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Carbon Dioxide Sequestration Capability of the Botanical Garden of Rome: Environmental and Economic Benefits

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Abstract

Carbon dioxide (CO_2) is one of the most abundant anthropogenic greenhouse gases contributing to increase air temperature. Urban areas covered by parks, gardens, tree-lined avenues, sports fields, and hedges are important sinks for CO_2. Urban green areas should include the Botanical Gardens, taking into consideration their key role in *ex situ* plant conservation as well as air quality amelioration and social benefits. In such context, the CO_2 sequestration capability of the most representative plant collections developing in the Botanical Garden of Rome and their influence on microclimate was analyzed. Our results highlight that plant collections have a CO_2 sequestration capability of 6947 Mg CO_2 year^{-1}. The CO_2 sequestration capability and air temperature lowering by plant collections growing in the Botanical Garden have positive effects ($p \leq 0.05$) on the surrounding area resulting in 4% CO_2 concentration and 1˚C air temperature decreasing at 150 m from the centre of the Garden.

Keywords

Air Quality Amelioration, Plant Collections, Urban Greening

1. Introduction

Urban areas are rapidly expanding globally and it is expected that 60% of the world's population will be living in cities by 2030 [1]. Cities account for more than 70% of the energy-related to global greenhouse gases [2] [3] and carbon dioxide (CO_2) is one of the most abundant anthropogenic greenhouse gases contributing to increase air temperature [4]. The exchange of CO_2 over cities is mostly governed by anthropogenic emissions originating from road traffic and local heating with natural gas, oil and coal [5]. As urbanization increases globally, it is becoming important to better clarify the carbon (C) dynamics of urban ecosystems [6]. European cities are sharing their knowledge of climate policy initiatives. In particular, London, Paris, Berlin, and Rome have signed the Covenant of Mayors including commitments to implement sustainable energy policies (e.g. increased energy efficiency and development of renewable energy sources) that meet and exceed the EU's 20% CO_2 emissions reduction objective. In addition to the energy efficiency and renewable energy sources, CO_2 emissions reduction can be achieved by plants [3]. Plants remove CO_2 from the atmosphere through photosynthesis and storing the carbon excess as biomass in roots, stems, and branches [4]. Nevertheless, today the relationship between vegetated urban areas and CO_2 emissions reduction has not been clarified and recently only the use of plants to ameliorate urban air quality has become a focus of research [7] [8]. In particular, urban areas covered by parks, gardens, tree-lined avenues, sports fields, and hedges are important sinks for CO_2 [8]. The CO_2 sequestration capability is related to species, plant age and growing conditions [9]. Urban greening also contributes to decrease air temperature through shading, blocking wind and evapotranspiration, thus counteracting the urban heat island effects [10] and lowering building energy used for cooling [10]. Moreover, green spaces serve important social, psychological, health, aesthetic and ecological functions within urban areas [11]. When exposed to green areas, people show a greater well-being with physical and psychological benefits [12]. Among green areas, Botanical Gardens have a key role in plant conservation. The Botanic Gardens Conservation International (BGCI) defined Botanical Gardens as "Institutions holding documented collections of living plants for the purposes of scientific research, conservation, display and education" [13]. There are more than 1700 Botanical Gardens worldwide [14]. Europe has the highest number of Botanical Gardens (527): Germany (74), France (66), United Kingdom (61), Italy (48) and the Netherlands (39) [14]. Botanical Gardens have a significant role in plant *ex situ* conservation [15], taxonomic research [16], horticultural and economic Botany [17], public education and natural history appreciation [18]. Botanical Gardens also offer economic benefits associated with attracting tourists [19]. Some visitors appreciate the educational experiences and opportunities to view unusual or rare species, and others their role in maintaining local traditions and community identity [20]. In this context, we analyzed an additional role for the Botanical Gardens that should be considered, *i.e.* the contribution to environmental quality amelioration. In particular, the CO_2 sequestration capability of the most representative plant collections developing in the Botanical Garden of Rome (Italy) and their influence on microclimate was analyzed.

2. Methods

2.1. The Study Area

The study was carried out in the period January-May 2016 inside the Botanical

Garden of Rome (41˚53'53" N, 12˚28'46" E; 53 m a.s.l.). The Botanical Garden covers an area of 12 ha in the city centre, between Lungara Street and the Gianicolo Hill. The plane area is enriched with tree species, the Palm Collection and meadows, while the hill area is occupied by Ferns, *Eucalyptus* collection, Bamboos, Rose Garden, Japanese Garden, Rock Garden and Geophytes, Mediterranean Wood and Gymnosperms [21].

