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Carbon Capture Capacity of Green Areas: A Sustainable Socioeconomic Approach Based on the Ecosystem Services of Ramón Castilla Park, Lince, Lima, Peru

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This study aimed to evaluate the ecosystem services provided by the urban forest of Ramón Castilla Park in Lima, Peru, focusing on its capacity to store CO_2 as a mechanism mitigate global warning. A comprehensive forest inventory was conducted, collecting dendrometric data, including Diameter at Breast Height (DBH), total height (TH) and UTM coordinates for all trees. A total of 45 native and exotic tree species were identified. *Phytolacca dioica* exhibited the highest DBH (180 cm) and CO_2 storage capacity (1.2353 t CO_2/ha). Species were grouped based on abundance as follows: One individual – *Persea americana*, 0.1916 t CO_2/ha - USD 17.91 (S/. 65.73); two individuals – *Phytolacca dioica*, 1253 t CO_2/ha - USD 115.44 (S/.423.70); 3 to 50 individuals – *Ceiba pentandra*, 0.1558 t CO_2/ha - USD 14.56 (S/. 53.45); and 50 or more individuals – *Gleditsia triacanthos*, 0.2295 t CO_2/ha - USD 21.45 (S/. 78.72). The park's total CO_2 storage was estimated at 1,476.52 t CO_2/ha, with economic valuation of USD 137,995.62 (S/. 506,443.92). Allometric modelling showed high coefficients of determination, such as 99.23% for *Koelreuteria elegans*, 99.10% for *Shinus molle*, and 98.40% for the general model. These results underscore the ecological and economical significance of urban forests in carbon sequestration and climate change mitigation.
Keywords: Carbon capture, urban parks, economic valuation.

1. Introduction

Carbon dioxide (CO_2) is one of the main greenhouse gases responsible for the increasing global temperature. It is estimated that by 2035, global temperature will increase by 2°C, with a probability of 77–79% (Santori et al., 2018). According to historical reports, the CO_2 concentration increased by 121 ppm from the pre-industrial era (278 ppm) to the present (399 ppm). The United Nations Framework Convention on Climate Change (UNFCCC) has highlighted the fundamental role of trees and forests in absorbing CO_2, which acts as a carbon sink by storing fixed biomass during the growth stage. This knowledge is crucial, but its application to urban forests requires further research to assess the social, environmental, and economic impacts of forests, which also provides biodiversity and specific ecological functions and contributes to scientific knowledge about the interaction between urban ecosystems and climate change. Therefore, it is crucial to conduct further studies on carbon stocks in these areas, considering species diversity.

For example, fast-growing trees have been proposed as a green solution for ecosystem services, such as reducing particulate matter, regulating the hydrological cycle, reducing temperatures in urban areas, and hosting a wide variety of fauna. On the other hand, unplanned urbanization in major cities in the world has negative repercussions on quality of life, as it deteriorates the relationship between the human population and the availability of green spaces for recreational activities, such as sports and social relationships.

It is essential to identify the benefits that urban forests can provide through the characteristics of vegetation and the environment (Jo et al., 2019). Likewise, the application of the economic valuation of ecosystem services raises awareness of the value of biodiversity. This information also enables the implementation of environmental policies in different institutional organizations. Thus, improving valuation procedures allows for the incorporation of monetary incentives for conservation through plans centered on market mechanisms. Estimating total tree biomass (TB) requires the use of allometric equations that include variables such as trunk diameter and total

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height (Paniagua-Ramirez et al., 2021). The objective of this research is related to the economic valuation of the green areas of San Ramón Castilla Park, which accumulates CO_2 in the Lince District of Lima, Peru.

2. Materials and methods

2.1 Study area

The research was carried out in Ramón Castilla Park, located at the UTM coordinates east (277795.99) and north (8662814.69), in the Lince district, Metropolitan Lima (Peru). Similarly, the Municipality of Metropolitan Lima established the park in 1956, and in 2010, it was declared a Natural Reserve Area (NRA) by ordinance No. 1391. The park has an area of 11 ha and a value of USD 136,017.82, and there are more than 1000 trees between native and exotic species.

