect reveals the challenges of ascribing economic value to ES, despite the economic and environmental damages caused by floods in urban spaces.

4.4.1 Conclusions

Urban trees are essential for improving the environment and well-being of city residents by providing multiple benefits. The study is part of a wider project aimed at assessing the urban ecosystem services of the city of Boadilla del Monte in collaboration with the local administration. The main goal was to analyze the role of urban trees on the surrounding environment. Results show that public green spaces in urban areas are an effective adaptation and mitigation strategy for addressing climate change challenges. Trees play a crucial role in reducing urban air pollution, surface water runoff, and carbon sequestration and storage, while also producing oxygen. The presence of trees in Boadilla del Monte is an invaluable resource for promoting environmental sustainability in the city. Additionally, this analysis demonstrates that the ecosystem services provided by urban green spaces have significant social value, including improving the health and well-being of citizens through cleaner air and reduced exposure to hydrological risks. Furthermore, to highlight the economic value of these benefits, a cost-benefit analysis was conducted by estimating management expenses and monetary evaluations of various ecosystem services provided. The study also includes a chapter discussing the contribution of Boadilla's urban districts to the city's sustainability and identifying the most efficient tree species for future urban planning to support sustainable environmental development.

The utilization of meteorological data from 2015 serves as a limitation since it is not entirely consistent with the year of analysis. However, this decision was necessary as data from the reference station closest to the study area, containing complete meteorological and pollutant concentration data for 2015, was already included in the i-Tree Database (Sub-sub-chapter 2.4.1). While the database for the over 33 thousand trees in Boadilla del Monte was carefully obtained, its accuracy could have been enhanced having more additional recommended data: the health condition of trees, which affects leaf area and photosynthetic activity, as well as the growth rate, was not fully implemented in the software due to incomplete knowledge of the entire inventory. Additionally, including canopy width as input data could have improved result accuracy, as it directly influences leaf area, shading estimates, and the provision of ecological services and local temperature mitigation.

The present project, which resulted in a comprehensive ES analysis of the tree population within the urban areas of Boadilla del Monte, has ongoing developments. The primary focus is on mitigating Urban Heat Islands (UHI) in the city, provided by green areas, by combining the results obtained from i-Tree with considerations about managing urban temperatures, resulting in a more comprehensive summary of the benefits offered by urban greenery. To accomplish this, additional tools for evaluating ES are being implemented. Another crucial aspect of the project is to examine the cultural ecosystem services associated with it. Specifically, a collaboration with the Municipality of Boadilla del Monte resulted in a questionnaire addressed to residents with the deadline set for November 30, 2022. The questionnaire has ten sections and primarily aims to evaluate some socio-cultural indicators (recreational, sense of place, esthetics, cultural heritage) and to deepen the audience's understanding of the correlation between climate change and ES. Finally, the questionnaire also includes questions aimed at assessing the degree of citizen satisfaction with the Municipality's implementation of mitigation and adaptation solutions for current and future climate change, which results are commented in the next sub-chapter.

4.5 Cultural Ecosystem Services

4.5.1 Introduction

This part of the project focuses on a socio-cultural survey that was conducted among the citizens of Boadilla del Monte. The goal of this survey was to explore the cultural significance of the ecosystem services provided by the city's greenspaces, including the various classes of services identified in the literature. The study is unique in that it sought to gauge the general public's understanding of current environmental issues such as climate change and ecosystem services. The specific objectives of this research were: (i) to obtain a measure of the socio-cultural values of the urban tree population in Boadilla del Monte from the perspective of the users; (ii) to quantify citizens' knowledge of current environmental issues such as ecosystem services and climate change adaptation using statistical analysis; and (iii) to provide a platform for citizens to express their views on the measures taken by the Municipality thus far, as well as future plans to mitigate the impact of climate change. The paper is divided into several chapters, including Introduction, which provides an overview of the topic, Materials and Methods, which describes the survey's design and content, Results, which presents the findings of the survey, and Discussion and Conclusions, which summarize the main findings and draw conclusions on the survey's use in the future.

4.5.2 The socio-cultural survey

The survey was inspired by literature on the role of greenspaces in the city (Maury-Mola et al., 2022) and socio-cultural questionnaires used by organizations such as the Municipality of Turin, Municipality of Piacenza, and Polytechnic University of Madrid. It was further developed to deepen understanding of ecosystem services and climate change, drawing upon the expertise of the authors and professionals acknowledged in the study. The questionnaire was then modified and approved by the Department of Environment, Sport and Celebrations of the City Council of Boadilla del Monte before being disseminated anonymously and digitally through Google Forms. The survey was shared on the social media channels of the Municipality of Boadilla del Monte (Facebook, Instagram) and the official website of the Municipality. It was available online from October 25, 2022 to November 30, 2022 and was exclusively presented in Spanish, a faithful translation of which is provided in Appendix C. The confidentiality and anonymity of responses were ensured in accordance with current legislation.

The survey comprised of 84 questions across 10 sections, as described in Table 4.5. The aim was to assess citizens' perceptions of public green spaces in the city and their association with climate change. It covered individuals' profiles, evaluation of urban green areas based on socio-cultural aspects, insights into ecosystem services and climate change, and citizens' opinions on the Municipality's commitment. Most of the questions were compulsory, closed-form, and multiple-choice, while the optional open-ended questions were mainly used for citizens' comments and suggestions to the municipal administration and were not considered for the study.

Table 4.5: Structure of the questionnaire.

Section	Name	Description
1	Profile and use of green areas	General information about citizens and their use of greenspaces
2	Recreational value	Role of greenery as recreational space
3	Sense of place and cultural heritage	Role of greenery as place of identity and culture
4	Aesthetics and ecosystem services definition	Aesthetic value of greenery and citizens' knowledge survey about ecosystem services
5	Beneficiaries of urban green areas and monetary value	Comparison among urban beneficiaries and economic aspects linked to greenery
6	Current consequences of climate change	Citizens' knowledge survey about ongoing climate change
7	Future consequences of climate change	Citizens' knowledge survey about future climate change
8	Ecosystem services	Citizens' knowledge deepening about future climate change
9	Current commitment of the Municipality	What has been done so far by the Municipality to fight climate change
10	Future commitment of the Municipality	What will have to be done in the future by the Municipality to fight climate change

To ensure a cohesive structure, questions relating to the same topic were grouped together in a temporal, logical, and psychological order (Sierra Bravo, 1997). In contrast to Tobler et al. (2012) approach towards consumers' knowledge of CC, a five-point response scale ranging from 1 to 5 was used for most of the questions.