The study area is under a Mediterranean type of climate. The average total annual rainfall is 848 mm, most of it distributed in autumn and winter. The average maximum air temperature of the hottest months (July and August) is 31.7˚C ± 0.1˚C and the average minimum air temperature of the coldest month (January) is 4.9˚C ± 0.9˚C. The mean yearly air temperature is 16.7˚C ± 6.5˚C (data provided by the Lazio Regional Agency for Development and Agricultural Innovation; Meteorological Station of Rome, Lanciani Street, data for the period 2006 to 2016).

2.2. Carbon Dioxide Concentration and Microclimate Measurement

Atmospheric carbon dioxide concentration (CO_2, ppm), air temperature (T_a, ˚C) and air humidity (RH, %) were monitored simultaneously by handheld tools (Rotronic, CP11) along two Transects: Transect 1 from Garibaldi Square to the centre of the Botanical Garden and Transect 2 from Lungotevere della Farnesina Street to the centre of the Botanical Garden. Measurements were carried out in three different points of each transect: at the centre of the Garden (C), at 150 m from the centre (B_1 and B_2, for Transect 1 and 2, respectively) and outside the Botanical Garden (at 300 m from the centre, A_1 at Garibaldi Square and A_2 at Lungotevere della Farnesina, for Transect 1 and 2, respectively) (**Figure 1**). Traffic level (*i.e.* number of vehicles per minute) was monitored simultaneously with CO_2 measurements in Garibaldi Square and Lungotevere della Farnesina Street. The sites along each transect were chosen on the base of a progressive traffic intensity decrease from street densely congested to the inner of the Botanical Garden.

2.3. Plant Collections

The most important plant collections developing in the Botanical Garden were considered. In particular, the Mediterranean Garden (2050 m^2), Palms (4463 m^2), Gymnosperms (15,500 m^2), Bamboos (6205 m^2), Mediterranean Wood (17,850 m^2), *Eucalyptus* Collection (8500 m^2), Japanese Garden (2250 m^2), *Erythrina* Area (13,005 m^2), Ferns (4250 m^2), Rock Garden and Geophytes (5100 m^2), Rose Garden (4250 m^2) and Meadows (2423 m^2) (**Figure 2**).

The extension of each plant collection was measured by a Quantum Gis (QGIS), an Open Source Geographic Information System (OSGEO4W, version 1.8.0) running on Windows. QGIS determines the acquisition, recording, analysis, visualization and restitution of information by geographical data. The GIS

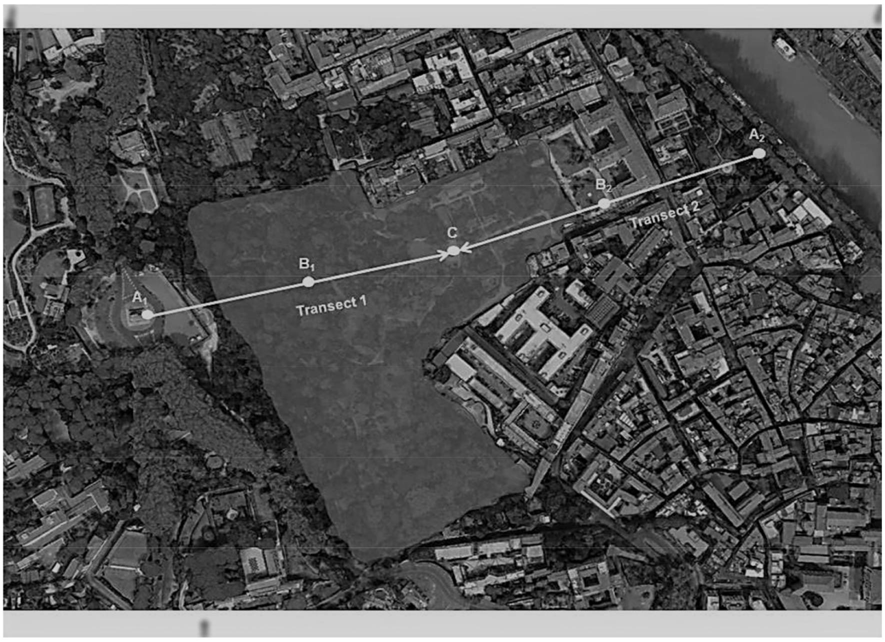

Figure 1. The two Transects monitored from the outside to the centre of the Botanical Garden of Rome (41˚53'53" N, 12˚28'46" E). Transect 1: A_1 (Garibaldi Square, at 300 m from the centre), B_1 (at 150 m from the centre), C (centre of the Botanical Garden). Transect 2: A_2 (Lungotevere della Farnesina Street, at 300 m from the centre), B_2 (at 150 m from the centre), C (centre of the Botanical Garden).

