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CARBON STOCK IN AN URBAN AREA AFFORESTED 50 YEARS AGO

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ABSTRACT

Climate change is a growing concern, driven by the accelerated emission of carbon dioxide resulting from human activities. Recent studies have indicated that urban trees contribute to mitigating these changes. Given that legal frameworks supporting the implementation of this landscape feature are already in place, this study aimed to evaluate the carbon stock and identify the species that contribute the most to it within the oldest area of the Main Campus of the State University of Maringá, in northern Paraná, which was established 50 years ago. The study area comprises 11.5 hectares. Based on the floristic survey of trees and large palms, measurement of the diameter at breast height (1.30 m), total height, and wood density values obtained from specialized literature, local biomass and carbon stock were estimated using three allometric models available in the literature. The area contains 998 specimens belonging to 27 botanical families, 68 genera, and 83 species, 49.40% of which are native to the northern region of Paraná. The estimated carbon stock was 402.76 Mg C or 35.25 Mg C ha^{-1}, a value considered significant when compared to other Brazilian urban areas. Fabaceae accounted for 65.72% of the total carbon stock, followed by Bignoniaceae (10.23%) and Arecaceae (9.85%). The species that contributed the most to carbon storage were *Cenostigma pluviosum, Tipuana tipu, Delonix regia*, and *Dypsis lutescens* (exotic); and *Handroanthus heptaphyllus, Cordia trichotoma*, and *Holocalyx balansae* (native), in terms of both specimen count and DBH. Only *D. regia* exhibited high wood density, while the others presented intermediate values. These findings underscore the importance of urban forestry as a carbon sink and reinforce its contribution to the provision of ecosystem services to society.

Keywords: *Cenostigma pluviosum*; Carbon sequestration; Ecosystem services

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ESTOQUE DE CARBONO EM UMA ÁREA URBANA ARBORIZADA HÁ 50 ANOS

RESUMO As mudanças climáticas são uma preocupação crescente, impulsionadas pela acelerada emissão de CO_2 resultante das atividades humanas. Estudos recentes têm indicado que as árvores urbanas contribuem para a mitigação dessas mudanças e, considerando que já estão em vigência as disposições legais direcionadas à implantação deste elemento paisagístico, objetivou-se avaliar o estoque de carbono e quais espécies mais contribuem para isso na área mais antiga do Campus Sede da Universidade Estadual de Maringá, norte do Paraná, cuja arborização foi implantada há 50 anos. A área de estudo possui 11,5 hectares e, após o levantamento florístico das árvores e palmeiras de grande porte, mensuração do diâmetro à altura do peito (1,30 m), da altura total e obtenção da densidade da madeira na literatura especializada, a biomassa local e os estoques de carbono foram estimados com o uso de três modelos alométricos disponíveis na literatura. Na área encontram-se 998 espécimes pertencentes a 27 famílias botânicas, 68 gêneros e 83 espécies, das quais 49.40 % são nativas da região norte do Paraná. O estoque de carbono alcançou uma média de 402.76 Mg C ou 35.25 Mg C ha^{-1}, valor considerado representativo em relação a outras áreas urbanas brasileiras. Fabaceae contribuiu com 65.72 % do estoque total de carbono, seguida de Bignoniaceae (10.23 %) e Arecaceae (9.85 %). As espécies que mais contribuíram com o estoque de carbono foram *Cenostigma pluviosum, Tipuana tipu, Delonix regia* e *Dypsis lutescens* (exóticas); e *Handroanthus heptaphyllus, Cordia trichotoma* e *Holocalyx balansae* (nativas), tanto pelo número de espécimes, quanto pelo DAP. Apenas *D. regia* apresentou madeira de densidade do tipo dura e as demais possuem valores intermediários. Os resultados evidenciam a importância da arborização urbana como sumidouro de carbono, reforçando sua contribuição na oferta de serviços ecossistêmicos à sociedade.

