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CO_2 SEQUESTRATION AND O_2 PRODUCTION IN URBAN PARKS: THE CASE OF AN INTRODUCED SPECIES IN TROPICAL SOUTH AMERICA

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Abstract: Urban parks make up the most significant proportion of green areas in cities and significantly help to mitigate climate change and improve the physical and mental well-being of the city inhabitants. In Latin America, one of the predominant species within the vegetation in these parks is *Ficus benjamina* (*F. benjamina*). However, this species has a questionable history due to the damage it produces to public infrastructures and its invasive non-native origin has biased its potential to provide ecosystem services. This study quantifies the capacity *F. benjamina* has for storing carbon (C) and producing oxygen (O_2) in seven parks of one of the most affected districts of Lima, the Peruvian capital. The average C captured ranged from 2.31 ± 0.27 to 8.19 ± 1.88 t C ha^{-1}, ranging from 8.48 ± 0.99 to 30.04 ± 6.91 t CO_2 ha^{-1} and producing between 6.17 ± 0.72 and 21.85 ± 5.01 t O_2 ha^{-1}. These results show the benefits of these species in urban areas and should be considered for conserving these trees. Further research on ornamental plants, management policies implementation based on an ecological approach and good arboricultural practices will guarantee urban center purification in this global context.

Keywords: Cities, climate change, ecosystem services, *Ficus benjamina*

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INTRODUCTION

By 2050, demographic overflow and migration rates are expected to accelerate the urbanization process and, in this scenario, 68% of the world's population will reside in cities (UN DESA, 2018). Cities cover only 2.8% of the earth's surface; however, they are globally responsible for three-quarters of the carbon dioxide (CO_2) emitted, being the most harmful long-lived greenhouse gas (LLGHG) (Putman *et al*., 2016; REN21, 2019). The atmospheric concentrations of CO_2 have risen 146% since 1750, with 278 ppm to 413.95 ppm by 2020 and it is responsible for 82% of global warming in the last five years (WMO, 2018; WMO, 2019; NOAA, 2020). This continuous increase could represent an unprecedented threat to human health and has a synergistic effect with current environmental problems (Bardescu and Legendi, 2015; Barrett *et al*., 2015; Franchini and Mannucci, 2015).

Worldwide emissions of CO_2 in cities increased by 92% between 1990 and 2020, mainly due to high traffic volume (Gorham, 2002). During peak hours, transport in urban canyons constantly modifies airflow patterns and favors the augmentation of down-welling long-wave radiation which promote the accumulation of CO_2 in low and poorly ventilated areas (Koerner and Klopatek, 2002; Gratani and Varone, 2005; Briber *et al*., 2013). Despite the importance, the exact magnitude and distribution of LLGHG contamination in urban areas needs to be better quantified (Nemitz *et al*., 2002; Kordowski and Kuttler, 2010). Nevertheless, global concern has led to the investigation of methods that could significantly reduce the atmospheric load of CO_2 and allow urban conglomerates to adapt to climate change as an alternative to the prevailing crisis (Gomi *et al*., 2010).

In this scenario, one of the relatively more cost-efficient solutions is constituted by the preservation of ecosystem services derived from the vegetation present in green areas of the cities (McPherson and Simpson, 1999; Oleyar *et al*., 2008; Gorte, 2009; Nagendra and Gopal, 2011; Pimienta-Barrios *et al*., 2014; Velasco *et al*., 2016; Vásquez, 2016; Song *et al*., 2018; Vargas-Gómez and Molina-Prieto, 2020). Specifically, in tropical and subtropical urban areas, tree species are capable of storing carbon (C), reducing atmospheric CO_2 concentrations and producing oxygen (O2) in significant proportions during their photosynthesis process (Escobedo *et al*., 2010; Pretzsch *et al*., 2017). Furthermore, trees also preserve urban fauna, aesthetics, recreation and tourism and retain metals and nutrients in soils. In addition, they reduce heat, and therefore, electrical consumption for cooling services, among others (Brack, 2002; Carrus *et al*., 2015; Gratani *et al*., 2016; Setälä *et al*., 2017; Watts, 2017; Walther *et al*., 2017; Wang *et al*., 2019).