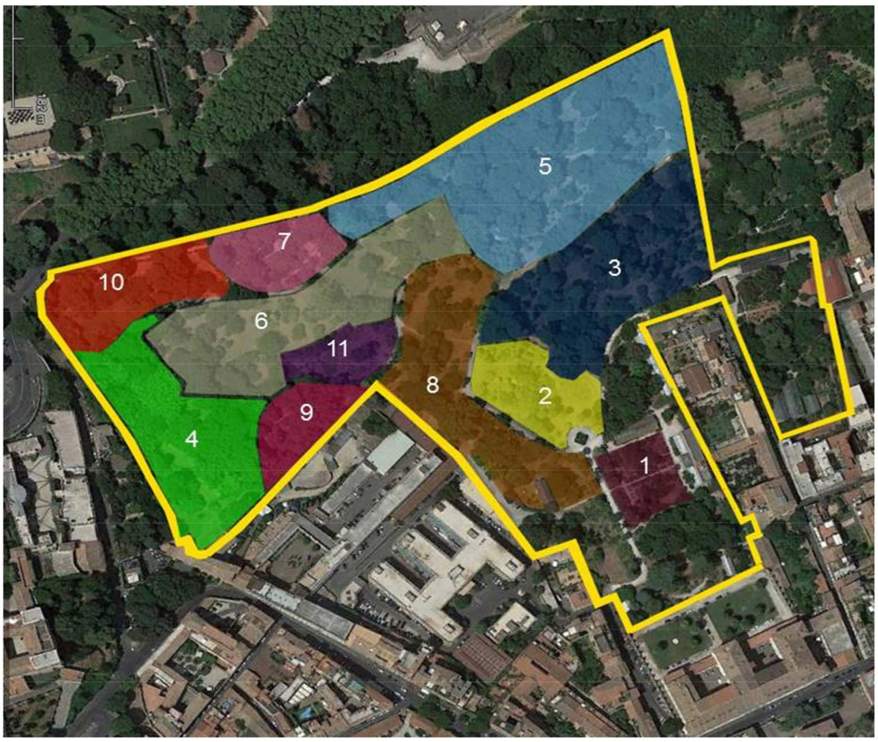

Figure 2. Map of the considered plant collections inside the Botanical Garden of Rome. 1 = Mediterranean Garden; 2 = Palms; 3 = Gymnosperms, 4 = Bamboos; 5 = Mediterranean Wood, 6 = *Eucalyptus* Collection; 7 = Japanese Garden; 8 = *Erythrina* Area; 9 = Ferns; 10 = Rock Garden and Geophytes; 11 = Rose Garden.

software is useful for the census of urban green areas by the analysis of digital cartographies.

2.4. Plant Traits

Leaf Area Index (LAI) was measured by the "LAI 2000 Plant Canopy Analyzer" (LICOR Inc., Lincoln, USA) for all the considered plant collections. Structural traits of each collection, excluding Meadows, were measured on representative plants (n = 10 per plant collection). In particular, tree diameter at breast height (DBH, m) was measured by callipers (Silvanus calliper—65 cm), and a DBH tape (length = 20 m) when diameter was larger than 65 cm. Plant height (H, m) was measured by electronic clinometers (Haglöf, Sweden). The total photosynthetic leaf surface area (TPS, m^2) of each plant collection was determined by multiplying each LAI value by the extension of the plant collection.

2.5. Carbon Dioxide Sequestration

The CO_2 sequestration capability for each plant collection was calculated multiplying TPS by the mean yearly net photosynthesis and the total yearly photosynthetic activity time (in hours), according to [22]. In order to compare CO_2 sequestration capability of the different plant collections, the CO_2 sequestration capacity per hectare (CS, Mg CO_2 $ha^{-1}\cdot year^{-1}$) was calculated. The total CO_2 sequestration capacity of the Botanical Garden was also calculated (CS_{Tot}).