As previously mentioned, the questionnaire targeted citizens residing in the municipality of Boadilla del Monte, part of the “Comunidad Autónoma de Madrid” (Spain). Boadilla del Monte is a representative suburban expansion of Madrid, with the majority of residents comprising young couples with children and a high socio-economic and educational status. The community boasts the highest income in the region, with the majority holding a higher education degree and occupying professional positions in stable employment situations. With an advantageous location close to nature and the capital, the municipality transitioned from being a second home area to a preferred residential location, reflected in the modern housing options (only 3.4% built before 1950) and prominent semi-detached urbanizations accompanied by vast green spaces and communal amenities.

This survey is part of a broader project, "Urban green infrastructure: ecosystem services and sustainable development objectives," collaboratively developed between Universidad Politécnica de Madrid and the Municipality of Boadilla del Monte, aimed at assessing the contribution of urban trees towards the ES provided by green infrastructure. Focusing on the socio-cultural ES, the project's quantitative evaluation is based on Busca et al. (2023) investigation. Out of 146 survey responses, the key findings are outlined and discussed in the subsequent chapter.

4.5.3 Sampled citizenship and use of greenery

The methodology outlined in the Sub-sub-chapter 4.5.2 was used for the drafting of a questionnaire to be submitted to the residents of Boadilla del Monte. Section 1 asked respondents to provide general information that would aid in defining the average profile of those being surveyed. Results (Table 4.6) indicate that the average age of respondents is largely concentrated between 40 and 64 years (over 65%) and gender participation is almost equal (51% and 49%). Nearly all participants are residents of Boadilla del Monte (99%) and are spread across the 23 neighborhoods listed in the survey. Respondents are mostly highly educated (77%) and currently hold full-time jobs (69%). According to data from the Spanish Statistics National Institute for 2022, the sample of citizens surveyed is a significantly representative sample of the population of Boadilla del Monte in terms of gender (with the same percentages) and age-distribution (with the exception of minors); furthermore, 62.1% of Boadilla del Monte's population has achieved higher education, which matches the results of the survey (Instituto Nacional de Estadística, Demografía y población; Ayuntamiento de Boadilla del Monte).

Table 4.6: Summary of the sample citizen profile.

General information	**Categories**	**%**
Age	<18	1.4
	18-29	8.2
	30-39	18.5
	40-49	35.6
	50-64	29.5
	≥65	6.8
Gender	Male	48.6
	Female	50.7
	Other	0.7
Education	No studies	0.0
	Primary studies	0.0
	Secondary studies	6.8
	Job training	10.3
	Higher education	76.7
	PhD	6.2
Employment	Full-time worker	68.5
	Part-time worker	6.8
	Occasional worker	1.4
	Student	5.5
	Unemployed	4.1
	Other	13.7

General information	Categories	%
Residential status	Resident in Boadilla del Monte	98.6
	Not resident in Boadilla del Monte	1.4

In order to provide a clearer profile of the group under examination, individuals were requested to answer questions regarding their usage of urban green spaces. The primary outcomes of these questions are showcased in Figure 4.12. The data showcases that the primary use of these spaces is for walking (roughly 58%) and with family. There is a minimal amount of individuals who walk through the area with colleagues from their study or work (less than 1%), nor for resting purposes (roughly 2%), transit (less than 1%), and reading/study (0.7%). The usage frequency is usually daily (40%) or possibly on weekdays (around 25%), with weekly use extending to over six hours in some cases (30%).

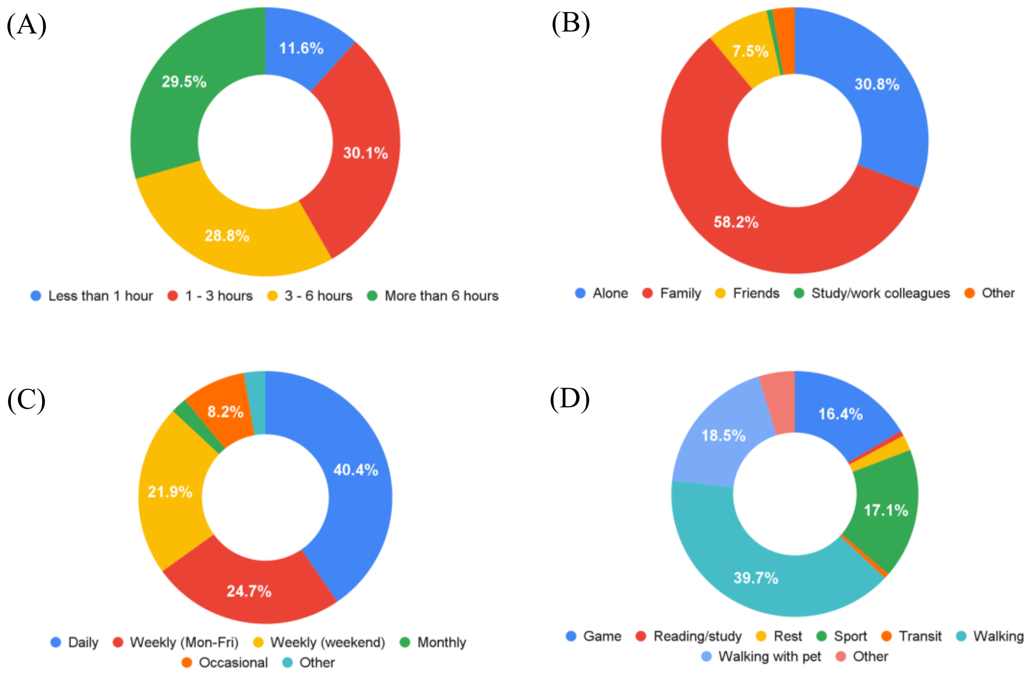

Figure 4.12: Use of greenery in Boadilla del Monte: (A) number of hours a week; (B) with who; (C) frequency; (D) reason.

Table 4.7 to Table 4.10 utilized a visual reading method to enhance immediacy, using color-coded cells that range from white (lowest percentages) to light blue (intermediate) to dark blue (highest) (surname, year). Tables 4.7 and 4.8 explore the utilization of urban green areas by age demographics. The most common reason for usage across age groups is walking, with the exception of the 30-39 age category, where gaming is the most frequent activity (Table 4.7). Those aged 40 to 49 demonstrate a more uniform distribution of activities. Table 4.8 reveals that while weekly or daily attendance appears common across all age groups, the ‘More than 65’ category sees a higher percentage of irregular attendance, with 20% utilizing urban green areas monthly or even occasionally. Almost 50% of individuals aged 30 to 49 frequently make use of green spaces on a daily basis, while the highest percentage of occasional usage (14%) is recorded among those 50 to 64 years old.

Table 4.7: Reason for use of green areas by age bracket in % for row total.