Palavras-Chave: *Cenostigma pluviosum*; Sequestro de carbono; Serviços ecossistêmicos

1. INTRODUCTION

Climate change emerges as one of the main global concerns, driven by the increasing carbon dioxide (CO_2) emissions generated by human activities (Maropo et al., 2019; Livesley et al., 2016). These emissions have accelerated global warming, with the latest report from the Intergovernmental Panel on Climate Change (IPCC, 2021), projecting that the average warming could reach 1.5 °C by 2030 compared to the pre-industrial period. In more severe emission scenarios, this increase could reach up to 5.7 °C, resulting in significant climate impacts on ecosystems and human populations, according to Heaviside et al. (2017).

Urban areas, due to their distinctive features, tend to exacerbate the impacts of climate change and are consequently more vulnerable to its consequences (Hobbie & Grimm, 2020). The albedo effect of buildings, combined with the high concentration of concrete and asphalt, results in higher temperatures and more intense heat waves compared to rural areas (Heaviside et al., 2017). Since urban centers currently accommodate approximately 50% of the global population, and this prevalence is estimated to rise substantially in the coming decades (Bardekjian & Paqueo, 2019) these areas are likely to face intensifying pressure on public health infrastructure related to climate change impacts. This scenario demands the development of effective strategies for climate change mitigation and temperature reduction in urban environments.

Urban ecosystems can help mitigate climate change, especially through carbon sequestration by urban trees, which is defined as the long-term capture and storage of atmospheric CO_2 (Hilmi et al., 2021; Jenkins & Scraap, 2018). Assumpção et al. (2019) and Lee & Erickson (2017) report that maintaining and conserving urban trees are effective strategies for mitigating climate change, especially considering that cities are major emitters of CO_2. In addition to their role in carbon sequestration, trees in urban areas help regulate temperature, improve air quality, and perform ecological functions such as photosynthesis, carbon cycling, and nutrient cycling (Jones & McDermott, 2018; Zhao & Sander, 2015).

Carbon sequestration in urban forests is influenced by several factors, including the number of tree individuals, floristic composition, tree size and age (Khan et al., 2018). Areas with a higher number of individuals tend to store more carbon per unit area due to the larger amount of available biomass, which makes it necessary to standardize the estimates by area (Davies et al., 2011). Species composition is important for carbon storage, as species with denser wood, often characterized by slower growth rates, are more effective in long-term carbon accumulation (Mo et al., 2024; Pretzsch et al., 2015). Additionally, larger and older trees generally store more biomass and, consequently, more carbon than younger trees, despite the latter showing faster initial growth (Stephenson et al., 2014).

In light of this, increasing carbon sequestration in urban areas is closely tied to strategic planning and effective management practices, which include selecting suitable planting locations, tree species, and planting density (Pretzsch et al., 2015). Moreover, interventions such as pruning and soil management are essential to maintain tree health and ensure the continuity of ecosystem services (Sharma et al., 2024). However, it is important to acknowledge that certain maintenance practices, such as biomass removal and transportation, can also generate emissions, therefore reducing the net carbon storage balance in urban green spaces (Nowak et al., 2002).

The municipality of Maringá, located in the northern region of Paraná state, was founded in 1947. Its original lush vegetation cover, classified as Submontane Seasonal Semideciduous Forest, was cleared to accommodate urban development. However, according to the Maringá Urban Tree Management Plan (PGAU, 2019), an urban development strategy, strongly influenced by the garden city model proposed by Ebenezer Howard in 19th-century England, has already been outlined. To implement this vision, tree planting on streets and avenues began in the 1950's, resulting in the current total of over 123,000 urban trees (PGAU, 2019). In recognition of this long-standing effort, Maringá was designated one of the "Tree Cities of the World" in 2023 by the United Nations Food and Agriculture Organization (FAO), as noted by The Arbor Day Foundation (2023).

Considering that deforestation represents a major global concern (IPCC, 2013), this action may be less concerning in urban forests, especially in cities governed by strict regulations that limit tree removal or other environmentally harmful practices, as exemplified by Maringá. These conditions not only make local streets and squares suitable for tree planting but also help mitigate carbon emissions.