Nowadays, *Ficus benjamina* (*F. benjamina*) (*Moraceae*) is one of the most controversial ornamental fig trees from the Asian and Australian tropics located in urban areas of many Latin American countries (Ibarra-Manríquez *et al*., 2012). One of the main questions regarding the possible benefits of *F. benjamina* is its aggressive root system which causes severe collateral damage in the surrounding infrastructure including architectural constructions, civil works (sidewalks and roads), home service networks (sewage and gas) and public lighting (Vargas-Garzón and Molina-Prieto, 2010). On the other hand, its perenniality, low production cost, water stress and salinity tolerance, vast foliar development and adaptability may significantly help to improve the quality of life of city inhabitants (Pérez, 2013; Barbaro *et al*., 2014). Preliminary studies in Peru have shown that *F. benjamina* can assimilate between 17.81% and 39.62% more CO_2 than other urban species such as *Schinus molle* (Aldana, 2017; Baca, 2017).

In Peru, 76% of LLGHG emissions correspond to CO_2 (MINAM, 2016). Approximately 36.1% of the total population of Peru resides in Metropolitan Lima and it is ranked as one of the South American capitals with the highest C footprint (15.43 Mt CO_2) (CAF, 2014a; CAF, 2014b; CPI, 2021). The district with the second highest recorded CO_2 rate is Chorrillos (2.03 Mt CO_2), mainly because of its elevated vehicle density, energy consumption and solid waste disposal (Guzmán *et al*., 2016). According to Martínez (2011), *F. benjamina* has played an essential role in the environmental well-being of this district due to its predominance in green areas. The same study reported that this species represents 27.63% of the trees in Chorrillos. Nonetheless, there are only 3.04 m^2/inhab. of green areas in this district due to its intrinsic degradation, compromising the benefits that *F. benjamina* provides (Ferreira *et al*., 2018; Lima Cómo Vamos, 2018). In this context, it is crucial to quantify the benefits of biodiversity in the urban areas of this district to protect the ecosystem services. This study aimed to quantify C storage, CO_2 sequestration, and O_2 production of *F. benjamina* in the seven main parks of Chorrillos. This information could help design awareness programs, improve decision-making, develop efficient management plans to avoid damage to public equipment, and project new areas by choosing species based on their ability to mitigate the effects of climate change.

2. METHODS

2.1 Study area

The study was carried out between October and December 2019 in Chorrillos district, located in the southern part of Metropolitan Lima, Peru (281 579.87 E; 8652 194.25 S). This area has an arid subtropical climate, with an average annual rainfall ranging from 0^{-16} mm. The annual average evaporation reaches 514.4 mm and temperatures in the hottest months (December to April) range between 20 - 28 °C and between 12−19 °C in the coldest months (June to September). The relative humidity varies between 65 - 90%. Southern winds predominate with an average speed of 13.9 km/h and usual high stratiform clouds of 6/7 cover 74.95% of the atmosphere (Municipalidad de Chorrillos, 2016).

2.2 Evaluation of tree selection

Seven parks in Chorrillos were selected based on their size (>0.3 ha) and proximity to the central streets of the district (**Fig. 1**). The species coverage and the specifications of each park and quality indicator ratings according to Rivera (2014) are shown in **Table 1**. Eight healthy *F. benjamina* trees were chosen in each park following phytosanitary status analysis according to Cadahia *et al*. (1991).

2.3 Structural parameters and dry biomass

A non-destructive method was used to evaluate indicators. The diameter at breast height (DBH, cm) of each tree was measured with a winch (Kamasa - 50m) according to Rügnitz *et al*. (2009).