Age	**Game**	**Reading or study**	**Rest**	**Sport**	**Transit**	**Walking**	**Walking with pet**	**Other**
< 18	0.00	0.00	50.00	0.00	0.00	50.00	0.00	0.00
18-29	0.00	0.00	8.33	8.33	0.00	33.33	33.33	16.67
30-39	44.44	0.00	0.00	14.81	0.00	22.22	7.41	11.11
40-49	23.08	0.00	1.92	26.92	0.00	28.85	15.38	3.85
50-64	0.00	0.00	0.00	11.63	2.33	58.14	27.91	0.00
≥ 65	0.00	10.00	0.00	10.00	0.00	70.00	10.00	0.00
Total	16.44	0.68	2.05	17.12	0.68	39.73	18.49	4.79

Table 4.8: Frequency of use of green areas by age bracket in % for row total.

Age	Daily	Weekly (Mon-Fri)	Weekly (weekend)	Monthly	Occasional	Other
<18	0.00	50.00	50.00	0.00	0.00	0.00
18-29	33.33	41.67	8.33	0.00	8.33	8.33
30-39	44.44	33.33	18.52	0.00	3.70	0.00
40-49	44.23	15.38	30.77	0.00	5.77	3.85
50-64	39.53	25.58	13.95	4.65	13.95	2.33
≥ 65	30.00	20.00	30.00	10.00	10.00	0.00
Total	40.41	24.66	21.92	2.05	8.22	2.74

Table 4.9: Reason for use of green areas by employment status in % for row total.

Employment	Game	Reading or study	Rest	Sport	Transit	Walking	Walking with pet	Other
Full-time worker	18.00	0.00	2.00	22.00	0.00	35.00	17.00	6.00
Occasional	0.00	50.00	0.00	0.00	0.00	50.00	0.00	0.00
Other	5.00	0.00	0.00	5.00	5.00	60.00	25.00	0.00
Part-time worker	40.00	0.00	0.00	0.00	0.00	40.00	10.00	10.00
Student	0.00	0.00	12.50	12.50	0.00	50.00	25.00	0.00
Unemployed	16.67	0.00	0.00	16.67	0.00	33.33	33.33	0.00
Total	16.44	0.68	2.05	17.12	0.68	39.73	18.49	4.79

Tables 4.9 and 4.10 present an analysis of the reason and frequency of use of urban green spaces based on employment type. ‘Walking’ was found to be the most common reason across all categories. However, it is noteworthy that part-time workers recorded the highest percentage of ‘Game’ as the reason for using green spaces (40%), occasional workers reported ‘Reading/study’ (50%), and one out of three unemployed citizens used green spaces for ‘Walking with pet’ (Table 4.9). Moreover, ‘Unemployed’ recorded the highest daily usage percentage (50%), and all occasional workers surveyed had a tendency to use green spaces on a weekly basis.

Table 4.10: Frequency of use of green areas by employment in % for row total.

Employment	Daily	Weekly (Mon-Fri)	Weekly (weekend)	Monthly	Occasional	Other
Full-time worker	43.00	24.00	26.00	1.00	4.00	2.00
Occasional worker	0.00	50.00	50.00	0.00	0.00	0.00
Other	35.00	15.00	10.00	10.00	25.00	5.00
Part-time worker	40.00	30.00	20.00	0.00	10.00	0.00
Student	25.00	37.50	12.50	0.00	12.50	12.50
Unemployed	50.00	33.33	0.00	0.00	16.67	0.00
Total	40.41	24.66	21.92	2.05	8.22	2.74

4.5.4 Socio-cultural indicators

A considerable portion of the survey focused on researching citizens' opinions on green areas. This was done through multiple-choice questions such as "What do you think about the green areas and, in particular, the area of the previous question, in reference to:", which were rated on a scale of 1 to 5, where 1 corresponded to "very low" and 5 to "very high". The collected responses helped establish three distinct socio-cultural indicators: (i) recreational - pertaining to how green areas can create an environment promoting relaxation and improve overall well-being (Hermes et al., 2018); (ii) sense of place and cultural heritage - in relation to the emotional, functional, and cognitive responses triggered by a specific location as well as the sense of belonging derived from green spaces and the preservation of cultural heritage (Foote & Azaryahu, 2009; Žlender & Gemin, 2020); (iii) aesthetics - accounting for the population's perception of natural beauty and artistic value of the environment (Figueroa-Alfaro & Tang, 2017).

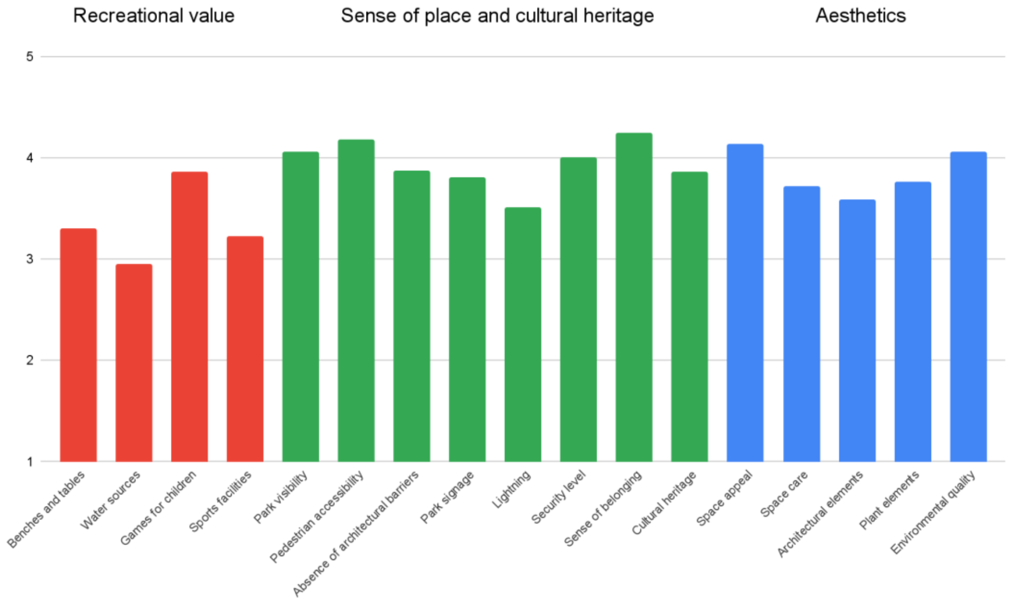

Figure 4.13: Socio-cultural indicators for: recreational value (red), sense of place and cultural heritage (green) and aesthetics (blue) on a 1 (very low) to 5 (very high) scale.

