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Woody Vegetation Carbon Storage in La Conejera Wetland, Bogotá (Colombia)

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Abstract

The carbon storage in a secondary forest undergoing restoration in La Conejera Wetland, Bogotá, Colombia, was estimated. This involved zoning areas with woody vegetation, followed by biomass estimation using an allometric model that incorporates height and diameter at breast height (DBH) data (collected in the field) and wood density (secondary information). The carbon value stored per hectare (Mg ha^{-1}) per zone and the tons of carbon per species were determined. In the analyzed transects, 28.73 t of carbon were found, equivalent to an average of 226.68 Mg ha^{-1} of carbon per biozone or 763.92 Mg CE ha^{-1}. Introduced species stored more carbon than native ones (20.27 Mg and 8.47 Mg, respectively). The species with the highest carbon content were *Eucalyptus globulus* (18.33 Mg), *Salix humboldtiana* (4.24 Mg), and *Alnus acuminata* (1.7 Mg).

Keywords

Allometric model, biomass, climate change, ecological succession, ecosystem services, urban forest.

Introduction

One of the main global concerns is the imminent increase in the average temperature of the Earth (an increase of >1.5°C), caused by deforestation, fossil fuel production and consumption (Intergovernmental Panel on Climate Change (IPCC) 2021). Although it is a natural phenomenon, anthropogenic processes have exponentially accelerated the production of greenhouse gases (GHGs), increasing temperatures (Solomon et al. 2007).

Globally, it is estimated that the use of fossil fuels generates around 86% of the emitted carbon dioxide (CO2) (Intergovernmental Panel on Climate Change (IPCC) 2021). According to the latest national and departmental greenhouse gas inventory in Colombia, for Bogotá in 2012, emissions and absorptions were 10.6 and 0.02 megatons of GHGs, respectively, where CO2 contributed the most to total emissions with 77.33% (IDEAM et al. 2016). In Bogotá, the balance between emission and absorption is very low, making urban forests and urban ecosystems crucial for carbon storage and adaptation to climate change (Secretaría Distrital de Ambiente 2022).

The significance of vegetation lies in its role in absorbing and capturing carbon through the process of photosynthesis (Zuluaga Zuluaga and Castro Escobar 2018). Therefore, assessing the biomass of woody vegetation is essential to evaluate carbon sequestration and its dynamics (Dixon et al. 1994). Reducing GHGs is one of the objectives within the framework of the Sustainable Development Goals (SDGs) (Intergovernmental Panel on Climate Change (IPCC) 2021).

On the other hand, the contribution of natural forests to carbon storage is recognized globally. However, with the majority of the population increasingly concentrating in cities, urban ecosystems play an increasingly vital role in providing this type of service (Hernández 2010, Hutyra et al. 2011, Nowak and Crane 2002). Nevertheless, most trees in cities are located along roads, avenues, or in isolated settings, making them more susceptible to heat island effects, water deficits, and pests (Long et al. 2019), reducing their carbon storage capacity (Meineke et al. 2016). Having urban forest masses would contribute to mitigating these issues (Long et al. 2019).

In Bogotá, the Conejera wetland has been impacted by a reduction in its area from 1950 to 1989, decreasing from 145.02 Ha of water surface to 21.59 Ha. Since the 1990s, the construction of urban developments in the Suba locality intensified, resulting in an 85.11% reduction of the wetland (Cruz-Solano et al. 2017), reaching its current area of 58.9 Ha (Secretaría Distrital de Ambiente 2015). According to a multi-temporal study in the wetland, the delimited area has experienced a progressive 26% reduction from 2003 to 2010, affecting vegetation cover and buffer and recovery zones (Rodríguez Espinosa 2015).

Urban ecosystems, particularly wetlands, are considered strategic elements for biological dynamics, biodiversity, and ecosystem services (Cortés Ballén 2018, Alikhani et al. 2021). La Conejera Wetland, being one of the most biodiverse wetland ecosystems in the city (Rosselli and Stiles 2012), is part of the ecological corridor of the Salitrosa micro-watershed and the Thomas Van Der Hammen Ecological Reserve. However, social transformations and population growth have led to the reduction of these ecosystems, disregarding their value in providing ecosystem services (Ramírez et al. 2013), and their importance for urban sustainability in terms of adaptability to climate change (Franco Vidal et al. 2013, Pinilla Moscoso and Puertas 2018).