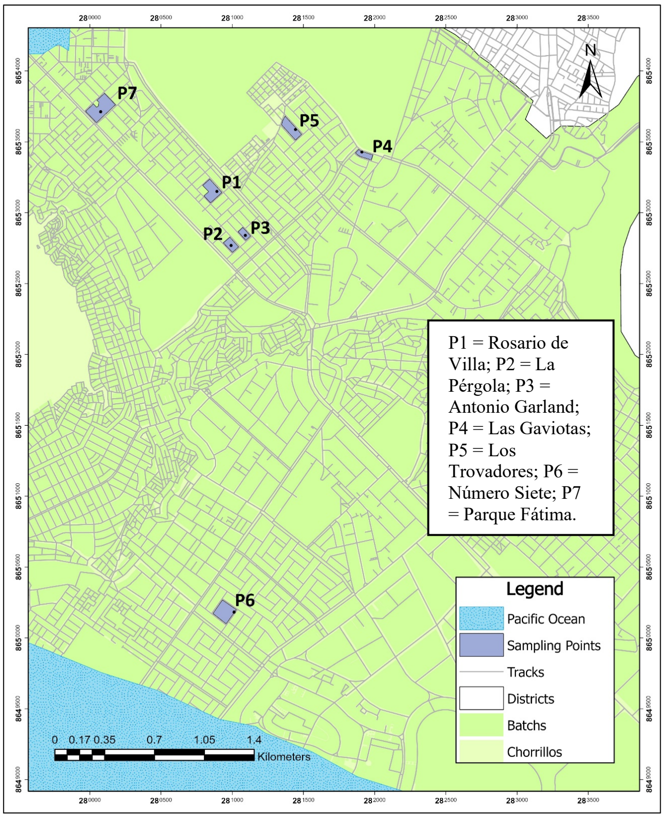

Fig. 1. Map of the parks evaluated within the Chorrillos district.

Finally, the dry matter content of *F. benjamina* was calculated based on an allometric equation described by Chavé *et al*. (2005) as follows:

M = ρw * exp (-0,67+1,78 Ln (DBH)+0,207(Ln (DBH))2-0,028(Ln (DBH))3)

where M is the accumulated dry biomass of the tree in kg, ρw is the species wood specific density given by the factor 0.65 according to Brown (1997) and DBH is the diameter at breast height in cm.

2.4 Quantification of C storage, CO_2 sequestration and O_2 production

The variability of C content depends on tree species and their tissue, although it is assumed that this compound constitutes 50% of the total biomass (Gayoso and Guerra, 2005). Thus, the total C stored per tree (TCC, t C) was calculated based on the dry biomass multiplied by the conversion factor 0.5 (Nowak and Crane, 2002). Likewise, the total CO_2 sequestered per tree (TCS, t CO_2) and O_2 produced per tree (TOP, t O2) are the results of the C stocks per the constants 3.67 and 2.67, respectively (Nowak *et al*., 2007; Aguaron and McPherson 2012; Cabudivo 2017).

To use a comparable unit, the assimilative capacity of C, CO_2 and O_2 per hectare were used (CC, t C ha^{-1}; CS, t CO_2 ha^{-1} and OP, t O_2 ha^{-1}). For this purpose, the area occupied by each individual was calculated using the polygon tool in Google Earth Pro (V. 7.3.2.5491).

2.5 Statistical analysis

The mean differences of the capacity per hectare, total C accumulation, CO_2 sequestration, and O_2 production among parks were determined with the SPSS V.25 software using the Kruskal-Wallis test, prior non-verification of normality with Shapiro-Wilk and homoscedasticity with the Levene test. Then, a non-parametric Dunnet test for multiple comparisons was performed. Subsequently, descriptive statistics including means and standard deviation of the variables above and DBH were used to compare the values of *F. benjamina* in the present study with others. A p value < 0.05 was considered statistically significant.

3. Results

3.1 Structure of *F. benjamina* within parks

The DBH of *F. benjamina* varied in each park, with the Rosario de Villa (58.14 ± 6.62 cm) and Antonio Garland (51.79 ± 3.99 cm) parks representing the highest mean values (**Fig. 2**).

Table 1. Sampling point specifications.