The urban green spaces of Boadilla del Monte were assessed for their recreational function, using five categories of facilities available to citizens (Figure 4.13, in red). The average score obtained was 3.33 on a scale of 1 (very low) to 5 (very high) (see Appendix C - Section 2 for score description). The highest score was obtained for children's games (3.86) while the lowest was for the presence of water sources (2.95). The socio-cultural value, based on the sense of place and cultural heritage (Figure 4.13, in green), was the best-evaluated category for an overall average index score of 3.94/5, close to the "high" score (4/5). The assessment considered factors such as park visibility, signage, lighting, pedestrian accessibility, safety, sense of belonging, and cultural heritage preservation. The lighting category had the highest deviation from the average score (3.51). The aesthetic value was assessed by sampled citizens using five categories (blue in Figure 4.13) with an average score of 3.80. Space appeal and environmental quality had values above the 4/5 score. The overall socio-cultural indicator obtained from the analysis demonstrated a positive multifunctional role of the urban greenery of Boadilla del Monte, with an average score of 3.77, close to the "high" score (4) of the scale considered, and only one category below the "medium" score (3), which was associated with the presence of fountains and water sources.

4.5.5 Ecosystem Services

Parts of section 4 and 5, as well as the entirety of section 8, were devoted to exploring Urban Ecosystem Services (UES) in the context of green areas in the city. Results showed that 84.2% of the surveyed citizens had never heard of UES, which is consistent with current efforts to disseminate and promote the concept, as noted in Collins et al. (2019) and EU policies (Bouwma et al., 2018), among other initiatives (Quintas-Soriano et al., 2018; EASME, 2018). When asked to define SE, only a small subset of participants were able to offer accurate definitions. However, most responses indicated some level of understanding related to environmental attention, ecology, and benefits. The second part of section 5 explored the multi-value features of ES, revealing that only 4.1% of participants believed economic benefits to be the most valuable, while the majority cited environmental (over 65%) and social (30.8%) benefits. Of note, close to 90% of respondents had never heard of Payment for Ecosystem Services (PES), pointing to the need for greater education around SE and their role in the economy.

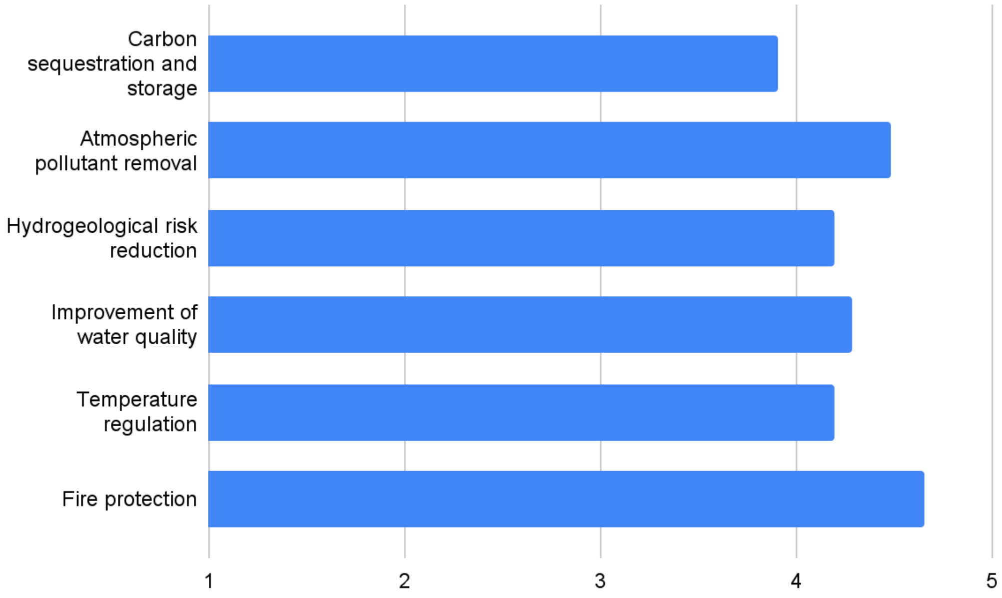

Figure 4.14: Importance of main ecosystem services against climate change on a 1 (not at all) to 5 (very important) scale.

Section 8 of the survey focused on examining the role of ecosystem services (ES) in combating climate change. Participants were asked to provide their responses on a scale of 1 (not important at all) to 5 (very important), with six primary benefits of public green spaces identified in the city (see Appendix C - Section 8 for score description). Despite the limited knowledge in this area, our results indicate an average score of more than 4/5, with Carbon sequestration and storage identified as the least crucial ecosystem service (3.91/5), and Fire protection being the most important (4.66/5) in the context of climate change. Additionally, we found that only a maximum of 15% of participants provided "negative" responses (scores of 1 or 2) in the Carbon sequestration and storage category, indicating that the general public has a basic understanding of the issue (Figure 4.14). To enhance the readability of the results, we used a visual method for Tables 4.11 and 4.12. The cells were colored, with white indicating the best results, and red representing the worst results for the first and third questions. Similarly, for the second question, the cells were colored, with white representing the lowest percentages, and dark blue indicating the highest percentages.

Table 4.11: ES knowledge by age bracket in % for row total.

Age	Have you ever heard about ES?		Which is the greatest value that urban green areas provide?			Have you ever heard of PES?	
	No	**Yes**	**Economic**	**Environ.**	**Social**	**No**	**Yes**
< 18	100.00	0.00	0.00	50.00	50.00	100.00	0.00
18-29	66.67	33.33	8.33	58.33	33.33	83.33	16.67
30-39	81.48	18.52	0.00	48.15	51.85	81.48	18.52
40-49	86.54	13.46	3.85	73.08	23.08	90.38	9.62
50-64	86.05	13.95	4.65	72.09	23.26	97.67	2.33
≥ 65	90.00	10.00	10.00	50.00	40.00	80.00	20.00
Total	84.25	15.75	4.11	65.07	30.82	89.73	10.27

The understanding of Ecosystem Services (Table 4.11) was moderately linked to age: the age bracket of 18-29 was the group that had a better grasp of the terminology (1 out of 3), while citizens over 65 had the most awareness about PES, although with very low percentages (less than 1 out of 5). Similarly, for identifying the greatest value that urban green spaces offer, individuals over 65 answered 'economic benefit' the most (1 out of 10).

Meanwhile, higher levels of education did not always translate to more knowledge (Table 4.12): people with 'Secondary studies' as their educational attainment were the most aware of ES (30%), but were also the least knowledgeable about PES (0%); on the other hand, PhD holders had the least familiarity with ES (11.1%) but the most understanding of PES (22.2%). ‘Environmental’ value of urban green areas was perceived as the most significant benefit by people with 'Higher education' (over 70%) and 'Job training' (more than 50%). The ‘Social’ value was prioritized by individuals with 'Secondary studies' (60%) and 'PhD' (over 55%), while those with 'Job training' were most likely to mention the Economic value (13.3%).