The net photosynthetic rate (N_P, $\mu mol\cdot m^{-2}\cdot s^{-1}$) was measured by an open infrared CO_2 gas analyzer (ADC LC*Pro*+, UK), equipped with a leaf chamber (PLC, Parkinson Leaf Chamber). Measurements were made *in situ* on cloud-free days (PAR > 1000 $\mu mol\cdot m^{-2}\cdot s^{-1}$), in the morning (from 9:00 am to 12:00 pm), to ensure that near maximum daily N_P was measured. On each sampling occasion, fully sun expanded leaves were used (Varone *et al.*, 2015). Leaves were retained in their natural position during measurements. Measurements were carried out at ambient air temperature on five representative plants per each collection (three leaves per plants).

2.6. Monetary Value of CO_2 Sequestration

The monetary value of CO_2 sequestration for the collections growing in the Botanical Garden was estimated assuming a monetary value of $ 0.00334/lb (*i.e.* $0.00736/kg) for sequestered CO_2, according to [23].

2.7. Statistical Analysis

Differences of the means were tested by one-way analysis of variance (ANOVA), and Tukey test for multiple comparisons. Moreover, in order to understand how LAI, TPS and N_P (predictors) affected CS (response variable), the predictors were combined via Principal Component Analysis (PCA) across plant collections. Then, a simple linear regression analysis between the axis explaining the largest proportion of the variance (*i.e.* PC_1) and CS was carried out. All statistical tests were performed using a statistical software package (Statistica, Statsoft, USA).

3. Results

3.1. Carbon Dioxide Concentration and Microclimate

The mean CO_2 concentration during the study period was 485 ± 22 ppm (mean value of Transect 1 and Transect 2) peaking in January (522 ± 21 ppm, mean of A_1 and A_2) (**Table 1**). The highest CO_2 concentration was monitored where the traffic level was the highest (31 ± 1 vehicles·min^{-1}, mean of A_1 and A_2) decreasing by 8% in May (mean of A_1 and A_2) associated to a 21% decrease of the traffic level (mean of A_1 and A_2). Along the Transect 1, A_1 had a 6% lower CO_2 concentration compared to A_2 (Transect 2) with a 70% lower traffic level. Moreover, CO_2 concentration decreased, on average, 9% from outside to the centre of the Botanical Garden in both the Transects. In particular, CO_2 concentration decreased 2% and 6% from A_1 to B_1 and from A_1 to C, respectively, along Transect 1, and 6% and 12% from A_2 to B_2 and from A_2 to C, respectively, along Transect 2.

A similar trend was observed in T_a decreasing, on average, 14% from the outside to the centre of the Botanical Garden. In particular, T_a decreased 7% and 13% from A_1 to B_1 and from A_1 to C, respectively, along Transect 1, and 8% and 14% from A_2 to B_2 and from A_2 to C, respectively, along Transect 2. An opposite trend was observed for RH, increasing, on average, 7% from outside to inside the Botanical Garden (**Table 1**).

3.2. Plant Traits

Structural traits of plant collections are shown in **Figures 3(a)-(d)**. The highest LAI ($p \leq 0.05$) was measured in Bamboos (2.90 ± 0.06) and the lowest in Meadows (0.40 ± 0.05, mean value). The Mediterranean Wood had the highest ($p \leq 0.05$) TPS (43,197 m^2) and the Meadows the lowest (969 m^2). DBH was the highest ($p \leq 0.05$) in the Gymnosperms (1.16 ± 0.30 m) and the lowest in Rose Garden (0.06 ± 0.03 m). The *Eucalyptus* Collection had the highest ($p \leq 0.05$) H (26.8 ± 2.3 m).