2.2 Forest inventory and species identification

Data were collected from 100% of the forest population using a forest inventory, and 45 tree species were recorded (Table 1). DBH was measured for each tree at a height of 1.30 m using a tape measure.

Table 1: Tree species of the Ramón Castilla Park, Lince (Lima-Peru)

Scientific name	Common name	Trees (n)	Scientific name	Common name	Trees (n)	Scientific name	Common name	Trees (n)
Ailanthus altissima	Tree of Heaven	13	*Malus sylvestris*	Wild Apple	1	*Jacaranda mimosifolia*	Blue Jacaranda	22
Artocarpus heterophyllus	Jackfruit Tree	1	*Mangifera Indica*	Mango	2	*Juglans nigra*	Black Walnut	17
Bougainvillea peruviana	Bougainville a	2	*Melia azedarach*	Chinaberry	46	*Koelreuteria elegans*	Flamegold Tree	50
Caesalpinia pulcherrima	Peacock Flower	1	*Morus alba*	White Mulberry	14	*Koelreuteria paniculata*	Golden Rain Tree	12
Callistemon viminalis	Weeping Bottlebrush	8	*Myoporum laetum*	Ngaio Tree	18	*Ligustrum lucidum*	Glossy Privet	24
Casuarina Cunninghamia na	River She-oak	2	*Palaquium formosanum*	Formosan Nato Tree	2	*Spathodea campanulata*	African Tulip Tree	42
Cedrela odorata	Cedar	75	*Persea americana*	Avocado	1	*Syzygium jambos*	Rose Apple	1
Ceiba pentandra	Kapok Tree	17	*Phytolacca dioica*	Ombu Tree	2	*Tecoma stans*	Yellow Bells	12
Ceiba speciosa	Silk Floss Tree	1	*Pinus strobus*	Eastern White Pine	8	*Tipuana tipu*	Tipu Tree	138
Delonix regia	Royal Poinciana	2	*Pithecellobiu m dulce*	Manila Tamarind	2	*Gleditsia triacanthos*	Honey Locust	109
Eriobotrya japonica	Loquat	1	*Populus alba*	White Poplar	5	*Hevea brasiliensis*	Rubber Tree	1
Erythrina crista-galli	Cockspur Coral Tree	3	*Populus nigra*	Black Poplar	5	*Schinus molle*	Peruvian Pepper Tree	50
Eucalyptus globulus	Blue Gum	162	*Prunus serrulata*	Japanese Cherry	26	*Schinus terebenthifoli us*	Brazilian Pepper Tree	118
Ficus benjamina	Weeping Fig	193	*Robinia pseudoacaci a*	Black Locust	6	*Fraxinus uhdei*	Shamel Ash	23
Fraxinus angustifolia	Narrow-leaf Ash	59	*Saraca indica*	Ashoka Tree	42	*Schefflera actinophylla*	Umbrella Tree	27
Total							1366	

2.3 Quantitative assessment of the inventoried tree species

Biomass, total carbon, and the economic value of CO_2 were estimated sequentially using formulas proposed by various authors, according to Table 2.

Table 2: Proposed equations for estimating biomass, total carbon and economic value of CO_2

Variable estimada	Formula	Autores
Aboveground biomass (AB)	$AB = 0.026 \times DBH^{1.529} \times TH^{1.747}$	(Muñoz & Vásquez, 2020)
Plant root biomass (BR)	$BR = AB \times 0.20$	(Chinguel-Laban & Charcape-Ravelo, 2019)
Total green biomass (TGB)	$TGB = AB + BR$	(Burga, 2022)
Total dry biomass (TDBM)	$TDBM = TGB - (TGB \times 40) / 100)$	(Espíritu, 2016)
Total aerial carbon (TAC)	$TAC = TDBM \times 0.5$	(Odar, 2018)
Plant root carbon (CR)	$CR = TAC \times 0.24$	(Muñoz & Vásquez, 2020)
Total carbon (TC)	$TC = TAC + CR$	(Muñoz & Vásquez, 2020)
Accumulated CO_2	$CO_2\ (t) = (TC \times 3.66) / 1000$	(Mollocondo & Aguilar, 2019)
Economic value per CO_2 storage (EV)	$EV = CO_2 \text{ x } MP$	(Sosa J, 2016)
Market Price (MP)		

2.4 Coefficient of determination (R^2)

This statistical value indicates the fit of the variables and the relationship between the total variance, with the aim of obtaining greater precision based on a specific dataset. Likewise, this study considered variables such as total height (TH) and normal diameter (DBH) to predict the carbon biomass of tree species and the entire urban park.