Table 4.12: ES knowledge by education in % for row total.

Education	**Have you ever heard about ES?**		**Which is the greatest value that urban green areas provide?**			**Have you ever heard of PES?**	
	No	**Yes**	**Economic**	**Environ.**	**Social**	**No**	**Yes**
Higher education	85.71	14.29	3.57	70.54	25.89	90.18	9.82
Job training	80.00	20.00	13.33	53.33	33.33	86.67	13.33
PhD	88.89	11.11	0.00	44.44	55.56	77.78	22.22
Secondary studies	70.00	30.00	0.00	40.00	60.00	100.00	0.00
Total	84.25	15.75	4.11	65.07	30.82	89.73	10.27

4.5.6 Climate change

Two sections of the questionnaire were focused on climate change, specifically the current (section 6) and future (section 7) consequences. In general, citizens expressed a significant level of concern regarding climate change: 79.5% acknowledged its existence, while 11.6% did not agree and 8.9% chose not to respond or did not know. In relation to Boadilla del Monte, 74.0% believed that climate change was directly affecting the urban area while 8.2% felt it was happening elsewhere. Responses to the optional open question about the ways in which climate change is affecting Boadilla del Monte included an increase in temperatures, periods of drought, shortened winters, extreme weather events, as well as damage to flora and fauna.

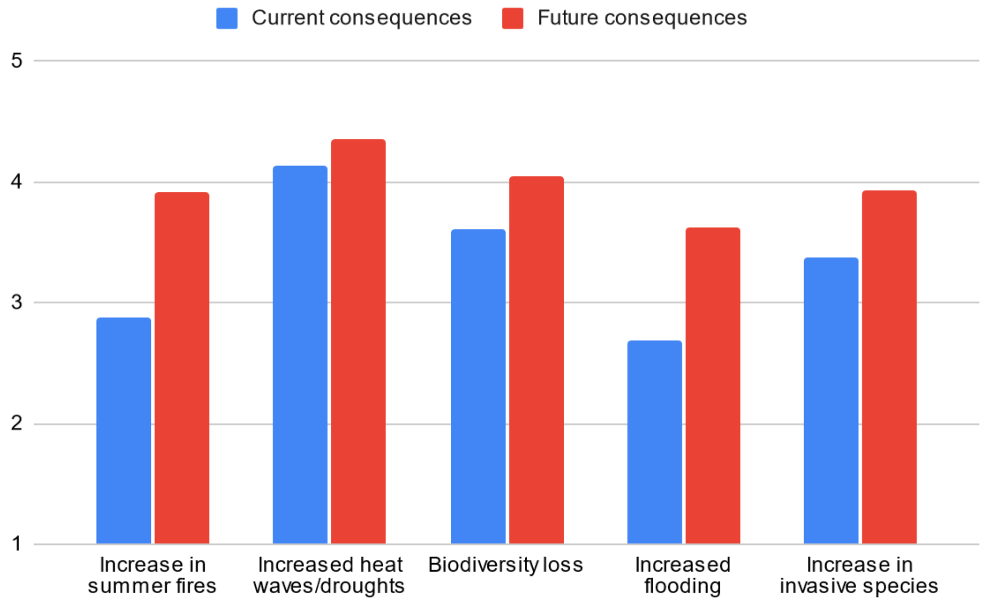

Figure 4.15: Current and future consequences of climate change on a 1 (not at all) to 5 (very evident) scale.

Following that, two sections were dedicated to exploring five particular outcomes that are directly or indirectly linked to climate change - namely, the rise in summer wildfires, increased occurrences of heat waves or droughts, loss of biodiversity, increased flooding, and an increase in invasive species. These categories were chosen due to their strong connection with green spaces, specifically in an urban context.

The assessment was conducted through a series of multiple-choice questions rated on a scale of 1 (not evident at all) to 5 (very evident) (see Appendix – Section 6 and 7 for score descriptions). The questions asked "How evident are the following effects of climate change in Boadilla del Monte at present?" (section 6) and "How do you think they will be in the future?" (section 7), with each of the five outcomes being assessed. The key findings are summarized in Figure 4.15, with blue representing present and red representing future outcomes. The most significant finding was an average increase of 21% in the rating index for future consequences compared to present ones.

Citizens anticipate that the impact of climate change will become increasingly apparent in the coming decades. They expect to see a considerable rise in summer fires (+35.6%) and floods (+35.0%), but only a slight increase in heatwaves or droughts (+5.3%). It is evident that there will be a biodiversity loss (+12.5%) and an increase in invasive species (around +16%). Presently, the overall average score for the effects of climate change in Boadilla del Monte is 3.33/5. This means that citizens generally consider the consequences to be "quite evident," with values below average for Increased flooding (2.68) and Increase in summer fires (2.88), and higher values for Increased heat waves or droughts (4.14). It is worth noting that 26.7% of the surveyed inhabitants rated Increased summer fires with a 1 ("not at all evident") and 30.8% did the same for Increased flooding. Based on the results, the most striking finding is that citizens believe that Increased heat waves or droughts is currently the most apparent effect on their urban landscape, but it will grow the least in the future. Summer fires and floods will have a more marked increase over the coming years, although they are currently the least evident. Tables 4.13 and 4.14 use a color-coding system (ranging from white for the best to red for the worst results) to aid visual interpretation of the results.

Table 4.13: CC knowledge by age bracket in % for row total.

Age	**Do you think there is really climate change?**			**Do you think it is affecting our city in any way?**	
	Do not know/ no answer	**No**	**Yes**	**No**	**Yes**
<18	0.00	0.00	100.00	0.00	100.00
18-29	25.00	8.33	66.67	33.33	66.67
30-39	3.70	18.52	77.78	18.52	81.48
40-49	13.46	11.54	75.00	36.54	63.46
50-64	2.33	9.30	88.37	18.60	81.40
≥65	10.00	10.00	80.00	20.00	80.00
Total	8.90	11.64	79.45	26.03	73.97

When analyzing results by age group (Table 4.13), the group with the highest skepticism towards the existence of climate change was the '30-39' bracket. On the other hand, the '18-29' group had a lower number of affirmative responses due to 25% of respondents stating they did not know or refused to answer. Our research also discovered that all participants under the age of 18 recognized climate change as a real phenomenon. The same results were observed in the urban area of Boadilla del Monte, with the exception of the '40-49' age bracket, which had the highest percentage (36.54%) of citizens who did not believe in the effects of climate change on their city.

In addition, our research (Table 4.14) revealed a moderate relationship between climate change awareness and age. Participants with secondary education diplomas appeared to be the most likely to believe in the existence of climate change in the context of Boadilla del Monte. Individuals with vocational training or lower levels of education were the most unsure (20%) about the topic in general, and those with a PhD were the least likely (66.67%) to acknowledge the effects of climate change on Boadilla del Monte.

