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Assessment of the Potential Contribution of the Urban Green System to the Carbon Balance of Cities

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Abstract: Reducing greenhouse gas emissions is a crucial challenge in urban areas characterized by high energy consumption and reduced exposure to nature. In this context, the urban green system could play a pivotal role. In the literature, scholars have analyzed both the ability of species-specific and layout-specific green infrastructure to increase carbon sequestration and the best location sites for new green infrastructure to increase the provision of overall ecosystem services. There is a lack of studies helping green urban planners and designers choose where and which green infrastructure to implement based on vegetation species-specific performance and the local carbon emissions of city components. This paper uses tree inventory data from a medium-sized city in central Italy (Perugia) to develop a spatial analysis of urban park performance in carbon sequestration. Then, the method evaluates the carbon emission of a public city building to generate a spatialized balance between building demand and tree supply to support local decisions about the best locations for new green infrastructure and the choice between species. The paper contributes to GIS-based tools that vary the recommended location sites and species for new green infrastructure based on the demanded ecosystem service.

Keywords: urban park; carbon balance; carbon sequestration; urban trees maintenance; scenario analysis; i-Tree Eco; tree cadastre; tree inventory; proximity services; ecosystem services

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1. Introduction

The European Green Deal, converted into the European Climate Law [1], aims to achieve climate neutrality by 2050, developing multiple and multi-sectorial actions. Actions dedicated to cities represent a critical challenge because urban areas require an uninterrupted energy supply. In this context, the valorization of the urban green system for climate mitigation and adaptation through carbon sequestration and storage is becoming increasingly relevant [2].

The urban green system is a complex collection of urban areas covered by vegetation having high variability of functions, dimensions, and characteristics, such as parks, forests, community gardens, representative green spaces, street trees, green roofs and walls, and service and marginal green areas [3]. Scholars studied the carbon sequestration potentiality of different types of urban green areas. Kong et al. [4] studied urban turfgrass in Hong Kong and Shenzhen, showing they could represent carbon sinks by adopting efficient management strategies. McPherson et al. [5,6] studied street trees in Los Angeles, comparing their carbon balance in scenarios with different pruning strategies and types of equipment and vehicles for their management. Park and Jo [7] estimated the carbon balance of Korean urban parks over their life cycle. Among these types of areas, urban parks and urban forests are crucial for implementing carbon sequestration strategies thanks to their high numbers of trees [8,9].

Urban parks offer greenery that aids in carbon storage and sequestration, along with providing citizens with numerous ecosystem benefits such as the mitigation of urban heat islands [10], the improvement of air quality through pollutant absorption and deposition [11,12], the enhancement of flood protection via increased soil permeability [13], and the promotion of human well-being [14]. Quantifying the capacity of the urban green system to impact the city-level carbon balance and offset anthropogenic emissions is a complex issue. Furthermore, this estimation is strongly influenced by the type of data collected and the methodological approaches used for collecting them [2]. Concerning the data for urban greenery, at the international level, there is no standard for realizing urban tree databases, but generally, the attributes are localization, genus, species, diameter at breast height (DBH), height, crown dimension, and health status [15]. The fieldwork to collect them requires much effort, and public administrations struggle to complete their tree database [16]. Overall, these databases that many public administrations are implementing represent valuable input data to estimate the provision of ecosystem services, including carbon storage and sequestration, and the i-Tree Eco software is an international standard for achieving this goal. This software belongs to i-Tree, a suite of freely available open software tools designed and certified by the United States Forest Service [17]. i-Tree Eco uses data about trees to quantify their effects on the environment, the forest structure, and their value to the community. Concerning the estimation of carbon sequestration, this software uses the yearly diameter increase of every tree according to a computerized model based on the growth rate, which considers the expected annual growth of the tree (adjusted for the local growing season), the media growth rate by species, the competition with other trees, and the percentage of crown dieback [17]. Results depend on the quantity and quality of the input data, the methodological approach for their collection, and their level of detail [2,18].

In addition to the challenge of reliable estimation of carbon sequestration in an urban park, carbon flux dynamics also have a complex structure [19]. Indeed, urban parks are social-ecological systems with flexible feedback and interactions with internal and external variables [20,21]. Therefore, carbon flux dynamics are composed of vegetation, which sequesters and stores carbon [8,22], and people performing actions such as design and build, greenery management, and the uses of equipment and structures which release carbon [7,23]. Developing a new urban park releases carbon due to its realization and the subsequent maintenance of vegetation and connected services [24–26]. Some authors have used life cycle assessment approaches to evaluate various urban green typologies in the last decade. For example, Nicese et al. [27] assessed the carbon balance connected with planning, planting, and maintaining an urban park in Milan, Italy. Zhang et al. [23] studied the carbon sequestration and emissions of four urban parks in China over 50 years.