3.3. Carbon Dioxide Sequestration

Bamboos had the highest CS (210 Mg CO_2 ha^{-1}·year^{-1}, corresponding to 57.4 Mg C ha^{-1}·year^{-1}) among plant collections, followed by the Mediterranean Wood (133 Mg CO_2 ha^{-1}·year^{-1}, corresponding to 36 Mg C ha^{-1}·year^{-1}) while Ferns had the lowest CS (7.1 Mg CO_2 ha^{-1}·year^{-1}, corresponding to 1.9 Mg C ha^{-1}·year^{-1}) (**Figure 4**). Considering the extension of each plant collection, the Mediterranean Wood had the highest CO_2 sequestration capability (150 Mg CO_2 year^{-1}, corresponding to 65 Mg C year^{-1}), followed by the Bamboos (130 Mg CO_2 year^{-1}, corresponding to 36 Mg C year^{-1}), the *Erythrina* Area (110 Mg CO_2 year^{-1}, corresponding to 30 Mg CO_2 year^{-1}), Gymnosperms (109 Mg CO_2 year^{-1},

Table 1. Carbon dioxide concentration (CO_2), air temperature (T_a) and air humidity (RH) monitored during the study period (January-May) along the two Transect from the outside to the centre of the Botanical Garden of Rome. Transect 1: A_1 (Garibaldi Square, at 300 m from the centre), B_1 (at 150 m from the centre), C (centre of the Botanical Garden). Transect 2: A_2 (Lungotevere della Farnesina Street, at 300 m from the centre), B_2 (at 150 m from the centre), C (centre of the Botanical Garden). Mean values for each point during the study period are indicated in bold. The differences between the three points of each Transect were always significant at $p \leq 0.05$.

	CO_2 (ppm)			T_a (˚C)			RH (%)		
				Transect 1					
Month	A_1	B_1	C	A_1	B_1	C	A_1	B_1	C
Jan	507 ±1	491 ± 4	474 ± 1	6.1 ± 0.1	5.9 ± 0.1	5.3 ± 0.1	72.5 ± 0.9	73.2 ± 0.3	76.4 ± 0.4
Feb	502 ± 2	497 ± 1	479 ± 2	5.7 ± 0.3	4.9 ± 0.1	4.8 ± 0.2	71.2 ± 0.8	75.2 ± 0.4	78.5 ± 0.4
Mar	502 ± 1	495 ±0.1	489 ± 2	10.4 ± 0.1	10.3 ± 0.1	9.1 ± 0.1	70.0 ± 0.1	72.4 ± 0.8	77.4 ± 0.5
Apr	463 ± 2	458 ± 0.1	427 ± 1	12.8 ± 0.5	12.7 ± 0.1	12.5 ± 0.1	68.5 ± 0.5	70.2 ± 0.6	72.3 ± 0.9
May	455 ±4	444 ± 1.2	425 ± 1	22.4 ± 0.1	19.7 ± 0.1	18.4 ± 0.1	56.4 ± 0.2	60.2 ± 0.8	63.1 ± 0.2
	486 ± 25	**477 ± 24**	**459 ± 30**	**11.5 ± 6.8**	**10.7 ± 6.0**	**10.0 ± 5.6**	**67.7 ± 6.5**	**70.2 ± 5.9**	**73.5 ± 6.3**
				Transect 2					
	A_2	B_2	C	A_2	B_2	C	A_2	B_2	C
Jan	536 ± 6	499 ± 1	474 ± 0.9	6.8 ± 0.3	6.7 ± 0.1	5.3 ± 0.1	74.5 ± 0.3	83.1 ± 0.7	76.4 ± 0.4
Feb	529 ± 1	488 ± 2	479 ± 2	6.3 ± 0.1	5.8 ± 0.2	4.8 ± 0.2	75.4 ± 0.1	84.3 ± 0.2	78.5 ± 0.4
Mar	514 ± 2	496 ±1	489 ± 2	10.2 ± 0.2	8.6 ± 0.1	9.1 ± 0.1	74.6 ± 0.3	89.8 ± 0.7	77.4 ± 0.5
Apr	510 ± 3	469 ±9	427 ± 1	13.1 ± 0.1	13.0 ± 0.6	12.5 ± 0.1	69.1 ± 0.1	70.3 ± 0.6	72.3 ± 0.9
May	508 ± 2	476 ± 2	425 ± 1	22.3 ± 0.1	19.7 ± 0.1	18.4 ± 0.1	53.3 ± 0.5	61.6 ± 0.1	63.1 ± 0.2
	519 ± 12	**486 ± 13**	**459 ± 30**	**11.7 ± 6.5**	**10.8 ± 5.7**	**10.0 ± 5.6**	**69.4 ± 9.3**	**77.8 ± 11.5**	**73.5 ± 6.3**