Table 4.14: CC knowledge by education in % for row total.

Education	**Do you think there is really climate change?**			**Do you think it is affecting our city in any way?**	
	Do not know/ no answer	**No**	**Yes**	**No**	**Yes**
Higher education	8.04	11.61	80.36	27.68	72.32
Job training	20.00	20.00	60.00	20.00	80.00
PhD	11.11	11.11	77.78	33.33	66.67
Secondary studies	0.00	0.00	100.00	10.00	90.00
Total	8.90	11.64	79.45	26.03	73.97

4.5.7 Commitment of Municipality

Sections 9 and 10 provided a link between the content discussed in Sub-sub-chapter 4.5.6 on citizens' perception of climate change and the Municipality of Boadilla del Monte's case study. These two sections were solely dedicated to examining the efforts and initiatives undertaken by municipal agencies to reduce the impacts of climate change and prepare the urban landscape for potential future alterations.

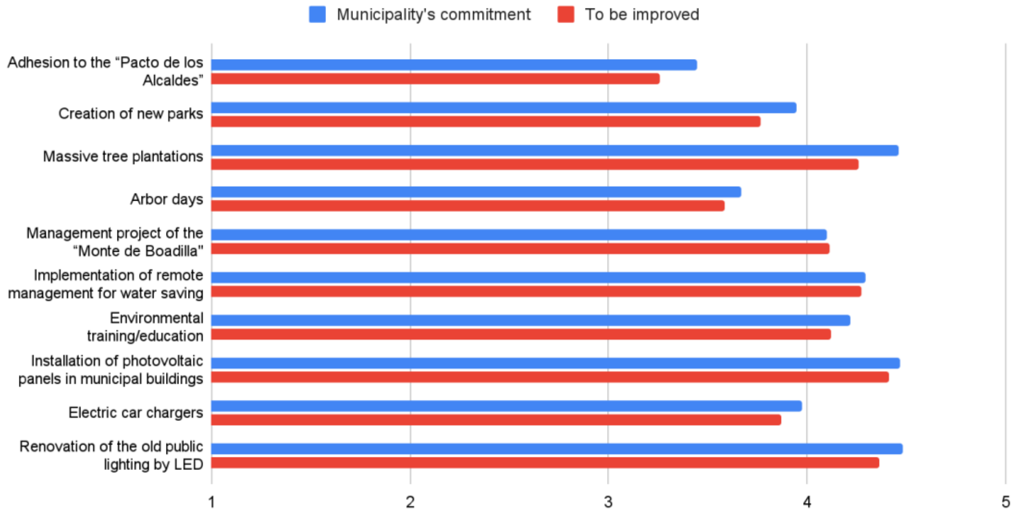

Figure 4.16: Current (blue) and future (red) commitment of the Municipality of Boadilla del Monte on a 1 (not at all) to 5 (very important) scale.

As depicted in Figure 4.16, the survey took into account ten actions that have been carried out or are currently in progress by the Municipality. Two questions were asked on a scale of 1-5, namely, how much has been accomplished and how much more effort should be put in by the Municipality according to the citizens. It is noteworthy that the actions were suggested by the Municipality itself, in line with its previous initiatives. With regards to the present scenario, the work carried out has received highly positive evaluations. The general average score exceeded 4/5 on the scale of 1-5 (see Appendix C – Section 9 for a description of the scoring system), with the highest scores being achieved for Renovation of the old public lighting (4.48), Installation of photovoltaic panels in municipal buildings (4.47), and Massive tree plantations (4.46). Among the ten actions considered, Adhesion to the "Pacto de los Alcaldes" (average score of 3.45) and Arbor days (3.67) were perceived as the least relevant in the fight against climate change. The "Pacto de los Alcaldes" refers to the Global Covenant of Mayors for Climate & Energy (GCoM), which is a leading global coalition of local community members and governments that have willingly committed themselves to actively combat climate change, by taking measures to limit gas emissions, increasing access to sustainable energy, and preparing for climate change impacts.

The results regarding citizens' opinions on the improvement of the considered actions in the future are presented in red in The obtained values generally follow the current commitment for each category, with a decrease in the average rating ranging from -0.5% (remote management implementation for water sawing) to -5.4% (adherence to the "Pacto de los Alcaldes"), with the exception of the "Monte de Boadilla" management project that showed a slight increase (+0.33%). A significant decrease can be interpreted in two ways: either the action has been adequately implemented or does not appear important enough to require further implementation. These reductions, however, are small and not necessarily indicative of a clear signal by citizens to make substantial changes in the future. In summary, citizens consider the municipality's actions of diverse nature as a great starting point that must be maintained for future years.

4.5.8 Discussion and conclusions

Green spaces are of paramount importance in urban areas because they offer a range of ecosystem services that fall into various categories, some of which are easily measurable while others are more challenging to quantify. In this study, we focused on the cultural category of ES, which is concerned with the well-being and health of people who use green ecosystems in the city. Although this category is difficult to quantify, we conducted a socio-cultural survey to directly involve citizens in our assessment of the ecosystem services provided by public parks in Boadilla del Monte, in collaboration with the Municipality. The study had three primary objectives, which are discussed in the following paragraphs: (i) to evaluate the socio-cultural aspects (recreational, cultural, aesthetics, and sense of place) of greenery in Boadilla del Monte; (ii) to investigate the knowledge of ecosystem services and their relationship to climate change; and (iii) to determine the satisfaction level of citizens with the current and future commitment of the Municipality.

The findings of the study have revealed interesting results. As indicators of socio-cultural behavior, the population that frequently visits the city's green areas and spends an average of more than 6 hours a week there, responded to the survey through numerical evaluations on a 1-5 scale. The citizens recognized the association of public parks with the social categories investigated, with varying proportions for the recreational (3.33/5), aesthetic (3.80/5), and sense of place and cultural value (3.94). However, over 80% of the citizens had never heard of ES or PES, and only 1 out of 20 believed that the economic value of nature holds the most significance. Studies conducted previously, such as those by Kabisch (2015) and Collins et al. (2019), have demonstrated similar results with different sample groups. As for the survey on the willingness to pay for green roofs in Cristiano et al. (2023), also in this study the questionnaire considered respondents with a decidedly high level of education (even if not intentionally) and this necessarily played a role in the results obtained since a higher level of education frequently corresponds to greater attention to the issues treated. Citizens between 18 and 29 showed more familiarity with the term 'Ecosystem Services,' but were less knowledgeable about 'Payment for Ecosystem Services.' Climate change was considered a significant issue by most of the respondents, but over 20% did not believe it was happening or chose not to comment on it. Citizens aged 30-39 and 40-49 were most skeptical about climate change, with 33.33% and 36.33% respectively stating that they believed it was not affecting Boadilla del Monte. Job training was found to be an undecided educational qualification regarding climate change. Researchers have highlighted the need to involve communities in climate change adaptation strategies, particularly given the expected intensification of climate change-related events, such as fires and floods, in the future. These findings align with previous studies, such as those by Taddicken et al. (2018) and Tobler et al. (2012), who have emphasized the importance of engaging with the population on climate change issues. Caroline et al. (2019) have also explored this concept in greater depth.