Given these considerations, this study assessed the carbon stock in the urban forest located within the oldest section of the Main Campus of the State University of Maringá (UEM), where most trees are approximately 50 years old, to address the following questions: I) What is the carbon stock value in the area? II) Which native and exotic species contribute most to the carbon stock? III) How does the study area perform compared to other tree-covered urban areas?

2. MATERIAL AND METHODS

2.1 Study area

The municipality of Maringá is located at the coordinates 23º 25' South Latitude and 51º 56' West Longitude, in the northern region of Paraná State, Southern Brazil (Figure 1A). It has a Cfa climate, classified as mesothermal humid subtropical under the Köppen-Geiger climate classification system (Beck et al., 2023), characterized by hot summers, a low frequency of severe frosts, and a tendency for rainfall to be concentrated in the summer.

The Main Campus of the State University of Maringá (CS/UEM) is situated near the city center (Figures 1B-C), hosting approximately 18,000 people on a daily basis (Paraná State News Agency, 2024). The CS/UEM comprises two distinct areas. The older area, along the BR 376 highway, features simpler buildings constructed in the 1970's and covers 11.5 hectares (Figures 1C and 2B-E), where tree planting began in 1974, as confirmed by historical records and photographs; it provides ideal conditions for studies on carbon stock assessment, with most tree individuals averaging 50 years of age. The second area, occupying more than 90 hectares, features buildings from the 1980's onwards, with tree planting effort occurring between 1985 and 2000.