Overall, the valorization of urban parks to achieve carbon neutrality in cities is a complex challenge without a valid solution internationally. Therefore, further studies are needed to develop multi-level scenarios and geo-specific and species-specific evaluations. This paper develops a yearly carbon balance of an urban park of a medium-sized European city (Perugia, Italy) to:

- Evaluate the carbon flux dynamic of a significant urban park in the city for the year 2023;
- Suggest species-specific and geo-specific solutions to move toward carbon neutrality;
- Upscale the carbon balance with different multi-level afforestation scenarios.

2. Materials and Methods

2.1. Study Area

The Municipality of Perugia is in central Italy (Umbria region). It covers 449.88 km^2 and has 178,283 inhabitants [28]. Figure 1a shows the land uses of the study area using the codes of the pan-European inventory Corine Land Cover [29]. The surface is covered 55% by agricultural areas, 31% by forest and semi-natural areas, 13% by artificial surfaces, and 1% by water bodies. The whole municipality has a population density of 396 inhabitants per km^2, and 63% of its population lives in the urban area of Perugia, which covers 41 km^2 and has 2731 inhabitants per km^2, reaching 7699 inhabitants per km^2 in the most populated neighborhoods (Figure 1b). Perugia has an altitude between 300 and 500 m and a transitional (temperate/Mediterranean) climate [30]. Air temperature is relatively mild, with the warmest month (August) ranging between 13.9 (Min) and 37.2°C (Max) and the coldest month (January) between −6.11 (Min) and 13.9 °C (Max) [31,32]. Mean annual precipitation equals 961.4 mm; two pronounced maximums characterize the precipitation pattern during May (154 mm) and November (235 mm). The yearly amount of photosynthetic radiation is 684,810.5 W/m^2, and the maximum hourly radiation is in June and is 436 W/m^2.

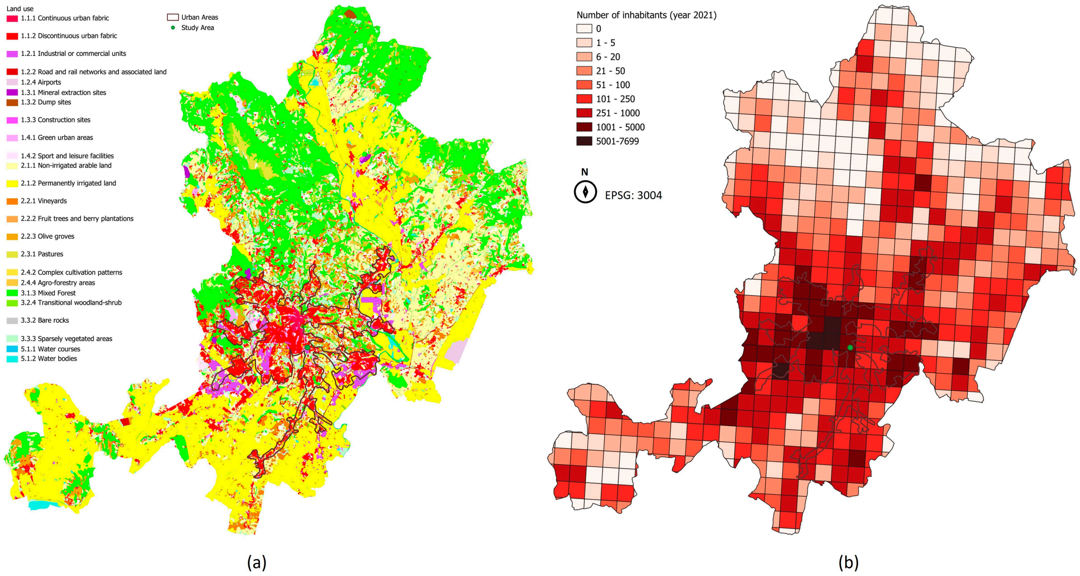

Figure 1. (**a**) Land use of the municipality of Perugia by interpretation of aerial images—year 2021 (5 m spatial resolution). (**b**) Distribution of inhabitants according to the population census of 2021 (spatial resolution: grid of 1 km^2).