2.5 Diameter at Breast Height (DBH)

The results showed that in Ramon Castilla Park, there were 45 tree species (Table 3), of which *Phytolacca dioica* presented the largest DBH (180 cm), followed by *Ceiba speciosa* (67.32 cm), *Gleditsia triacanthos* (58.17 cm), *Bougainvillea peruviana* (53.48 cm), *Ceiba pentandra* (52.58 cm), and *Cedrela odorata* (52.56 cm).

Table 3: Mean Diameter at Breast Height (DBH) and CO_2 Accumulation for each tree species

Group	Tree species	Trees (n)	Mean DBH (cm)	Group	Tree species	Trees (n)	Mean DBH (cm)
1	*Malus sylvestris*	1	10.19	3	*Ficus benjamina*	193	33.14
1	*Eriobotrya japonica*	1	13.37	3	*Saraca indica*	42	33.25
1	*Delonix regia*	2	16.55	3	*Tecoma stans*	12	33.66
1	*Erythrina crista-galli*	3	17.61	3	*Mangifera indica*	2	33.74
1	*Artocarpus heterophyllus*	1	18.14	3	*Schinus terebenthifolius*	118	34.23
1	*Callistemon viminalis*	8	18.18	3	*Ligustrum lucidum*	24	34.35
2	*Myoporum laetum*	18	20,65	3	*Robinia pseudoacacia*	6	34.54
2	*Morus alba*	14	21.33	3	*Eucalyptus globulus*	162	35.92
2	*Prunus serrulata*	26	21.41	3	*Caesalpinia pulcherrima*	1	36.61
2	*Fraxinus uhdei*	23	23.33	3	*Juglans nigra*	17	38.95
2	*Jacaranda mimosifolia*	22	23.41	3	*Syzygium jambos*	1	39.15
2	*Populus alba*	5	23.55	4	*Ailanthus altissima*	13	40.50
2	*Koelreuteria paniculata*	12	24.11	4	*Tipuana tipu*	138	42.12
2	*Schefflera actinophylla*	27	26.53	4	*Pithecellobium dulce*	2	45.36
2	*Koelreuteria elegans*	50	26.74	4	*Casuarina cunninghamiana*	2	46.63
2	*Populus nigra*	5	27.95	4	*Persea americana*	1	48.06
2	*Pinus strobus*	8	29.32	5	*Cedrela odorata*	75	52.56
2	*Schinus molle*	50	29.58	5	*Ceiba pentandra*	17	52.58
2	*Palaquium formosanum*	2	29.76	5	*Bougainvillea peruviana*	2	53.48
3	*Melia azedarach*	46	30.18	5	*Gleditsia triacanthos*	109	58.17
3	*Fraxinus angustifolia*	59	31.25	5	*Ceiba speciosa*	1	67.32
3	*Spathodea campanulata*	42	31.39	5	*Phytolacca dioica*	2	180
3	*Hevea brasiliensis*	1	33.10				

Note: Tree species were categorized into five groups based on their average diameter breast height (DBH, cm) as follows: Group 1 (0-20 cm); Group 2 (20-30 cm); Group 3 (30-40 cm); Group 4 (40-50 cm); and Group 5 (50-180 cm).

2.6 Economic valuation for CO_2 accumulation service

The mean carbon accumulation per hectare amounted to 36.57 t/ha.