The proposed study made a considerable impact on the municipal administration of Boadilla del Monte. Firstly, it collected quantitative data on the climate change adaptation plan that has been implemented by the Municipality in recent years. This plan included initiatives such as the creation of new parks, installation of photovoltaic panels in municipal buildings, and adhesion to the "Pacto de los Alcaldes". Secondly, it provided an opportunity to receive feedback on the management of urban green areas, although this topic was not extensively discussed in the paper. Additionally, the survey had a specific focus on the usage patterns of parks by citizens and their distribution among the urban districts. This valuable information will be used by the Department of Environment, Sports and Celebrations for the purpose of future territorial management and planning. The bibliographic references remain the same.

The study highlights strengths such as a rapid, fair, and functioning survey distribution system and the inclusion of various environmental issues, but also has weaknesses. The number of participants, out of a population of approximately 60,000 inhabitants, is notably low, perhaps due to the wide range of content and time required to complete the survey. Additionally, ecosystem services were given less emphasis to include other topics and avoid an excessively long questionnaire. Subsequent studies should address the knowledge scale for each topic and adapt the survey according to population type (city size, geographical location, country). Expanding the sample could shed light on the influence of varied characteristics. The results may be useful for determining the most appropriate activities for different citizen profiles, following the five levels of stakeholder engagement suggested by the International Association of Public Participation (IAP2) (Hauck et al., 2016), thereby enhancing environmental awareness and knowledge. Furthermore, the survey could be a helpful socio-cultural tool to guide urban/regional/national planners in developing territorial strategies for adapting to climate change and assessing ecosystem services. Finally, this work should serve as a call for further scientific research on the perception of ecosystem services by the urban population, as they are integral to improving well-being and mitigating climate change impacts.

4.6 Concluding remark of Part II

We conducted a cross-sectional assessment of the role of urban green areas in the municipality of Boadilla del Monte, in collaboration with municipal offices and the public green management company. The analysis focused on the provision of ecosystem services, delving into each of the three core values associated with them:

(i) the environmental aspect, by quantifying the environmental benefits in terms of air quality, water runoff, and carbon deposition; (ii) the economic value, relying on the most up-to-date scientific literature and contextualizing it to the areas of interest to attribute a unit benefit value to each analyzed ES; (iii) the cultural connotation, through the involvement of city residents to characterize the socio-cultural values of the utilized green areas and enhance knowledge related to them.

In particular, in the first part of the project, we focused on the mapping of over 33,000 urban trees in collaboration with the aforementioned public entities, assessing carbon storage and sequestration, air quality improvement, and reduction of surface water runoff through specialized vegetation software. Subsequently, these results were analyzed and discussed, on one hand, in relation to the 28 different urban districts, identifying strengths and weaknesses of the city, and on the other hand, by conducting an analysis of the efficiency in terms of ES provision per tree species. This analysis, providing essential information for future municipal planning, focused on the connection layer between trees, ecosystem services, and climate change adaptation. Finally, an in-depth analysis of the economic evaluation of the quantified benefits was carried out, comparing these economic estimates with the management costs, categorized according to municipal technicians, the most relevant figures responsible for the economic management of public costs related to green management in Boadilla del Monte.

In the second part of the study, the social aspect was integrated through a survey administered to all city residents. The evaluation of the ES cultural category was conducted through numerical scale questions, the responses to which quantitatively outlined the socio-cultural indicators recognized in scientific literature for decades, adapted by us to the city context and target audience. Subsequently, this quantification was complemented with a survey on the knowledge of environmental issues closely related to the investigated scope, further characterizing the socio-cultural assessment by considering the respondents' level of education on these topics. The survey concluded with a focus on the municipality's actions in combating climate change at the urban level.

The work conducted in Boadilla del Monte is valuable in the scientific field both due to the scale of analysis, covering an entire existing urban area, and due to its transversality within the realm of ES, as it considers the three main spheres (environmental, economic, and social) that define them and uniformly connects them.

Conclusions and Future perspectives

The aim of this thesis was to investigate the role of green spaces within urban environments, specifically focusing on the role of tree population within them. The guiding thread throughout the three-year research activity was the provision of ecosystem services, hence the title of the thesis.

The study focused on two main scales, sequentially explored: the scale of individual park/green area (Turin) and the city-level scale (Boadilla del Monte), interconnected by an intermediate dimension, the neighborhood scale, partially analyzed within the city scale. At the park scale, two main software programs from a suite were employed for assessing ecosystem services. The most interesting findings were obtained through the interaction of the quantification of outputs with significant processes such as land cover change, climate change, etc. One of the two previously used tools was then applied to investigate the urban scale. The collaboration with municipal offices of Boadilla del Monte was crucial in managing the vast amount of available data concerning the tree population, and our results proved that the beneficial effect produced is characterized by a clear transversality, including environmental, economic, and social implications.

The main objectives are briefly highlighted below in bold, along with their corresponding conclusions drawn.

To deepen a methodology for evaluating urban ecosystem services

The thesis work analyzed a specific software suite tailored for assessing vegetation in urban contexts, delving into the underlying mathematical model and the simplifying assumptions considered. The objective was to better understand how the complex realm of physical, chemical, and biological processes associated with trees and plants can be "mathematized" and studied through an analytical tool. Based on UFORE mathematical models, the thesis focused on the characterization of the ES provision through the evaluation of different parameters, such as: (A) leaf area and leaf biomass; (B) volatile organic compounds; (C) carbon storage and sequestration; (D) dry deposition of air pollution; (Hydro) tree effects on urban hydrology.

To quantify the environmental benefits associated with urban trees and green areas

Building upon the tools described in the previous section, results were obtained with a strong quantitative connotation that aligns with territorial planning in different scales of the environments they are embedded in. The calculation of the urban vegetation structure was the fundamental and necessary step for the application of the models mentioned in the previous point. A small park extending for a few thousand square meters produces, for example, an annual carbon sequestration of the order of a ton and a storage of a few tens of tons, but these values can significantly increase (doubling for some ES) considering a more vegetated configuration of the area; these quantities are 1-2 orders of magnitude greater in the case of green areas covering a few hundred thousand square meters.