Parks	Features						Qualification
	UTM Coordinates (18L Zone)		Altitude (m MSL)	Extension (ha)	*F. benjamina* Area (%)	Principal Streets	
	East	South					
Rosario de Villa	280892	8653150	48	1 .41	10 .16	Defensores del Morro Avenue and Paseo de la República Prolongation	A
La Pérgola	281093	8652840	43	0 .42	29 .02	Defensores del Morro Avenue and Matellini Avenue	D
Antonio Garland	280993	8652770	41	0 .64	23 .83	Defensores del Morro Avenue and Paseo de la República Prolongation	A
Las Gaviotas	281911	8653429	44	0 .45	27 .78	Sol Avenue and Matellini Avenue	D
Los Trovadores	281444	8653587	43	1 .04	10 .76	Sol Avenue and Matellini Avenue	A
Número Siete	281014	8650183	23	1 .53	8 .36	Alameda Sur Avenue	D
Parque Fátima	280076	8653712	70	2 .27	8 .13	Defensores del Morro Avenue	O

Note: O = Optimum; A = Acceptable; D = Deteriorated; I = Ineligible.

3.2 C capture, CO_2 sequestration and O_2 production

The highest mean TCC, TCS and TOP values were found in the parks of Rosario de Villa (1.17 ± 0.27 t C, 4.27 ± 0.98 t CO_2 and 3.11 ± 0.71 t O2) and Antonio Garland (0.88 ± 0.14 t C, 3.22 ± 0.51 t CO_2 and 2.34 ± 0.92 t O2) while the lowest values were found in Los Trovadores (0.26 ± 0.03 t C, 0.95 ± 0.11 t CO_2 and 0.69 ± 0.08 t O2) ($p<0.05$) (**Fig. 3**). Similarly, the mean CC, CS and OP values were higher in Rosario de Villa (8.19 ± 1.88 t C ha^{-1}, 30.04 ± 6.89 t CO_2 ha^{-1} and 21.85 ± 5.01 t O_2 ha^{-1}) and Antonio Garland (5.76 ± 0.91 t C ha^{-1}, 21.12 ± 3.33 t CO_2 ha^{-1} and 15.36 ± 2.42 t O_2 ha^{-1}) and the lowest values were in Los Trovadores (2.31 ± 0.27 t C ha^{-1}, 8.48 ± 0.99 t CO_2 ha^{-1} and 6.17 ± 0.72 t O_2 ha^{-1}) ($p<0.05$) (**Fig. 4**).

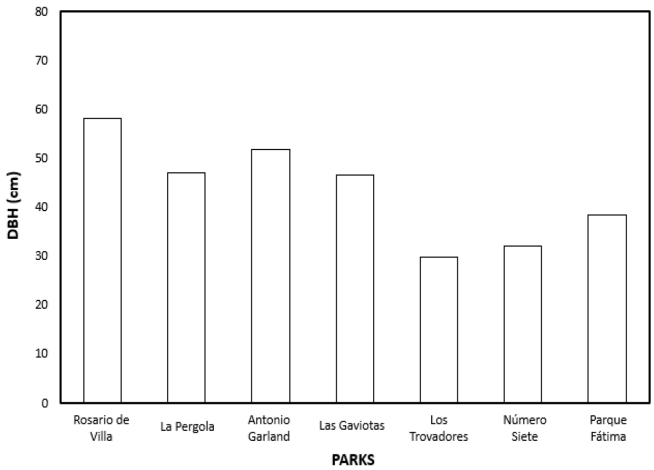

Fig. 2. Tree diameter at breast height (DBH) of *F. benjamina* in the Chorrillos urban parks evaluated. Mean values are shown.