The park chosen as the study area (the green point of Figure 1) is the city's botanical garden, covering 3 hectares. Created in 1962, this park is interesting for developing species-specific evaluations because it hosts young and mature trees and has the highest biodiversity among the parks in the city's urban green system. Concurrently, it hosts the tree species most represented in the urban areas of Perugia [33]. Carbon sinks in this study area are 362 trees belonging to 142 species organized in three sections: gymnosperms, angiosperms, and an angiosperm arboretum (Figure 2). A greenhouse, a service building, and the garden machines used for maintenance constitute carbon sources.

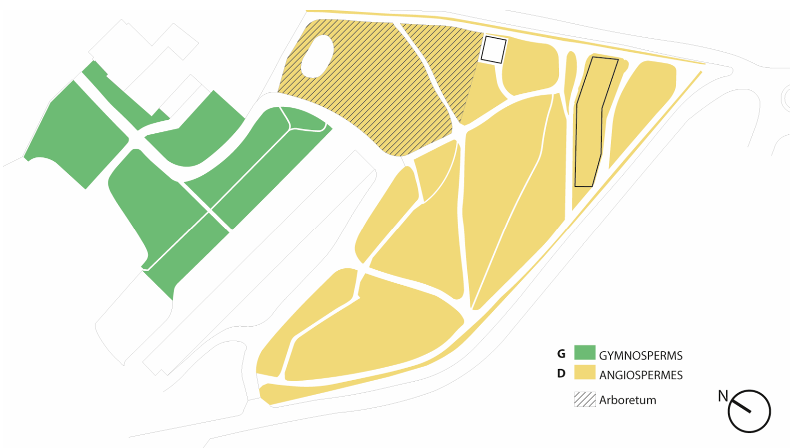

Figure 2. Urban park—case study.

2.2. Steps of the Method

The method consists first of the evaluation of the yearly carbon flux dynamic of the studied park (steps 1–5), then the ranking of species based on their performance in carbon sequestration (step 6), and finally the building of multilevel scenarios to balance the sinks and sources of carbon dioxide (step 7). The steps are:

1. TREE INVENTORY OF THE STUDY AREA. The tree inventory was realized through a single operator's fieldwork in November and December 2023. The operator is an expert in species recognition and tree health status evaluation. For the measurements, he used a device that combines laser, ultrasound, and tilt sensors to provide accurate and reliable distance, height, and angle measurements (distance accuracy of 4 cm; resolution height 0.1 m; resolution and typical accuracy of angles 0.1°) [34]. The tree inventory reports only trees higher than 1.8 m. The inventory developed for this paper has a row for every tree of the park and columns to describe their parameters. The columns regard localization, species, DBH at 1.3 m, height, crown dimension (height and width), crown light exposure, percentages of crown dieback, and percentage of crown missing.
2. YEARLY CARBON SEQUESTRATION. We used the i-Tree Eco software to calculate the annual carbon sequestrated by the trees in the study area. The mandatory data for the software are only tree species and DBH, but all the data inventoried in the previous step are highly recommended for improving the model estimations. In addition to data regarding trees, i-Tree Eco requires microclimatic information for a year (hourly temperature, hourly precipitation, hourly concentration of pollutants in the air) as input data for the study area. The data sources are free downloadable regional datasets [31,32,35] and are used by the software to develop geo-specific estimations of tree performance. The ecosystem services estimated by i-Tree Eco are air pollution removal, hydrology effects, and carbon storage and sequestration.
3. YEARLY CONSUMPTION TRENDS IN THE STUDY AREA. We inventoried all the activities of the study area that release carbon for their functioning. The park has a service room with gardeners' lockers and office staff, and we collected the yearly electricity (kWh) and natural gas (m^3) consumption for its lighting and heating. Furthermore, the park has a greenhouse that hosts tropical/subtropical species and succulent xerophytes, and we collected the consumption of liquefied petroleum gas (liters) for its functioning. Finally, we monitored the garden machines' yearly diesel (liters) consumption and the garden tools used to maintain the park. Electricity emits carbon dioxide (CO_2) during its production process, varying based on the method used to generate it, and natural gas, liquefied petroleum gas, and diesel, when burned, release carbon dioxide (CO_2) into the atmosphere as a byproduct of the combustion.
4. CONVERSION OF THE CONSUMPTION IN KG OF CARBON DIOXIDE EQUIVALENT. The Italian Institute for Environmental Protection and Research [36] annually publishes a report containing emission factors in Italy, the country of the case study. These factors are crucial for converting consumption measurements into kilograms of carbon dioxide equivalent. Emission factor databases play a vital role in this conversion process, transforming the units that calculate consumption factors into carbon dioxide equivalent. Emission factors vary between countries depending on the energy sources and technology used for production, energy infrastructure, fuel mix, and regulatory standards, as the International Energy Agency highlighted [37].
5. EVALUATION OF THE CARBON COMPENSATION LEVEL IN THE URBAN PARK. To assess the park's carbon compensation level, we compared the supply, represented by the yearly kilograms of CO_2 sequestered by the park's trees, and the demand, represented by the yearly kilograms of CO_2 equivalent produced for the park's management. This evaluation aims to determine the extent of annual compensation achieved within the urban park and ascertain whether the study area acts as a carbon sink or source.