Table 4: Economic valuation for CO_2 accumulation service

	Description	Unit	Value
a	Ramón Castilla Park Area	Ha	*11*
b	Accumulated carbon mass (b = a × 36,57 T)	t/ha	*402.3*
c	Accumulated CO_2 (c = b × 3.67)	t/ha	*1477*
d	Weighted Forest Price ($TnCO_2$) (Mean 2023)	USD/t	*93.46*
e	Total CO_2 revenue (e = c × d)	USD per year	*1E+05*
f	Exchange rate (Mean 2023)	S/.	*3.67*
g	Accumulated CO_2 Income (g = e × f)	S/.	*5E+05*
h	Economic value of CO_2	S/.	*5E+05*

2.7 Economic valuation of tree species

The species present with a single tree and the highest accumulated amount of CO_2 was *Persea americana* (0.1916 t CO_2/ha), with an economic value of USD 17.91 (S/.65.73). Other tree species that accumulate relatively high amounts of CO_2 are *Ceiba speciosa* (0.1878 t CO_2/ha) and *Caesalpinia pulcherrima* (0.1118 t CO_2/ha), with estimated prices of USD 17.55 (S/.64.40) and USD 10.45 (S/.38.35), respectively. Among the tree species with a significant number of individuals, *Phytolacca dioica* exhibits the highest carbon dioxide sequestration, amounting to 1.2353 t CO_2/ha, which corresponds to an economic value of USD 11.45 (S/.423.70). Within the group of tree species comprising 350 individuals (Figure 1c), *Ceiba pentandra* is notable for its substantial carbon dioxide accumulation of 0.1558 t CO_2/ha, with an associated economic value of USD 14.56 (S/.53.45). Other species demonstrating relatively high carbon dioxide sequestration include *Ailanthus altissima* (0.1340 t CO_2/ha) and *Juglans nigra* (0.1036 t CO_2/ha), with economic values of USD 12.52 (S/.45.96) and USD 9.68 (S/.35.53), respectively. For species with more than 50 individuals (Figure 2d), *Gleditsia triacanthos* sequesters the greatest amount of carbon dioxide at 0.2295 t CO_2/ha, yielding an economic value of USD 21.45 (S/.78.72). Additional species with notable carbon dioxide accumulation include *Cedrela odorata* (0.1793 t CO_2/ha), *Tipuana tipu* (0.1381 t CO_2/ha), *Koelreuteria elegans* (0.0582 t/ha), and *Eucalyptus globulus* (0.1092 t CO_2/ha), with corresponding economic values of USD 16.76 (S/.61.50), USD 12.91 (S/.47.37), USD 5.44 (S/.19.97), and USD 10.21 (S/.37.46), respectively.

3. Coefficients of determination (R^2)

3.1 Individual allometric equations

The species that presented a coefficient of determination (R^2) greater than 99% based on their individual allometric equations were *Koelreuteria elegans* (99.23%) and *Schinus molle* (99.10%), as shown in Table 5.

Table 5: Individual allometric equations by tree species between carbon biomass, DBH, and total height (TH)

N°	Tree species	Allometric Models	R^2
1	*Koelreuteria elegans*	$AB = (-8.096 + 0.5075 \times DBH + 1.0584 \times TH)^2$	*0.9923*
2	*Schinus molle*	$AB = (-3.306 + 0.005619 \times DBH^2 + 1.4176 \times TH)^2$	*0.991*
3	*Tipuana tipu*	$AB = (-10.346 + 0.50865 \times DBH + 1.2530 \times TH)^2$	*0.9882*
4	*Cedrela odorata*	$\text{Log}(AB) = 0.7689 + 0.03518 \times DBH - 0.000194 \times DBH^2 + 0.06966 \times TH$	*0.9874*
5	*Ficus benjamina*	$AB = (-9.466 + 0.42998 \times DBH + 1.3692 \times TH)^2$	*0.9874*
6	*Fraxinus angustifolia*	$AB = (-2.811 + 0.003622 \times DBH^2 + 1.3669 \times TH) + 0.000166 \times DBH^2 \times TH)^2$	0.9871
7	*Eucalyptus globulus*	$AB = (-6.043 + 0.004780 \times DBH^2 + 1.7509 \times TH)^2$	0.9862
8	*Gleditsia triacanthos*	$AB = (-13.872 + 0.47230 \times DBH + 1.6712 \times TH)^2$	*0.9858*
9	*Schinus terebenthifolius*	$AB = (-10.115 + 0.3739 \times DBH + 1.6168 \times TH)^2$	*0.9798*