4. DISCUSSION

Our results highlight that *F. benjamina* obtained a higher mean assimilation in the parks with better conservation states (Rosario de Villa and Antonio

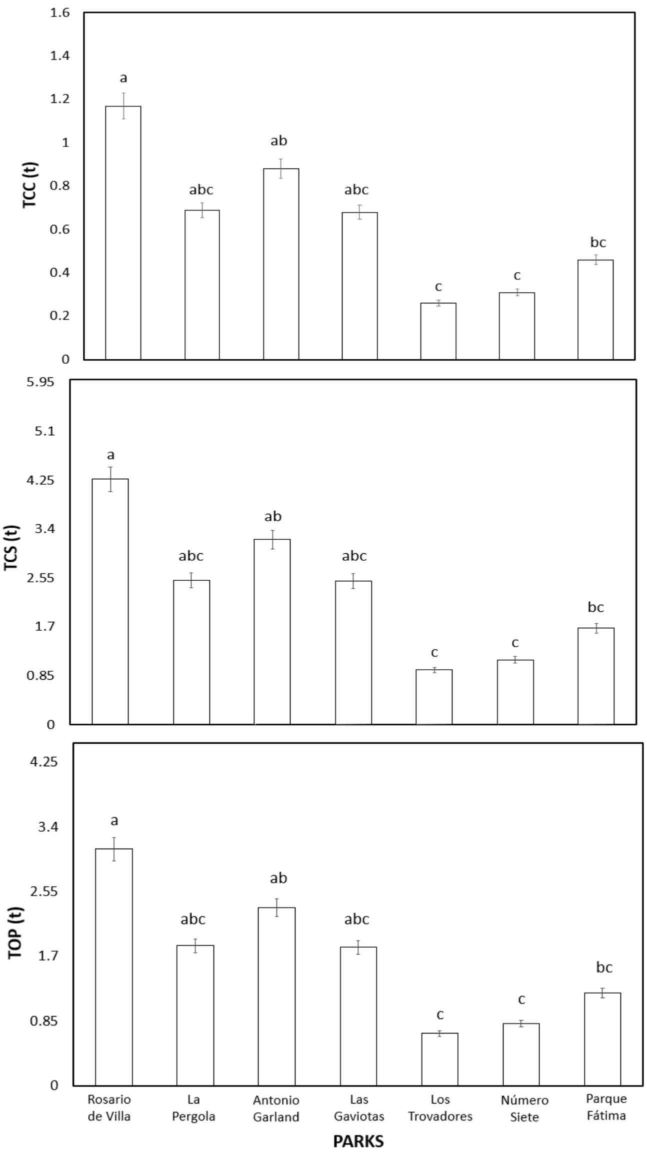

Fig. 3. Total C storage, CO_2 sequestration and O_2 production by *F. benjamina* in the Chorrillos urban parks evaluated. Mean values ± S.E. are shown. Mean values with the same letters are not significantly different.