6. SPECIES-SPECIFIC SOLUTIONS TO IMPROVE THE CARBON SEQUESTRATION POTENTIALITY. We ranked the species of the park based on their performance in carbon sequestration to define a dataset and suggest the optimal species in this regard. We used the Jenks Natural Breaks Classification to determine the classes of performance. This method is used to minimize within-group variance and maximize between-group variance. The Jenks optimization algorithm works by iteratively testing different potential class breaks to find the arrangement of breaks that produces the lowest total deviation from the class means, resulting in internally homogeneous and externally heterogeneous classes [38]. It is commonly applied in geographic information systems and spatial analysis to symbolize and analyze continuous data [39,40].
7. TOWARD CARBON NEUTRALITY. We used the resulting tree with the best performance in carbon sequestration to define the physical characteristics (canopy cover, leaf area, and biomass) and value of performance (yearly kilograms of carbon dioxide sequestered) of an Ideal Tree, called I-Tree_CS. Then, we used this tree to simulate three multi-level scenarios at different geographical scales to improve the carbon balance.

3. Results

The park has 362 trees that are taller than 1.8 m. Table S1 reports the resulting dataset. The information in the dataset regards tree structure (DBH, height, crown height and width, canopy cover, tree condition, leaf area, leaf biomass, Leaf Area Index, basal area, stratum) and performance in carbon sequestration (gr m^{-2} of carbon uptake by canopy cover, kg yr^{-1} of carbon sequestration; percentage of the total carbon sequestrated by the park; class of performance). Rows 366-375 of Table S1 report the main statistics. Overall, the park's trees have a canopy cover of 10,078 m^2, a leaf biomass of 6551 kg, and a value for the Leaf Area Index of 6.4. In 2023, they sequestered 3762 kg of carbon dioxide, and the individual trees' performance ranged from 0.1 to 76.3 kg yr^{-1}. Figure 3 reports the trees' classification resulting from the Jenks optimization algorithm. In the figure, the "null" class corresponds to trees that sequestrated less than 5.3 kg yr^{-1} of carbon dioxide; "very poor", between 5.3 and 11.8 Kg yr^{-1}; "poor", between 11.8 and 19.4 Kg yr^{-1}; "acceptable", between 19.4 and 27.6 Kg yr^{-1}; "good", between 27.6 and 48.5 Kg yr^{-1}; and "very good", greater or equal to 48.5 Kg yr^{-1}.

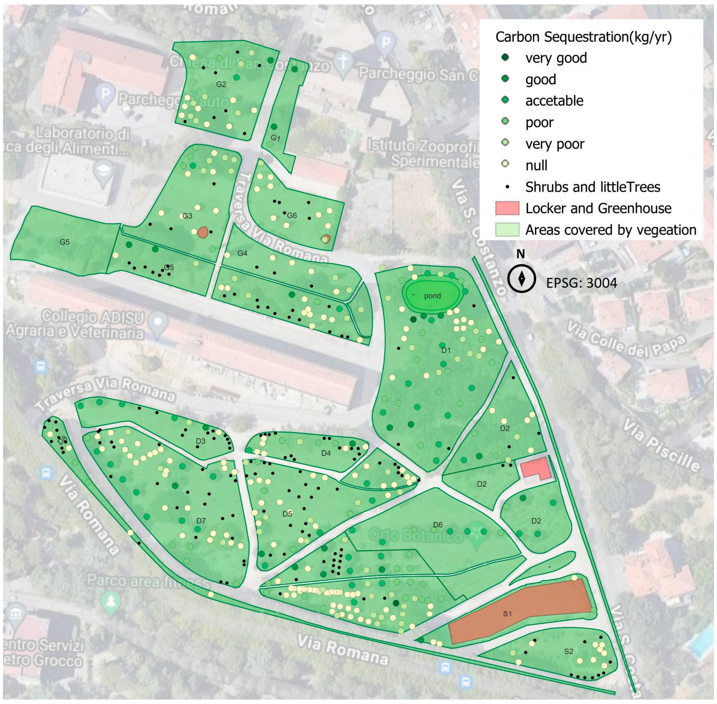

Figure 3. Inventoried trees classified per class of performance in carbon sequestration.