The aforementioned is compounded by the lack of implementation of existing control measures to prevent the degradation and reduction processes of urban ecosystems, which are leading to the decline of wetlands and consequently the ecosystem services they provide (Caro-Caro and Torres-Mora 2015)As a result, wetlands have reduced their capacity for regulation, buffering, and carbon capture (Franco Vidal et al. 2013). Moreover, the increase in air pollution levels is associated with negative effects on public health. For instance, carbon dioxide contributes to poor air quality in urban centers and in consequence to morbidity and mortality in vulnerable populations (such as children under 5 and individuals over 60) and those with respiratory limitations or pulmonary problems (Vargas et al. 2008).

In this context, estimating CO2 content in urban forests, such as La Conejera Wetland, is crucial for understanding the relationship between anthropogenic actions and natural cycles. Given the above, this research seeks to evaluate the importance of this natural space by indirectly assessing the amount of carbon in different biozones, determining which biozone has a higher contribution to carbon storage, and identifying species with a major contribution to carbon storage within the ecosystem.

Material and Methods

Study Area

La Conejera Wetland, recognized as a Ramsar Wetland (Alcaldía mayor de Bogotá 2021), is located between 4° 45’ latitude north and 74° 6’ longitude west, in the Bogotá Savannah, at an average altitude of 2542 m, with a current approximate extension of 58.9 ha (Fig. 1). It is bordered by low terraces of the plateau extending north and northwest of the savannah, flowing into the Bogotá River. The wetland is adjacent to Suba Avenue - Corpas Clinic (east), the Bogotá River (west), Hacienda Las Mercedes and the Thomas Van Der Hammen Reserve (north), and various neighborhoods in the Suba locality (south) (Secretaría Distrital de Ambiente 2015).

Definition of Working Zones

According to the environmental management plan of La Conejera Wetland (Secretaría Distrital de Ambiente 2015), the wetland area is divided into five biozones where restoration activities have been carried out. These biozones were used as a reference area for locating transects within them. The biozones are ordered by age, with biozone one being the oldest and biozone five being the youngest.

Due to a significant portion of the wetland being water bodies, only the terrestrial areas were considered for practical sampling purposes.

Data Collection

Transects of 10 x 2 m were used to measure woody individuals with a diameter at breast height (DBH) ≥ 4 cm. This diameter was chosen as it aligns with the allometric equations of the IDEAM for similar ecosystems in the Arrieros Cundinamarca wetland zone (Vanegas 2020). This type of transect was chosen due to the morphological characteristics of the ecosystem, specifically because the wetland's terrestrial strip is narrow, making it challenging to establish other types of sampling units. Trees within the transects were measured for diameter at breast height (DBH), stem height and total height.

For each biozone, were randomly selected five transects to carry out a pre-sampling with which were estimated 40 additional transects in addition to the 25 pre-sampling transects; a total of 65 measurement transects were established and distributed throughout the different biozones of the wetland (see Table 1).

Biomass and Carbon Calculation

The biomass of woody individuals was calculated using the regression model biomass-diameter-height (b-d-h) for the dry lower montane forest life zone (df-LM) and the methodology proposed by Yepes et al. (2011):

$\ln BA = a + B1 \times \ln(D2 \times H \times \rho)$ (1)

Where:

- ln: natural logarithm
- *D*: Diameter at breast height (cm)
- *H*: Height (cm)
- *ρ*: Wood density (g/cm^3)

DAP and height were measured in the field, while wood density was obtained from various sources (Cendales 2019, World Agroforestry 2022, Vasquez Valderrama and Solorza-Bejarano 2017, Rodríguez Alarcón 2018, Rodríguez-Alarcón et al. 2020).

To convert biomass to carbon, the protocol proposed for calculating captured carbon in tropical forests was implemented, where the carbon content is 50% of the total dry biomass in living trees (Clark 2002, Chave et al. 2005). Therefore, the total biomass was multiplied by 0.5 to determine the total stored carbon.

Finally, the equivalent carbon (CE) was calculated, considering that one ton of stored carbon is equivalent to 3.67 Mg of CE (Rügnitz Tito et al. 2009).