To estimate the economic value associated with ecosystem services

It is evident that this estimation, unlike the environmental evaluation, has a strong social connotation, as it emphasizes the dependency and consequences that certain substances (air pollutants, oxygen) or events (floods) have on the area of interest and surrounding zones. The results obtained on a park scale in the Turin area showed a variable range of values depending on the area size and the tree population, ranging from a thousand euros for small areas (Via Revello) to a hundred thousand euros for medium-sized areas (Le Vallere, Colonnetti), which it will be interesting to compare with the construction and maintenance costs of the same. On an urban scale, the survey specifically focused on the economic estimation of the benefits produced only by the urban trees sampled by the Municipality of Boadilla in its entirety and showed encouraging results for the future, taking into account the relatively young age of the tree population. Finally, it is interesting to analyze the variability and the strong dependence of the economic estimate of the air pollutants removed on the population density of the urban areas.

To assess socio-cultural indicators through citizen and resident participation

The aim was to integrate the quantification of benefits obtained purely from technological tools calibrated through decades of scientific research with the humanistic component that directly benefits from the respective areas. The result obtained through a multiple-choice questionnaire on a 1-5 scale produced an evaluation of different socio-cultural indicators (recreational, aesthetic and identity), an in-depth investigation into the knowledge of ecosystem services, climate change and their interconnection and an opinion on the role of the Municipality in the process of adaptation to climate change. The production of an ad hoc survey document for the city of Boadilla del Monte represents the innovative aspect of the study as the choice and organization of the sections were made according to the specific characteristics of the urban territory and the citizens.

Limitations and future research. Finally, we suggest some perspectives for future research that have emerged during the three-year research activity, arisen from the limitations of the analysis conducted in terms of methodology, the available data and the required time:

- **At the methodological level**

  Although i-Tree Eco provides valuable insights into the ecological benefits of urban trees, it has specific constraints. Firstly, it relies on simplified models and general assumptions that may not fully capture the complexities of urban ecosystems, potentially leading to inaccuracies. Secondly, it utilizes static models that assume constant conditions over time for urban areas, disregarding the dynamic nature of climate change and land use changes. Thirdly, extensive input data is required, which can be time-consuming and costly to obtain and manage for large areas. Lastly, the i-Tree Database has limited species diversity, particularly for shrubs, hindering accurate quantification of their benefits. However, the tool's strengths lie in the minimal uncertainty associated with estimating key parameters such as leaf area, leaf biomass and tree biomass, as they rely on direct tree and crown measurements. Future improvements for i-Tree Eco aim to address these limitations by developing more sophisticated models, automating and integrating data through remote sensing, citizen science initiatives, and open data platforms, and conducting fine-scale analysis using high-resolution spatial data and advanced geospatial analysis techniques.

- **At the input data level**

  One limitation was represented by the availability of data, specifically hourly data for an entire reference year. In order to make the analysis as up-to-date as possible, the choice was always made to refer to the most recent year for which the data was available in a comprehensive manner (through the software database or the managing entities of the reference station). However, this approach resulted in certain cases in a limitation in terms of the timeliness of the data compared to the time of the analysis and, secondly, a misalignment between the reference year for meteorological data and the year in which field investigations were conducted. We suggest resolving this issue by implementing specific investigations on the meteorological data of the area of interest using appropriate instrumentation to measure temperature, precipitation, and pollutant concentrations according to the requirements of the tool.

- **As continuation of ongoing projects**

  By examining the trajectory followed within the two main applied research projects in this thesis, the natural extensions of these research strands are as follows: (i) conducting a metropolitan-scale analysis of the entire public green sector in Turin, and subsequently incorporating private contributions (Turin project, Chapter 3); (ii) integrating the urban-scale analysis conducted in Boadilla del Monte (Chapter 4) with an evaluation of the UHI effect and its mitigation through urban green spaces (initiating work with the Urban Cooling program of the InVEST software suite) and, additionally, analyzing the energy-related effects on buildings caused by such green areas, considering their proximity (i-Tree is equipped with functionalities suitable for this purpose).

- **As future perspectives, applying and expanding the investigation to other urban environments**

  It should be applied the PhD investigation to other urban environments, different from those reported in the previous point: it could be interesting to observe how the conclusions drawn from this thesis are compatible with the variation of geographical (altitude, latitude), climatic (temperature, rainfall) and geomorphological (soil characterization) parameters. Then, as green roofs and green walls complement the category of green areas and parks within the broader context of urban greenery, it should be deepened the ES provision at the building scale in terms of theoretical knowledge, methodology (specific tools to quantify environmental and economic benefits for smaller scale) and specific needs. In the case of green roofs, for example, greater attention should be given to energy-related effects, with a lesser focus on large-scale effects such as urban hydrological cycles or air pollutant removal, which are more relevant at a larger scale, such as urban parks.

Abbreviations

Abbr.	Complete Name
AFP	Air Filled Porosity
ARPA	Regional Environmental Protection Agency
AS4.1	Área Sur 4.1
AS4.2	Área Sur 4.2
B	Bonanza
C	La Cárcava
CDAN	Compl. Deportivo Angel Nieto
CE	Club las Encinas
CICES	Common International Classification of Ecosystem Services
CMCC	Euro-Mediterranean Center for Climate Change
CN	Cortijo Norte
CS	Cortijo Sur
CU	Casco Urbano
DCIA	Directly Connected Impervious Area
DEM	Digital Elevation Model
EDS	Ecosystem Disservices
EEA	European Environment Agency
ES	Ecosystem Services
F	Los Fresnos
F2	Los Fresnos 2
FS.1	Future Scenario 1
FS.2	Future Scenario 2
GHG	Greenhouse Gas
GI	Green Infrastructure
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
L	Las Lomas
LAI	Leaf Area Index
MA	Millennium Ecosystem Assessment
ME	Monte de las Encinas

MP	Montepríncipe
NCP	Nature Contributions to People
NE	Norte Encinar
OBJTOP	Object-oriented, Topographic
OF3	Olivar Fase 3
OM	Olivar d Mirabal
P	El Pastel
PB	Parque de Boadilla
PC	Pino Centinela
PE	Prado del Espino
PP	Planting Program
PS	Present Scenario
RCP	Representative Concentration Pathways
S11	Sector 11
S234	Sector 2 3 y 4
SB	Sector B
TEV	Total Economic Value
UFORE	Urban Forest Effects
UGI	Urban Green Infrastructures
UGS	Urban Green Spaces
UHI	Urban Heat Island
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
V	Valenoso
VC	Valdecabañas
VES	Value of Ecosystem Services
VOC	Volatile Organic Compounds
VP	Valdepastores
VV	Viñas Viejas
WHC	Water Holding Capacity

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