Table 1 shows that 47.51% of trees belong to the class of performance equal to "null", 17.40% are classified "very poor", 14.92% "poor", 13.54% "acceptable", 5.80% "good", and 0.83% "very good."

Table 1. Statistics about the structural values and carbon sequestration capacity of the study park's trees by class of performance and for the resulting tree with the best performance, called I-Tree_CS.

		Class of Performance							
		Study Area	**Null**	**Very Poor**	**Poor**	**Acceptable**	**Good**	**Very Good**	**I-Tree_CS**
Trees (number)		362	172	63	54	49	21	3	1
Canopy Cover (m^2)	$\bar{x}$	27.84	11.24	24.95	40.20	47.72	85.30	91.00	132.70
	median	13.70	4.60	19.20	27.65	27.00	100.30	70.90	
	first quartile	4.50	2.38	10.50	13.80	22.50	24.25	70.15	
	third quartile	35.15	10.35	35.00	63.88	70.10	136.50	101.80	
Leaf Area (m^2)	$\bar{x}$	179.36	49.58	183.13	283.21	336.71	534.38	616.93	643.70
	median	47.30	8.15	143.40	129.35	124.50	534.36	643.70	
	first quartile	8.25	5.08	26.15	43.68	86.60	102.60	586.60	
	third quartile	208.50	27.45	268.20	510.75	567.80	743.75	660.65	
Leaf Biomass (kg)	$\bar{x}$	18.10	4.44	22.85	24.94	26.65	72.02	60.77	46.40
	median	4.00	0.85	13.30	10.25	9.60	42.10	62.60	
	first quartile	0.90	0.40	2.50	43.68	6.80	7.95	54.50	
	third quartile	20.38	2.40	26.60	36.70	44.40	56.65	67.95	
DBH (cm)	$\bar{x}$	26.32	11.73	26.20	38.96	47.24	58.21	72.4	86.30
	median	22.15	7.90	24.40	37.50	46.10	58.90	81.0	
	first quartile	8.33	5.05	19.45	30.65	38.40	44.45	65.50	
	third quartile	40.63	11.93	32.30	44.58	53.20	70.40	83.65	
Height (m)	$\bar{x}$	7.48	4.46	9.1	9.99	10.08	12.68	21.9	24.10
	median	4.95	3.35	7.6	8.85	5.70	14.80	23.5	
	first quartile	3.30	2.50	4.75	4.10	5.10	5.45	20.80	
	third quartile	11.83	5.00	13.40	15.55	15.90	16.70	23.80	
Carbon sequestration (kg yr^{-1})	$\bar{x}$	10.39	2.23	8.35	15.31	23.39	33.09	61.77	76.30
	median	6.10	1.90	8.30	15.25	23.50	30.80	60.50	
	first quartile	2.10	1.20	7.00	13.50	22.00	29.60	54.50	
	third quartile	16.68	3.10	9.90	16.98	25.00	33.05	68.40	

The tree with the best performance, used to define the characteristic of the I-Tree_CS, is a *Populus nigra* L. and reaches 76.3 kg yr^{-1} in carbon sequestration. Still, this value does not represent the inventoried trees because they have a high variability in species and dimensions. Table 1 shows that a tree in the study park sequesters 6.10 kg yr^{-1} of carbon dioxide (median), with values of first and third quartiles equal to 2.10 and 16.68 kg yr^{-1}. In an urban context, a single species of tree can have high variability in its performance linked to the space available for the growth and the type and intensity of pruning. Indeed, other trees of the park of *Populus nigra* L. (Table S1) belong to the carbon sequestration classes of performance "null", "poor", "acceptable", and "very good" (their DBH ranges between 10.5 to 86.3 cm, and their canopy cover ranges between 9.1 and 132.7 m^2.) The other species in the class "very good" are *Populus canadensis* Moench and *Eucalyptus camaldulensis* Dehnh. Angiosperms belonging to the class "good" are *Quercus ilex* L., *Populus canadensis* Moench, *Olea europaea* L., *Quercus cerris* L., *Ulmus pumila* L., *Platanus orientalis* L., *Liriodendron tulipifera* L., and the gymnosperms are *Cedrus deodara* (Roxb.) G.Don and *Pinus pinea* L.