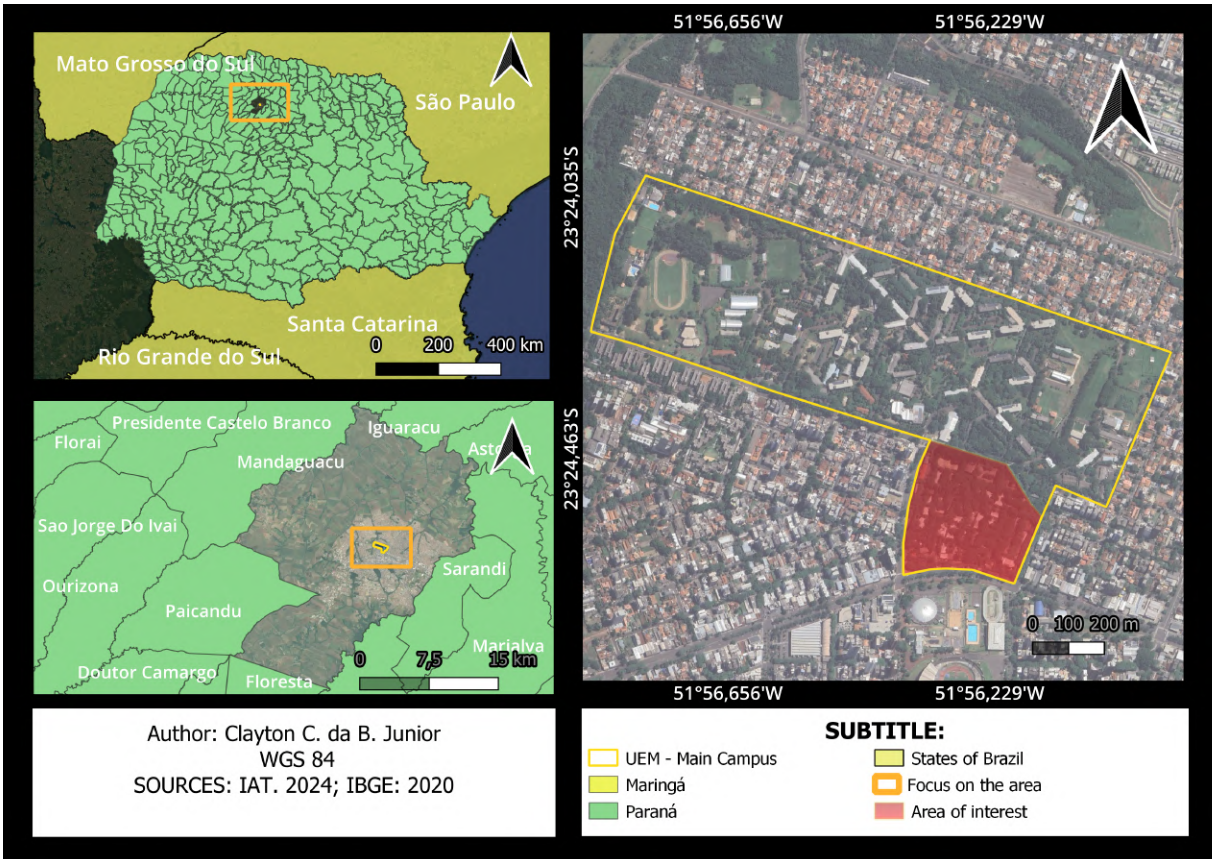

Figure 1. Geographic location of Maringá within the state of Paraná (A), the Main Campus of the State University of Maringá (CS/UEM) situated in the urban zone of the city (B), and the study area highlighted by a red polygon (C)
Figura 1. Localização do município de Maringá no mapa do estado do Paraná (A), do Campus Sede da Universidade Estadual de Maringá (CS/UEM) na zona urbana desta cidade (B) e da área de estudo (polígono vermelho) (C)

2.2 Sampling data

The collection was conducted from January 2021 to July 2022 to quantify the carbon stocks contained in the tree vegetation of the older area of CS/UEM (Figure 2E). The floristic survey included all trees and large palms with diameters at breast height (DBH = trunk diameter measured 1.30 m from the ground) equal to or greater than 5 cm. Specimens were identified to the species level and measured for DBH and total height (Ht), visually estimated by comparison with building heights or urban electricity network structures. At the end of the field sampling, the specimens were organized into 19 DBH classes (with 10 cm intervals up to 190 cm) and six height classes (2-4 m, 4.1-8 m, 8.1-12 m, 12.1-14 m, 14.1-16 m and 16.1-18 m).

To support the estimation of biomass and carbon stock parameters, the species were classified by wood density, according to Ferreira (2014), as light ($\rho < 0.500$ g/cm³), intermediate (ρ between 0.500-0.700 g/cm³), and hard ($\rho > 0.700$ g/cm³). Specific wood density values were obtained from specialized literature and databases, including Oliveira et al. (2019), Zimmermann Oliveira et al. (2019), and Chave et al. (2009). Both the mean values and the average values from the databases were adopted in case of data inconsistencies. Meanwhile, for species not included in these sources, wood density was estimated based on their genus or family.

The geographic distribution of the species was determined using data from the official databases: Flora e Funga do Brasil (2025), Powo (2025), and Tropicos (2025).