Data analysis

To compare different biozones and species and determine if there were differences between them, the Kruskal-Wallis test was used. Dunn's test was employed to determine where the differences occurred, and box-and-whisker plots were generated. Mann-Whitney's U test was used to compare introduced and native species. These analyses were performed using the Past program (Hammer et al. 2001).

Results

Carbon estimation

In the 65 established transects, 37 species and 273 individuals were evaluated, storing 57.46 tons of carbon (-105.45 Mg CE). The Kruskal-Wallis test showed significant differences in carbon content per hectare among the five biozones (KW = 11.28; p-value = 0.02359). On the other hand, the Dunn test indicated differences between biozone one and biozones two and three, as well as differences between biozone two and biozone four. Fig. 2 compares the carbon found in each of the biozones, highlighting the observed differences.

Biozone four had the lowest carbon per hectare with 48.88 $t.ha^{-1}$, while biozone five had the highest carbon storage with 532.34 $t.ha^{-1}$ (Table 2). All biozones showed atypical data corresponding to large individuals of *Alnus acuminata*, *Eucalyptus globulus*, and *Salix humboldtiana*.

Species-specific carbon estimation

Although introduced species store more carbon compared to native ones (20.27 Mg and 8.47 Mg, respectively), there were no significant differences between them (z = 1.4942, p-value = 0.1357) (see Fig. 3). The data dispersion is higher for introduced species, mainly due to the presence of large individuals of Eucalyptus globulus and small individuals of Sambucus nigra. In contrast, native species show less dispersed values, with outliers mainly due to Salix humboldtiana and Alnus acuminata.

Among native species, Salix humboldtiana (4.238 Mg), Alnus acuminata (1.75 Mg), and Croton mutisianus (0.701 Mg) had the highest carbon storage. For introduced species, notable contributors include Eucalyptus globulus (18.325 Mg), Sambucus nigra (0.765 Mg), and Pinus radiata (0.638 Mg) (Table 2).

Discussion

Urban forests play a crucial role in maintaining the ecosystem service of carbon regulation and storage, contributing to climate regulation, biodiversity, and social well-being (Chen et al. 2022, Hutyra et al. 2011). Proper management of these areas is vital as it is a suggested strategy for greenhouse gas reduction due to their sink function (Franco Vidal et al. 2013, Roa-García and Brown 2016, Zuluaga Zuluaga and Castro Escobar 2018). Spaces like the Conejera wetland, surrounded by forested areas, are essential for carbon storage in the urban matrix with limited vegetative coverage and, consequently, lower carbon absorption capacity.

It is evident that some areas of Conejera do not yet reach carbon storage values reported for natural forests by Phillips et al. (2011). For instance, biozones one and four (60.37 and

48.88 Mg ha^{-1}) are far below those reported for low montane dry forests (108 Mg ha^{-1}). This is attributed to the prevalence of small-sized individuals or early successional stages in most species. Despite the expectation that biozone one would have higher carbon storage due to a longer restoration process, these efforts were less successful, partly due to construction material-filled areas hindering tree development. On the other hand, biozones two, three, and five exhibit high carbon storage, especially biozone five (532.34 Mg ha^{-1}), attributed to the presence of mature *Eucalyptus globulus* individuals with hard wood and substantial dimensions. In dense forests in Addis Ababa (Ethiopia), similarly high carbon storage values (291 Mg ha^{-1}) were found, influenced by *Eucalyptus globulus* (Woldegerima et al. 2017). This underscores the significance of this naturalized species in providing this ecosystem service to the city, challenging its reputation as a species to be replaced due to its rapid growth and use in water body drainage (Molina 2022). Compared to other urban forests, the carbon storage values in biozones two, three, and five are notably higher. For example, a study conducted in several U.S. cities reported values ranging from 5 to 46 Mg ha^{-1} (Nowak and Crane 2002), while another study in Seattle (USA) found a maximum of 114 Mg ha^{-1} (Hutyra et al. 2011). This indicates that urban forests in the city, especially those bordering wetland networks, can play a crucial role in climate change adaptation and serve as carbon reservoirs.

This study identified high variability in biomass and carbon values within the biozones. This variability is mainly due to the diversity of woody species present in the wetland and the different restoration processes carried out. For example, there is a particularly atypical data point in biozone five due to a large and old *Eucalyptus globulus* (1 m DBH and 32 m height). In other cases, lower data values in some transects resulted from areas in early secondary succession.