corresponding to 29 Mg CO_2 year^{-1}), *Eucalyptus* Collection (35 Mg CO_2 year^{-1}, corresponding to 9 Mg CO_2 year^{-1}), Palms (28 Mg CO_2 year^{-1}, corresponding to 8 Mg CO_2 year^{-1}), Mediterranean Garden (17 Mg CO_2 year^{-1}, corresponding to 5 Mg CO_2 year^{-1}), Japanese Garden (15 Mg CO_2 year^{-1}, corresponding to 4 Mg CO_2 year^{-1}), Rose Garden, Rock Garden and Geophythes (10.4 ± 0.5 Mg CO_2 year^{-1}, mean value, corresponding to 2.8 ± 0.1 Mg CO_2 year^{-1}), Meadows (4.7 Mg CO_2 year^{-1} corresponding to 1.3 Mg C year^{-1}) and Ferns (3.0 Mg CO_2 year^{-1}, corresponding to 0.82 Mg C year^{-1}). Considering the total extension of plant collections (8.6 ha), the CO_2 sequestration capability for the Botanical Garden was of 6947 Mg CO_2 year^{-1}, corresponding to 1897 Mg C year^{-1}.

The PCA returned two axis of variations across plant collections. In particular, PC_1 was positively related to LAI and TPS accounting for 55% of the total variance. PC_2 was positively related to N_P accounting for 37% of the total variance. There was a significant linear regression between PC_1 and CS. Nevertheless, the relationship did not hold for Gymnosperms and Bamboos collections which felt apart from the fitted line. When they were removed from the analysis, the performance of the linear model significantly increased (**Figure 5**).