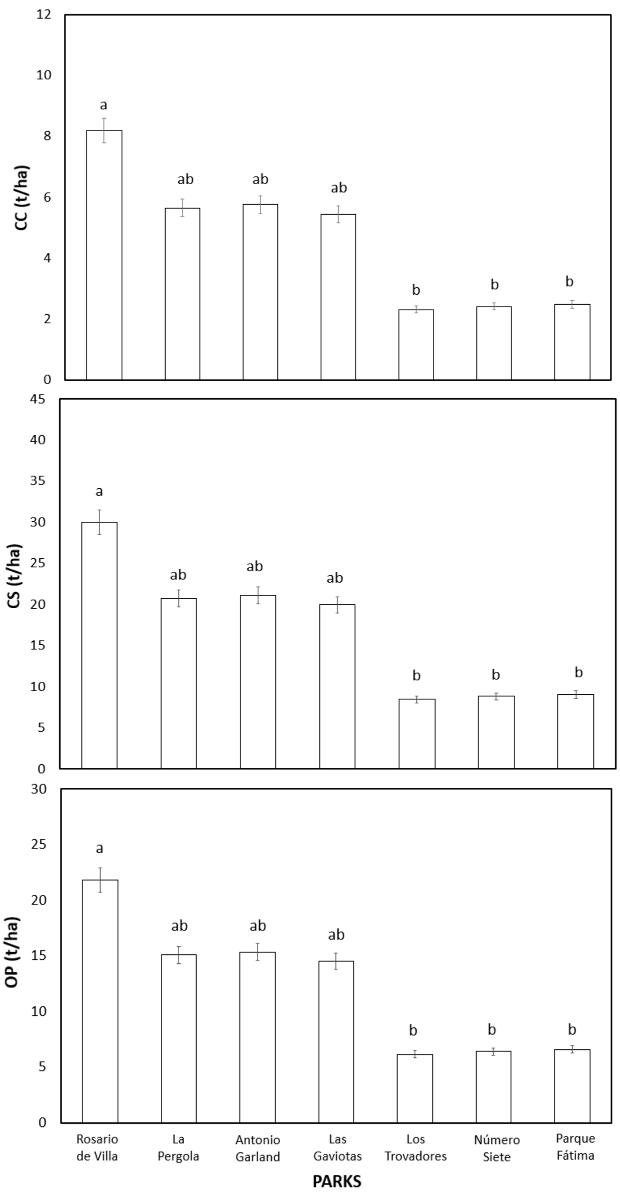

Fig. 4. C storage, CO_2 sequestration and O_2 production densities of *F. benjamina* in the Chorrillos urban parks evaluated. Mean values ± S.E. are shown. Mean values with the same letters are not significantly different.

Garland) compared to the most deteriorated parks (La Pergola, Las Gaviotas and Número Siete) or those with a significant remodeling (Parque Fátima and Los Trovadores) (**Table 2**). Despite the proximity to the most polluted avenues reducing the foliar area and destroying the species pigments (Pérez, 2013), the phenotypic plasticity of the species and its relative water content allowed the individuals to maintain an excellent physiological balance under these environmental stressconditions, favoring chlorophyll content and photosynthesis efficiency (Ramírez-Hernández *et al*., 2018). Other differences among the parks involve severe soil degradation in La Pergola, Las Gaviotas and Número Siete. Inadequate management techniques have produced fragments of bare soil, generating a 26 – 45% loss of the total surface area. Moreover, the values found in Parque Fátima and Los Trovadores may be explained by the sealing activities, specifically related to concrete and the reforestation in these parks in specimens in their first growth stages. The variability among parks may also be attributed to pruning techniques (McPherson *et al*., 2015), but more information is needed to confirm this hypothesis.

The provision of ecosystem services by *F. benjamina* was higher in Rosario de Villa than in the other parks of Lima (**Table 3**). Therefore, differences could be due to the variation in species DBH in each ecosystem. Concerning La Molina urban park, the rates of TCC and TCS do not represent an exacerbated dissimilarity since, in Rosario de Villa, at least 10% of the data analyzed were from *F. benjamina* individuals with DBH ≥ 77 cm, storing up to 1000 times more C and sequestering 90 times more CO_2 (Nowak and Crane 2002; Baca, 2017). On the contrary, more than 56% of *F. benjamina* trees in the Comas urban park had DBH <30 cm and the areas in which they developed were damaged, not complying with many of the healthy green area benchmarks (Aldana, 2017; Guerrero *et al*., 2007). The rates of *F. benjamina* measured in the present study were lower than those described in the cities of Villavicencio (Cortes and Matias, 2019), Jammur (Devi, 2017), Guayaquil and Antioquia (**Table 3**) (Mejía, 2021; Martinez, 2019). This may be explained in part by (i) an increased availability of data and better tree cover estimates derived from sampling efforts (Nowak *et al*., 2013), (ii) other structural parameters involved in the different allometric equations used, such as stems, basal diameters or heights (Chavé *et al*., 2005), (iii) species age, (iv) advantageous topographic and climatic conditions, such as altitude, precipitation, evapotranporation, temperature and light intensity, and (v) socio-economic conditions, such as per capita income, type of urban area or total population CO_2 emissions (Conghong and Nan, 2022).