Although no significant differences were found in carbon storage between native and introduced species, introduced species retain 70.53% of the carbon, partly explained by the size of *Eucalyptus globulus* individuals and the abundance of *Sambucus nigra*. However, it is essential to consider that most native individuals were young, indicating a high biomass storage potential, contrary to introduced species, which are mainly remnants of older planting processes. Over time, it is expected that the contribution of native species will become more significant, especially considering that introduced species represent only 23% of individuals.

The restoration models employed in the wetland favor the planting of fast-growing species. This is crucial to consider if carbon storage improvement is desired since, under high $CO2$ concentrations, fast-growing species will mature and die faster (Tangley 2001), affecting the mid- to long-term carbon storage in these forests. Restoration processes should focus on enriching spaces with slow-growing native species. Additionally, increasing species richness is important, as it influences the enhancement and maintenance of productivity, carbon reserves, and improves the resilience of these forests (Chen et al. 2022, FAO and UNEP 2020, Flombaum and Sala 2008).

Studies like those by Nowak and Crane 2002 show that urban forests can play a significant role in carbon capture compared to plantations, mainly due to the size trees can achieve.

Proper management of urban forests, including slow-growing species and hardwoods, can significantly enhance this ecosystem service (Tripathi 2022).

Conclusions

The Conejera wetland is a crucial element of Bogotá's green infrastructure, storing 4635 Mg ha^{-1} of carbon. Three biozones within the wetland show higher values than those reported for natural forests and other urban forests. Regarding species, it is essential to highlight that introduced species concentrate the most stored carbon; however, it is expected that the succession process will lead to a greater prevalence of native species. Additionally, the naturalized species *Eucalyptus globulus* is crucial, exhibiting the highest carbon storage. Finally, forest management in the wetland should consider enrichment with slow-growing species to ensure the maintenance and improvement of carbon reserves.

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Conflicts of interest

The authors have declared that no competing interests exist.

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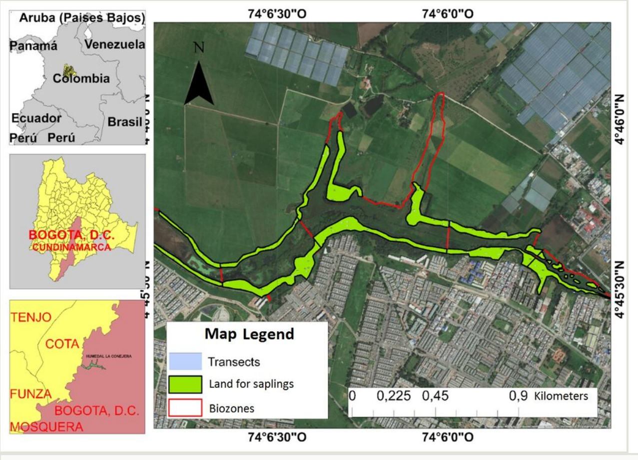

Figure 1.

The spatial location of La Conejera Wetland and the biozones where sampling was conducted.

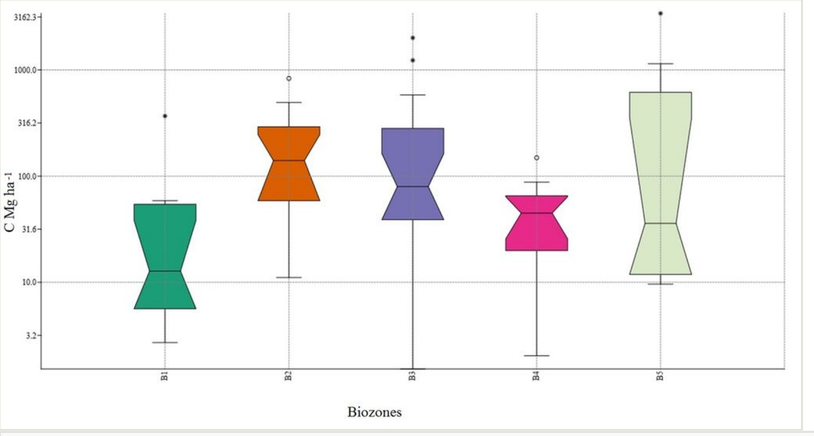

Figure 2.