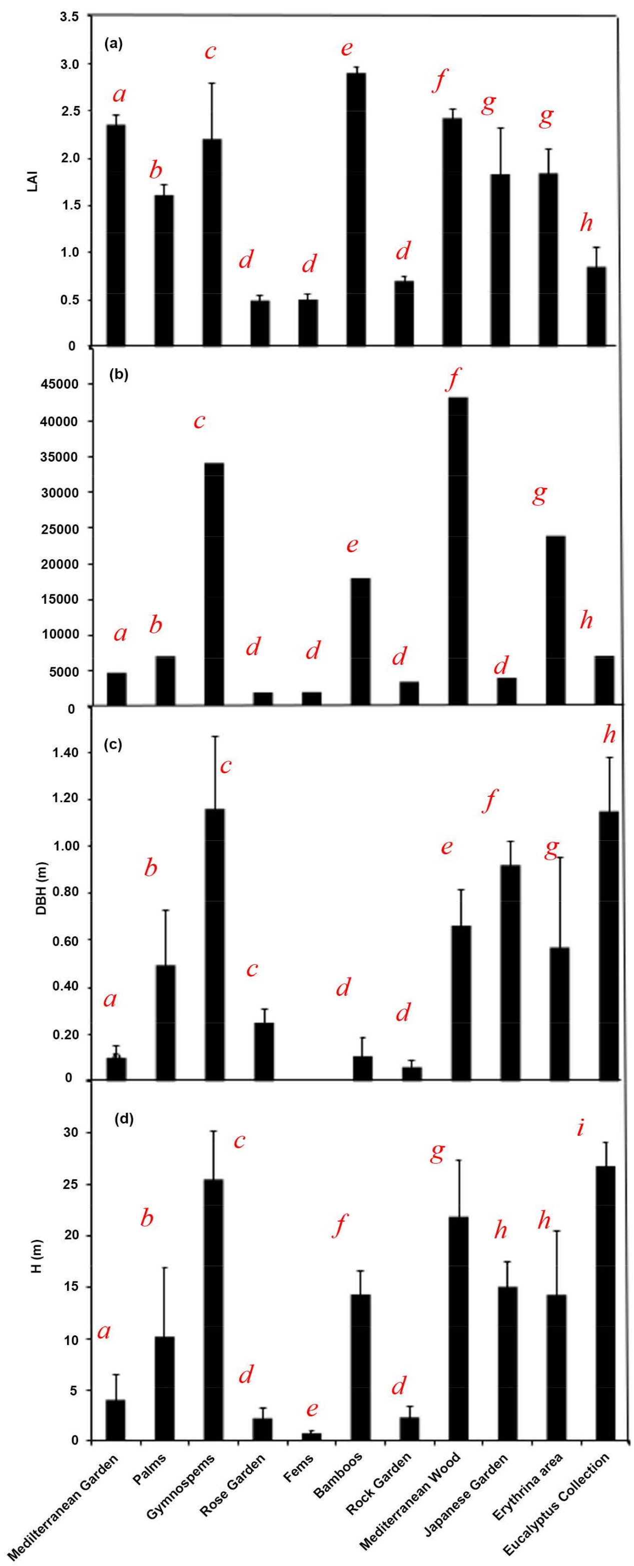

Figure 3. Leaf area index (LAI) (A), total photosynthetic leaf surface (TPS, m^2) (B), diameter at the breast height (DBH, m) (C) and plant height (H, m) (D) of plant collections growing in the Botanical Garden of Rome. Mean values ± S.E. are shown (n = 10). Mean values with the same letters are not significantly different ($p \geq 0.05$).

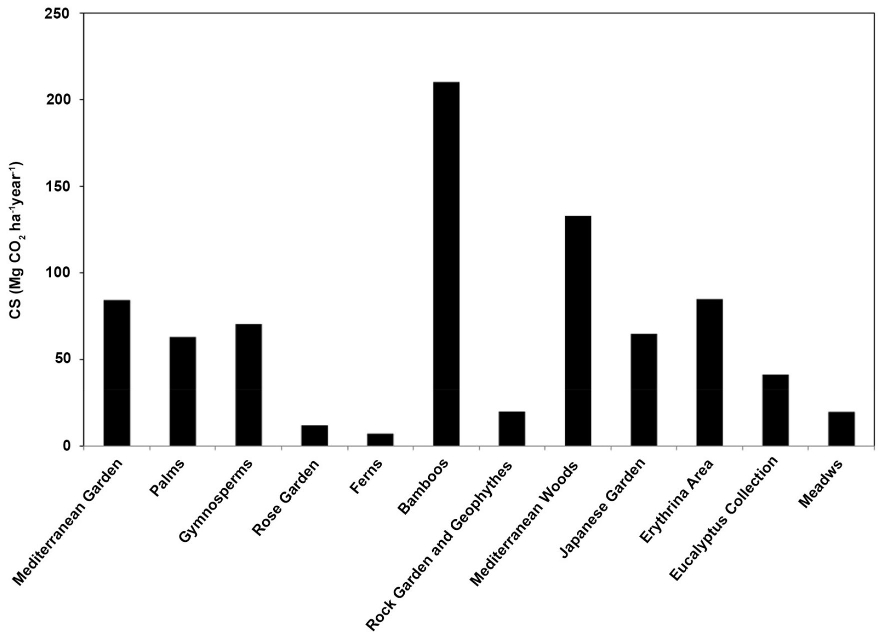

Figure 4. Carbon dioxide (CO_2) sequestration (CS, Mg CO_2 $ha^{-1}\cdot year^{-1}$) capability of the different plant collections growing in the Botanical Garden of Rome.

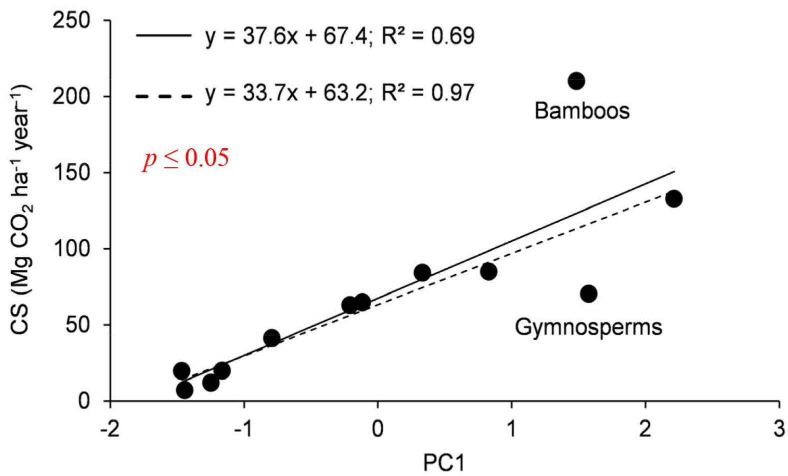

Figure 5. Linear relationship between the first principal component combining LAI and TPS (PC1) and the CO_2 sequestration capacity per hectare (CS, Mg CO_2 $ha^{-1}\cdot year^{-1}$) across the Botanical Garden of Rome plant collections. The solid line represents the relationship obtained including all the plant collections (n = 12); the dashed line represents the same relationship by excluding Bamboos and Gymnosperms (n = 8; See Results section for further details). The equations, as well as their R^2, are shown. The relationships were significant at $p \leq 0.05$.