The CC and CS values of *F. benjamina* in Rosario de Villa exceeded those found in vegetation assemblages in colder climate city parks, such as New Jersey (5.02 t C ha^{-1}, 18.42 t CO_2 ha^{-1}), Wyoming (3.30 t C ha^{-1}, 12.05 t CO_2 ha^{-1}) and North Dakota (7.20 t C ha^{-1}, 26.42 t CO_2 ha^{-1}) (Nowak and Crane, 2002) in the United States. Residential sites with a year-round active biosphere, such as subtropical areas, have a different CO_2 flux pattern. Unlike deciduous species in the conditions above, biogenic compound sequestration by perennials such as *F. benjamina* is not limited to a single growing season, and high photosynthetic rates are maintained throughout the year, even in winter and with diffuse solar radiation (Weissert *et al*., 2016). These conditions can also significantly contribute to O_2 production

Table 2. Summary of the results

Parks	DBH cm	TCC t C	TCS t CO_2	TOP t Oz	CC t C ha^{-1}	CS t CO_2 ha^{-1}	OP t Oz ha^{-1}
	M± SD	M± SD	M ± SD	M± SD	M ± SD	M ± SD	M ± SD
Rosario de Villa	58.14 ± 6.62	1.17 ± 0.27	4.27 ± 0.98	3.11 ± 0.71	8.19± 1.88	30.04 ± 6.91	21.85 ± 5.01
La Pérgola	46.94 ± 1.53	0.69 ± 0.49	2.53 ± 0.18	1.84 ± 0.13	5.65 ± 0.4	20.73 ± 1.47	15.08 ± 1.07
Antonio Garland	51.79 ± 3.99	0.88 ± 0.14	3.22 ± 0.51	2.34 ± 0.92	5.76 ± 0.91	21.12 ± 3.33	15.36 ± 2.42
Las Gaviotas	46.5 ± 2.11	0.68 ± 0.06	2.5 ± 0.24	1.82 ± 0.17	5.44 ± 0.52	19.97 ± 1.90	14.53 ± 1.38
Los Trovadores	29.73 ± 1.53	0.26 ± 0.03	0.95 ± 0.11	0.69 ± 0.08	2.31 ± 0.27	8.48 ± 0.99	6.17 ± 0.72
Número Siete	32.08 ± 1.88	0.31 ± 0.04	1.13 ± 0.16	0.82 ± 0.11	2.41 ± 0.33	8.83 ± 1.22	6.42 ± 0.88
Parque Fátima.	38.44 ± 2.19	0.46 ± 0.05	1.68 ± 0.2	1.22 ± 0.14	2.47 ± 0.29	9.08 ± 1.07	6.59 ± 0.78

Note: M = Mean, SD = Standard Deviation.

Table 3. Internacional comparison of C storage, CO_2 sequestration and O_2 production by *F. benjamina*