The year used to calculate the energy consumption for the park's management is 2023 (Table 2). The study park has a vast greenhouse (675 m^2) that hosts tropical/subtropical species and succulent xerophytes throughout the year and a building of 73 m^2 with lockers and a service room. Furthermore, the park's management (pruning and lawn mowing) needs numerous energy-intensive garden machines. Overall, the yearly carbon dioxide emissions are 42,774.50 Kg CO_2e. Comparing carbon emissions and sequestration shows that the percentage offset is currently 9%.

Table 2. CO_2 emission to manage the study area in the year 2023 expressed in kilograms of carbon dioxide equivalent (CO_2e).

Sources of Consumption	Power Supply (Measure Unit)	Power Supply (Value)	Conversion Factor (Measure Unit/kWh)	Energy Consumption (kWh)	Emission Factors (Kg CO_2/kWh)	(Kg CO_2e)
locker and service rooms	derived electricity (kWh)	1957	1	1957.00	0.43	841.51
	natural gas (m^3)	1453	9.94	14,442.82	0.19	2744.14
greenhouse	LPG (liters)	17,706	10.3	182,371.80	0.21	38,298.08
garden machines	diesel (liters)	333	10.7	3563.10	0.25	890.78
			total	202,334.72	total	42,774.50

In the last step of the method, we organized three different scenarios, increasing the surface used to improve the offset and using the characteristics of the I-Tree_CS to calculate the carbon sequestration potentiality. Scenario 0 is the current composition of the park, having an offset of 9%. Scenario 1 maintains the surface of scenario 0 and evaluates the number of I-Tree_CS that could be put in place; scenario 2 keeps the same number of trees of scenario 0 and evaluates the necessary surface with all I-Tree_CS; scenario 3 converts the overall municipality's areas classified as mixed forest, sparsely vegetated areas, and green urban areas (Figure 1, lett. a) in green spaces with I-Tree_CSs and evaluates the overall potentiality of carbon sequestration. Table 3 shows the three scenarios and their percentage offset, except for scenario 3, which involves the whole city. Indeed, scenario 3 estimates the municipality's carbon sequestration potentiality, which should be compared with the city's overall carbon emissions.

Table 3. Scenarios toward carbon neutrality.

	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Trees (n.)	362	175	362	98,644
Surface (m^2)	23,234	23,234	48,037	13,090,000
Surface (ha)	2.32	2.32	4.80	1309.00
Surface (%)	100	100	207	56,339
Canopy Cover (m^2)	10,078	23,223	48,037	13,090,000
Leaf Area (m^2)	64,930	112,648	233,019	63,496,858
Leaf Area Density (m^2/ha)	27,945	48,483	48,508	48,508
LAI (Leaf Area Index)	6.44	4.85	4.85	4.85
Tree Density (n. of trees/ha)	156	75	75	75
Leaf Biomass (kg)	6551	8120	16,797	4,577,061
Carbon Sequestration (kg yr^{-1})	3762	13,300	27,512	7,496,910
KgCO_2e	42,775	42,775	42,775	-
% Offset	9	31	64	-

The scenario analysis reveals that substituting the existing arboreal mix with optimal trees in the study area would decrease the tree count by 52% to ensure a suitable growth space, with a resultant offset of 31%. Conversely, maintaining the current tree count with all trees possessing I-Tree_CS traits would necessitate doubling the area, yielding a 64% offset. Additionally, the third scenario shows that covering all the suitable areas in the municipality with optimal trees would sequester 7497 tons of carbon annually.

4. Discussion

4.1. Urban Parks:Sinks or Sources of Carbon?

Currently, the study park is a carbon source, not a sink. Indeed, the park's trees sequester 9% of the carbon emitted for its functioning. The high carbon emissions related to the study park's maintenance confirm the need to decarbonize the emission sectors substantially [2]. The case study hosts a greenhouse designed to generate different climate conditions for non-native plants, following the main aim of the botanical garden, which consists of preserving and showing worldwide biodiversity. Considering that the city's other urban parks do not have greenhouses, we have also evaluated the carbon balance without the carbon emission linked to the greenhouse. In this case, the park studied reaches an offset of 84%. Therefore, the study park remains a carbon source due to its high maintenance cost. This result confirms the need to reduce maintenance operations generally carried out in urban green areas [4–6]. Many strategies are implemented in this regard. For example, Teixeira et al. [41] have applied an adaptive planting design and management for urban climate change adaptation and mitigation in the city of Porto (Portugal). Management strategies to change this balance include different pruning or thinning intensities [27], decreasing mulch application rates and expanding tree canopy extent, permitting spontaneously growing species by a reduced management intensity [42], and management frequency [21].