3.2 General allometric equation

In Table 6, four allometric models are observed in the following decreasing order: Model 1 (98.40%), Model 2 (95.61%), Model 3 (93.38%), and Model 4 (89.40%). Regarding carbon biomass (CB), Model 1 was highly dependent on diameter at breast height (DBH) and total height (TH), being the best allometric model relative to R2 for all individuals in the studied park

Table 6: General allometric equation between carbon biomass, DBH, and total height (TH)

Model	Allometric Equation	R^2
1	$AB = (-10.418 + 0.46726 \times DBH + 1.3781 \times TH)^2$	0.984
2	$\log(AB) = 0.6719 + 0.024956 \times DBH - 0.000093 \times DBH^2 + 0.09519 \times TH$	0.9561
3	$AB = (-6.660 + 0.001410 \times DBH^2 + 2.1451 \times TH + 0.000104 \times DBH^2 \times TH)^2$	0.9338
4	$\ln(AB) = -3.0042 + 2.5096 \times \ln(DBH))$	0.894

4. Discussions

Ramón Castilla Park (11 ha) stores an average carbon stock of 36.57 tC, equivalent to 1,472.52 t CO_2/ha, with an annual economic value of USD 137,995.62 (S/.506,443.92), based on the 2023 SENDECO2 price (USD 93.46/t). These results are lower than those of Danau Sentarum National Park, Indonesia (USD 219,243.44/ha; Roslinda, 2019), but higher than values reported for Dr. Claudio Pavetti Park in Paraguay (USD 168.11; Pérez de Molas et al., 2022). According to Rodriguez-Sánchez et al. (2021), CO_2 sequestration represents an indirect use value, though it can also be classified as a direct use value due to its role in mitigating climate change. A total of 45 tree species were identified. Among single-individual species, *Persea americana* had the highest CO_2 accumulation (0.1916 t CO_2/ha; USD 17.91), though lower than values reported by Huayanay (2020). For two individuals, *Phytolacca dioica* stood out (1.2353 t CO_2/ha; USD 115.45). For groups of 3–49 individuals, *Ceiba pentandra* was notable (0.1558 t CO_2/ha; USD 14.56), while in species with >50 individuals, *Gleditsia triacanthos* reached 0.2295 t CO_2/ha (USD 21.45). The DBH (≥10 cm) strongly influenced carbon storage: *Phytolacca dioica* (180 cm) and *Ceiba speciosa* (67.32 cm) accumulated the most. Similar results were reported in Seoul parks, where DBH was more determinant than height (Jo et al., 2019), and by *Paniagua-Ramírez* et al. (2021), who confirmed proportionality between DBH and CO_2 accumulation. Allometric models were developed only for species with >50 individuals. Nine species achieved R^2 >97%, with *Koelreuteria elegans* (99.23%) and *Schinus molle* (99.10%) showing the best fits. These results are consistent with Begazo and Jave (2018), Khan et al. (2020), and Morales & Túllume (2022), who highlight the predictive power of DBH and height in carbon biomass estimation. The general equation for the park reached R^2 = 98.40%, confirming the high precision of these models.

4. Conclusions

In Ramón Castilla Park (11 ha), trees with a DBH ≥10 cm were analysed. Phytolacca dioica recorded the largest DBH (180 cm) and the highest CO_2 accumulation (1.2352 t CO_2/ha), confirming that DBH positively influences carbon storage. The park's total CO_2 stock was 1,476.52 t CO_2/ha, with an economic valuation of USD 137,995.62, reflecting its contribution to greenhouse gas reduction and climate change mitigation. A total of 45 tree species were identified, with higher CO_2 accumulation directly linked to higher economic value, reinforcing the importance of species diversity for sustainable urban ecosystem services. For species with ≥50 individuals, nine species were modeled, achieving high determination coefficients (R^2 >97%), with Koelreuteria elegans (99.23%) and Schinus molle (99.10%) showing the best fits. A general allometric equation for the park yielded an R^2 of 98.40%. Overall, DBH, total height, and species diversity are key predictors for accurate biomass estimation and highlight the ecological and economic value of the park's urban forest.

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