3.4. Monetary Value of CO_2 Sequestration

The monetary value of CO_2 sequestered by the Botanical Garden was 59-56$ $ha^{-1}\cdot year^{-1}$, to which Bamboos and Mediterranean Wood gave the highest contribution (26% and 16%, respectively), and Ferns, Rose Garden (1%) and Meadows (2%) the lowest.

4. Discussion

Quantifying CO_2 sequestration by urban vegetation is necessary for the development of low-neutral carbon cities or climate-friendly cities [24]. Urban green areas should include the Botanical Gardens, taking into consideration their key role of *ex situ* plant conservation as well as air quality amelioration capability and social benefits. The city of Rome signing the Covenant of Mayors is committed to adopt an integrated approach to tackling climate change mitigation. Thus, a better awareness of the role of urban greening in CO_2 reduction achieved should be included.

On the whole, our results show that plant collections inside the Botanical Garden of Rome cover 8.6 ha corresponding to 72% of the Botanical Garden extension (12 ha). The analyzed plant collections show different structural traits. In particular, *Eucalyptus* and Gymnosperm collections have the highest H and DBH (26.2 ± 0.9 m and 1.16 ± 0.01 m, respectively, mean value). LAI ranges from 2.90 ± 0.06 (Bamboos) to 0.40 ± 0.05 (Meadows). LAI is an important variable for characterizing vegetation structure and function [8]. It is related to photosynthesis and plant biomass [25]. The results show that structural traits are good predictors of plant collection CO_2 sequestration capability as attested by the relationship between PC_1 and CS. In particular, Gymnosperms have, on average, a lower CS (70 Mg CO_2 $ha^{-1}·year^{-1}$) while Bamboos (210 Mg CO_2 $ha^{-1}·year^{-1}$) a higher, than that predicted by the linear model. Nevertheless, the two collections show the same z-score on the obtained PC_1 even if strongly differed in terms of CS. The same z-score for these collections can be explained by TPS and LAI. Gymnosperms have 89% higher TPS compared to Bamboos, with the latter being characterized by a 32% higher LAI. The high net photosynthetic rates of Bamboos [26] explain the divergence in CS compared to the other collections and the high contribution to CS_{Tot} (26%). The lower CS of Gymnosperms compared to the other collections and the lower contribution to CS_{Tot} (9%) is linked to their low net photosynthetic rates [27]. Among the other collections, the Mediterranean Wood has the highest contribution to CS_{Tot} (16%), with a CS of 133 Mg CO_2 $ha^{-1}·year^{-1}$. Moreover, the Mediterranean Garden and the *Erythrina* Area contribute 10% to CS_{Tot} with a CS of 84 and 85 Mg CO_2 $ha^{-1}·year^{-1}$, respectively. The Rose Garden and Ferns have the lowest CS, contributing less than 2% to CS_{Tot}. Considering the extension of each collection, the Mediterranean Wood (17,850 m^2) has the highest CO_2 sequestration capability (150 Mg CO_2 $year^{-1}$) while Ferns (4250 m^2) the lowest (3.0 Mg CO_2 $year^{-1}$). A total CO_2 sequestration of 809 Mg CO_2 $ha^{-1}·year^{-1}$ is obtained for the Botanical Garden of Rome, corresponding to 221 Mg C $ha^{-1}·year^{-1}$. There is no comparative data since there have been no other studies on Botanical Gardens. This value is in the range of the most important historical parks in Rome [8]. The effects of CO_2 sequestration of the plant collections growing inside the Botanical Garden results in 4% CO_2 reduction outside (150 m from the centre of the Botanical Garden). Moreover, plant collections decrease air temperature by 1˚C inside the

Botanical Garden with positive effects on the surrounding area.

Extending the CS_{Tot} value for all the plant collections growing in the Botanical Garden of Rome, we obtain a total CO_2 sequestration capability of 6947 Mg CO_2 $year^{-1}$, corresponding to 1897 Mg C $year^{-1}$. This results in an annual economic value of 51,133$. The obtained results can suggest appropriate policy interventions in order to facilitate future urban designs enhancing the environmental and social benefits from green areas that should also include Botanical Gardens.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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