The main weakness of the method developed to evaluate the urban park's carbon balance is to gate the study to a single year. Other scholars used a life cycle assessment approach, considering the emissions for planting and managing vegetal residues, pruning, lawn mowing, and the carbon stored inside them during their lives [7,27]. Nicese et al. [27], studying a well-managed park in northern Italy, showed a carbon sequestration capacity ten times higher than the carbon emissions over 50 years. A further limitation of the method is that it focuses on the carbon sequestrated by the trees higher than 1.8 m in the study area, neglecting the contribution of little trees, shrubs [15], and lawns [4]. Despite these weaknesses, this paper contributes to developing methods for using data-informed and nature-based patterns that Convertino [43] highlights as essential for achieving optimal strategic decisions. Future development of our work will apply a life cycle assessment approach to this park and other city parks, considering all the vegetational components and defining the optimal planting, maintenance, and residue-converting strategies to refurbish the network of the city's urban parks and transform them into valuable sinks of carbon.

4.2. Carbon Balance Requires a Multi-Level Approach

Currently, the park's carbon offset is 9%. This percentage rises to 31% using ideal trees (trees having optimal performance in carbon sequestration) and to 64% by maintaining the same number of trees but doubling the surface to ensure adequate growth. The park studied, using ideal trees and without the greenhouse, passes from carbon source to carbon sink and reaches an offset of 297%.

These results confirm previous findings highlighting that the urban green system, when not a source of carbon due to its high maintenance costs [4], contributes marginally to the carbon balance of cities. Brilli et al. [2] evaluated the current offset by urban forests to achieve carbon neutrality of an Italian town (Prato) at 7.1%, reaching up to 11% using an afforestation scenario. Teo et al. (2021) observed that 17.6% of worldwide city areas suitable for afforestation could offset about 1% of city emissions. Doorga et al. [44] developed a scenario to move toward Mauritius's carbon neutrality by converting all inhabited lands into forests.

A multi-level approach follows the regional science approaches that address the issue of local interactions and consider the concepts of space and distance as essential in landscape planning and design processes [45,46]. Geographical proximity, defined as the physical distance between two entities, weighted by the cost in time and money of covering that distance, can reinforce interactions between actors and generate positive externalities [47].

However, activating the benefits of this proximity depends on the studied benefit because the urban green system provides both proximity and territorial services. That is, some ecosystem services need proximity to the inhabitants to be best provided, such as neighborhood greenery for the daily inhabitants' walks [47] or proximity to the emission sources, such as the green areas planned to absorb PM_{10} and PM_5 [3], while other services are territorial and do not need proximity to be provided. This is the case with the carbon balance, so it is possible to evaluate its compensation also varying the scale of the investigation.

Scenario 3 of this paper varies the level of study and develops a hypothesis involving the whole municipality. It uses the ideal tree's characteristics to evaluate the optimal performance obtainable by mixed forests, sparsely vegetated areas, and green urban areas. Table 3 shows this scenario offers 7,496,910 kg yr^{-1} of carbon sequestration potential. Comparing the 21% of the carbon sequestered with this scenario (1,574,351 kg yr^{-1}) with the consumption of Prato (465,800 Kg CO_{2e} yr^{-1}) [2], an Italian city with a surface equal to 21% of Perugia and a population equal to 110% [28], we obtain an offset of 338%. This result seems to be promising. A further development will calculate the carbon emissions of the city of Perugia and its hamlets. It is crucial to highlight that scenario 3 represents an ideal solution limited to carbon sequestration. For this reason, it represents only a hypothetical scenario to offer a value of maximum potentiality. Indeed, many trees and shrubs that do not perform well in this sense provide numerous other ecosystem services and increase the biodiversity of territories [20,48,49].

4.3. Species-Specific Suggestions to Move toward Carbon Neutrality

Our results show high variability in carbon uptake by tree canopy cover (median 434.29, interquartile range from 226.73 to 913.15 g m^{-2}, Table S1), confirming that an adequate species selection can influence the carbon balance [27]. Findings of previous studies in other areas report values inside our interquartile range, such as 600 ± 200 g m^{-2} in a study in Boston [50] and 283 g m^{-2} in a study in Prato [2]. The high variability in the carbon sequestration of trees in this case study is due to the variety of species (142 species) and the different trees' dimensions. Furthermore, the age of the trees affects the amount of carbon sequestration, and i-Tree Eco estimates this value using DBH and species identification.