Region / Species	DBH cm	TCC t C	TCS t CO_2	TOP t O_2	CC t C ha^{-1}	CS t CO_2 ha^{-1}	OP t O_2 ha^{-1}	References
F. benjamina estimates in urban green areas								
Chorrillos, LIM	58.14	1.17	4.27	3.11	8.19	30.04	21.85	
La Molina, LIM	25.96	1.14	4.2	n/a	n/a	n/a	n/a	Baca, 2017
Comas, LIM	29.49	0.04	0.15	n/a	n/a	n/a	n/a	Aldana, 2017
Villavicencio, CO	107.55	2.45	9	6.54	n/a	n/a	n/a	Cortes and Matias, 2019
Jammur, IND	n/a	47.85	n/a	n/a	n/a	n/a	n/a	Devi, 2017
Guayaquil, EC	32.53 n/a	12.08	44.34	n/a	n/a	n/a	n/a	Mejía, 2021 Martinez, 2019
Antioquía, CO	n/a	16.37	60.08	n/a	n/a	n/a	n/a	Martinez, 2019
Comparison of tropical and subtropical ornamental species estimates								
Eucaliptus globulos	25.53	17655	64794.5	n/a	2716.23*	9968.56*	7252.33*	Baca, 2017; Abhijit et al., 2017*
Schinus molle	24.12	0.04	0.14	n/a	n/a	n/a	n/a	Aldana, 2017
Delonix regia	n/a	n/a	n/a	n/a	1350.41	4956	3605.59	Abhijit et al., 2017
Ficus religiosa	n/a	n/a	n/a	n/a	1073.7	3940.48	2866.78	Abhijit et al., 2018
Azadirachta indica	n/a	n/a	n/a	n/a	141.01	517.51	376.5	Abhijit et al., 2019
Swietenia mahagoni	n/a	n/a	n/a	n/a	219.02	803.8	584.78	Abhijit et al., 2020
Araucaria heterophylla	n/a	0.11	0.41	n/a	n/a	n/a	n/a	Martinez, 2019
Schefflera actinophylla	n/a	0.26	0.95	n/a	n/a	n/a	n/a	Martinez, 2020
Enterolobium cyclocarpum	n/a	0.79	2.89	n/a	n/a	n/a	n/a	Martinez, 2019
Jacaranda mimosifolia	37.52	3.74	13.73	n/a	n/a	n/a	n/a	Mejía, 2021
Spathodea campanulata	31.13	0.35	1.29	n/a	n/a	n/a	n/a	Mejía, 2021
Spondias purpurea	42.07	0.16	0.59	n/a	n/a	n/a	n/a	Mejía, 2021
Roystonea regia	39	0.06	0.23	n/a	n/a	n/a	n/a	Mejía, 2021
Acacia nilotica	n/a	1.49	n/a	n/a	n/a	n/a	n/a	Devi, 2017

improving local life quality. Likewise, other hot weather ornamental species such as *Schinus molle*, *Araucaria heterophylla*, *Schefflera actinophylla*, *Enterolobium cyclocarpum*, *Spathodea campanulata*, *Spondias purpurea* and *Roystonea regia* also present lower assimilation rates than *F. benjamina* (Table 3). Meanwhile, the results of individuals such as Eucaliptus globulus, *Delonix regia*, *Ficus religious*, *Azadirachta indica*, *Swietenia mahagoni*, *Jacaranda mimosifolia*, and *Acacia nilotica* considerably exceed those of the present study (**Table 3**) (Abhijit *et al*., 2017; Aldana, 2017; Baca, 2017; Devi, 2017; Mejía, 2021; Martinez, 2019). These differences can mainly be attributed to the different adaptive capacities due to phenotypic plasticity in response to environmental factors (Gratani, 2014).

This study is one of the first on the ecosystem services of the parks of Lima. The main limitation of this study was the need for more information for the analysis; for example, no forest inventories were available to determine the ages of *F. benjamina* and obtain more accurate annual capture rates for comparison. Nevertheless, this study highlights the importance of *F. benjamina* and the factors related to the differences found. Municipal action needs to be taken to improve the conservation of the ecosystems where this species develops. It should be noted that with the results of studies such as the present and detailed local data, urban vegetation managers can easily design and implement strategies to maximize the ecological function to protect and enhance a particular forest (Millward and Sabir, 2011).

The results of our study indicate the importance of (i) increasing the number of green areas in city planning, (ii) recording urban biodiversity, (iii) evaluating physiological reactions of green areas to other LLGHG such as nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) to determine the development of adverse effects (stomatal damage, leaf injury, senescence premature, reduced permeability in the membrane, among others), since not all species have the same level of resilience as *F. benjamina* (Pérez, 2013), (iv) implementing species selection strategies based on their potential to mitigate climate change and reforest urban spaces (García-García *et al*., 2016), and finally, (v) maintaining excellent tree management considering that arboriculture techniques are crucial for the provision of ecosystem services (Astiaso, 2017; Schram-Bijkerk *et al*., 2018; Conway *et al*., 2019). Moreover, these data can be incorporated into a geographic information system allowing the monitoring of spatial variations of C, CO_2 and O_2 concentrations over time since they can become sources of pollution in later stages (Nowak *et al*., 2013).

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