Box-and-whisker plot comparing the carbon found per biozone per hectare.

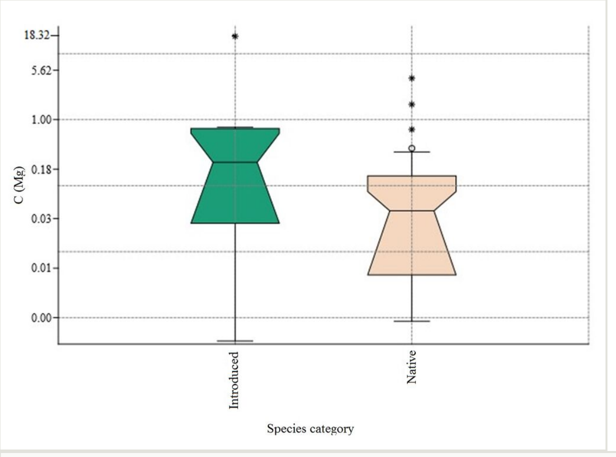

Figure 3.

Box-and-whisker plot comparing the carbon stored by introduced and native species.

Table 1.

Total transects by biozones, showing the area of the biozones, biomass and carbon found, and carbon and carbon equivalent (CE Mg ha^{-1}).

Biozon	Number of transecs	Area (Ha^{-1}) –(%)	Biomass (Mg)	Carbon (Mg)	Average carbono (Mg ha^{-1})	Average CE (Mg CE/ Mg ha^{-1})
B1	9	2.16 (10.24)	2.17	1.09	60.37	-203.51
B2	12	3.87 (18.35)	10.56	5.28	219.98	-741.32
B3	21	8.1 (38.41)	22.83	11.42	271.82	-916.06
B4	14	4.66 (22.1)	2.74	1.37	48.88	-164.72
B5	9	2.3 (10.91)	19.16	9.58	532.34	-1794.01
Total	65	21.09	57.47	28.73		

Table 2.

Carbon sequestration and CE of native and introduced species.

Species	Carbon (Mg)	CE (Mg)	Category
Eucalyptus globulus	18.3255	67.2547	Introduced
Salix humboldtiana	4.2377	15.5524	Native
Alnus acuminata	1.7010	6.2425	Native
Sambucus nigra	0.7649	2.8071	Introduced
Croton mutisianus	0.7099	2.6053	Native
Pinus radiata	0.6379	2.3411	Introduced
Cytharexylum subflavescens	0.3683	1.3515	Native
Quercus humboldtii	0.3245	1.1909	Native
Juglans neotropica	0.2409	0.8841	Native
Pittosporum undulatum	0.2374	0.8713	Introduced
Acacia melanoxylon	0.2147	0.7881	Introduced
Myrsine coriacea	0.1473	0.5405	Native
Solanum ovalifolium	0.1341	0.4921	Native
Solanum stellatiglandulosum	0.1115	0.4093	Native
Vasconcellea pubescens	0.0912	0.3349	Native
Psidium cattleianum	0.0771	0.2830	Introduced
Myrcianthes leucoxyla	0.0629	0.2309	Native
Escallonia pendula	0.0552	0.2025	Native
smallanthus pyramidalis	0.0470	0.1727	Native
Solanum sp.	0.0419	0.1536	Native
Escallonia paniculata	0.0416	0.1526	Native
Solanum oblongifolium	0.0371	0.1360	Native
Oreopanax bogotensis	0.0318	0.1166	Native
Oreopanax incisus	0.0280	0.1029	Native
Brugmansia arborea	0.0213	0.0782	Native
Acacia decurrens	0.0102	0.0374	Introduced
Senna multiglandulosa	0.0068	0.0249	Native
Myrcianthes rophaloides	0.0064	0.0236	Native
Xylosma spiculiferum	0.0048	0.0175	Native
Lafoencia acuminata	0.0041	0.0151	Native
Bocconia frutescens	0.0024	0.0087	Native
Ficus americana	0.0023	0.0084	Native
Phyllanthus salviifolius	0.0022	0.0081	Native
Dahlia imperialis	0.0017	0.0063	Native

Viburnum triphylum	0.0012	0.0045	Native
Billia columbiana	0.0009	0.0032	Native
Fuchsia boliviana	0.0004	0.0016	Introduced