Regarding the species having the best results in carbon sequestration (*Populus nigra* L.), the study park also hosts specimens that belong to classes of performance equal to "null", "poor", and "acceptable" because they had different available spaces to grow. Table S1 shows that their DBHs range between 10.5 and 86.3 cm, and their canopy covers between 9.1 and 132.7 m^2. This result confirms that, to optimize ecosystem services provided by the urban green system, in addition to considering species selection, there is a need to consider the physical needs of every species in their different growth phases and respect them [20].

In our study, the other species with optimal carbon sequestration performance are *Populus canadensis* Moench and *Eucalyptus camaldulensis* Dehnh. In a different geographical context (China), Zhang et al. [23] suggest *Populus tomentosa* Carrière, *Fraxinus chinensis* Roxb, and *Lonicera maackii* (Rupr.) Maxim. In the Sultanate of Oman, Al-Nadabi and Sulaiman [51] suggest *Ficus* spp., followed by *Azadirachta indicia*, *Conocarpus erectus*, and *Tabebuia rosea*. These findings show that geographical contexts and the existent species in the case studies influence the different findings.

Instead, it is significant to develop a reflection about the three best-performing species in our paper (*Populus nigra* L., *Populus x canadensis* Moench, and *Eucalyptus camaldulensis* Dehnh), which well exemplify the need for broader evaluations to select species. First, ecological and morpho-physiological factors are to be considered. Indeed, poplars are scarcely drought-resistant plants from humid environments with fast growth but a short lifecycle and weak and brittle wood [52,53].

Studies show that elevated CO_2 can lead to reductions in cell wall thickness and changes in vessel diameters, affecting wood quality in *Populus nigra* L. and highlighting the importance of nitrogen availability in managing water uptake and hormone modulation during acclimation to drought [54,55].

The i-Tree modeling results of this study refer and thus are limited to the current environmental conditions, not considering the CO_2 increase scenarios and their consequences. Recurring and intensified droughts might represent a potential, significant limitation to water availability and carbon sequestration since water and nutrients are key factors influencing both plant physiology and morphology. Specific strategies can reduce this negative impact involving the species choice and management. Fertilizing to guarantee good nitrogen availability can be considered to contrast and compensate for the effects of water scarcity on carbon assimilation [55], whereas there is a quantified positive balance between benefits and related ecological costs.

A further important element to incorporate in the species' evaluation is their biogenic volatile organic compound emissions [56], and the two best-performing species in this paper are strong emitters of these [57–59]. The biogenic organic compounds are volatile, reactive precursors of O_3 (ozone), one of the main air pollutants that can thus promote its formation in the troposphere. Being also O_3 sinks, plants' role in regulating its concentration results from a complex balance; nevertheless, these compounds' relevance as O_3 precursors are expected to grow within the urban environment [60] and must be considered.

The overall species choice should also feature an adequate biodiversity rate. This can enhance the ecosystem services provided, such as the air pollutant removal capacity, and minimize the potential adverse effects, such as volatile organic compound emissions [56]. Furthermore, biodiversity can contribute to pests and disease containment, another relevant factor for the species choice. An additional ecological aspect to address is that *Populus canadensis* Moench and *Eucalyptus camaldulensis* Dehnh are exotic plants naturalized in many regions of Italy, manifesting invasive behavior in the most favorable climates [52].

It is then essential to clarify that the resulting species, poplar and eucalyptus, should not be considered the best ones in absolute terms for the design of every park in every context. We used them as proxies for this specific ecosystem service, CO_2 sequestration, to highlight the problematic differential between CO_2 absorptions by the plants and CO_2 emissions produced by maintenance practices.

Overall, these findings suggest that the choice should result from a cost-benefit combination of these aspects: the type and quantities of ecosystem services provided, the species' demands, the lifecycle duration (compared to the growth rate), and the interaction with the human environment and the local flora.

5. Conclusions

Urban parks provide differentiated ecosystem services to citizens living in urban areas, and their sustainable development and management should be encouraged and stimulated. However, from the carbon emission mitigation perspective, this study's results indicate that cities should not limit their planning effort to urban green areas but must effectively implement green infrastructure in the whole municipality. Furthermore, our results suggest that, from a carbon neutrality perspective, implementing actions to reduce carbon dioxide emissions should be considered the priority, in parallel with valorizing the trees' performance in natural and rural areas. Therefore, the key points to guide the plans and designs of urban green systems should focus on choices to ensure that they represent a carbon sink, not a source of it. This only results from a process evaluating adequate species with high performance in carbon sequestration and, at the same time, low maintenance requirements, leaving trees adequate spaces for their healthy growth and optimizing other ecosystem services that are needed in proximity to inhabitants.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments11050098/s1, Table S1: dataset of the tree inventory of the study park.

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