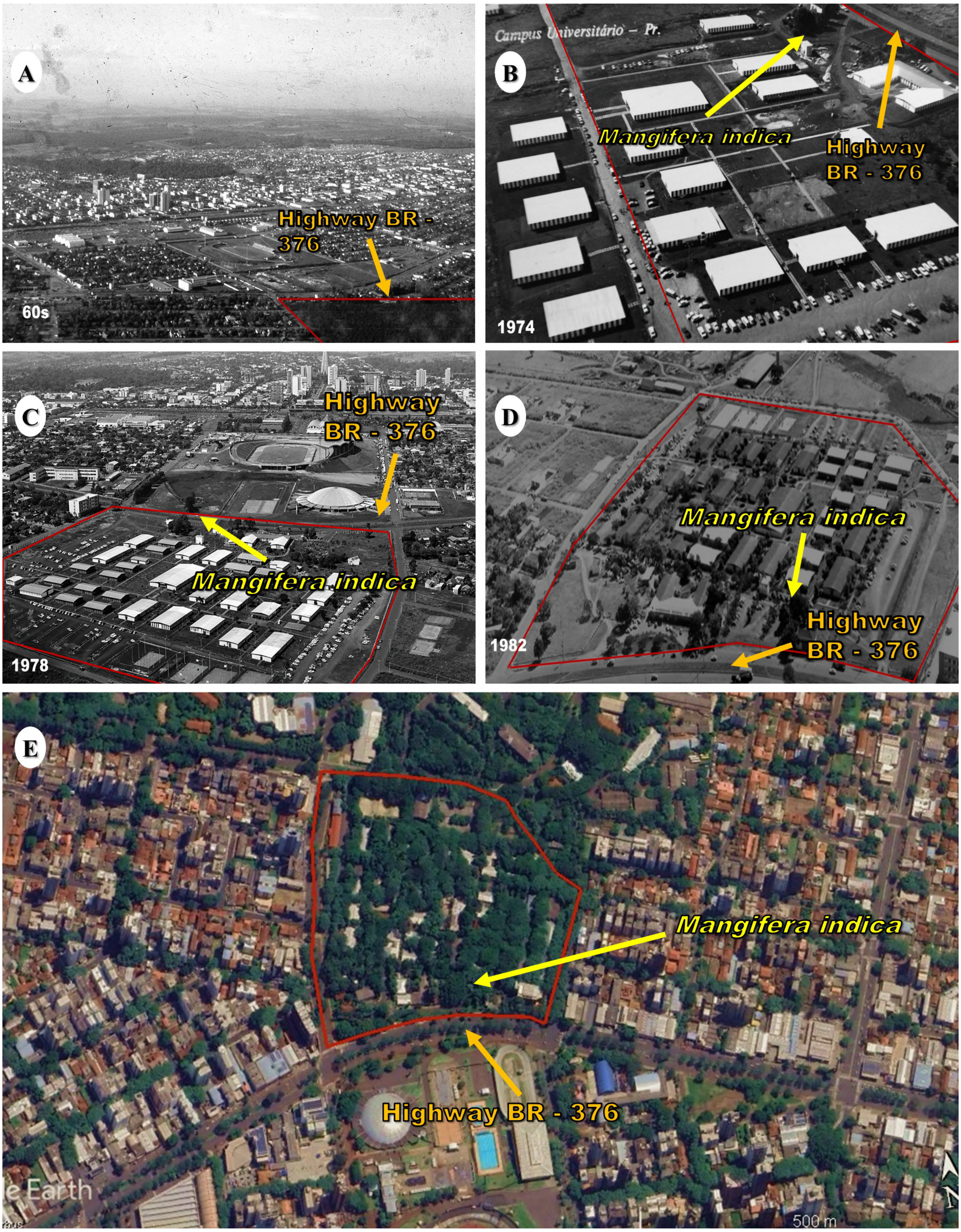

Figure 2. Landscape of the study area. Maringá city in 1960's (A), part of the Main Campus of UEM in 1974 (B), in 1978 (C), in 1982 (D), and at present (E), highlighting *Mangifera indica* specimens, already adult in the 1970's, near BR 376 highway. Source of A-D: Maringá Histórica (2025); E: Google Earth Pro (2025)

Figura 2. Paisagem da área de estudo. Cidade de Maringá na década de 1960 (A), parte do Campus Sede da UEM em 1974 (B), em 1978 (C), em 1982 (D) e nos dias atuais (E), com destaque para os espécimes de *Mangifera indica*, adultos já na década de 1970, próximos à Highway BR 376. Fonte de A-D: Maringá Histórica (2025); E: Google Earth Pro (2025)

2.3 Biomass and Carbon Stock

The biomass estimates for the study area were obtained using non-destructive allometric modeling methods, which apply mathematical equations based on measurable attributes, such as wood density, diameter at breast heigh, and height of the individual, proposed by Chave et al. (2014) (Eq.1), Chave et al. (2005) (Eq.2) and Brown et al. (1989) (Eq.3), as the following:

$$AGB = 0{,}0673*(\rho*DBH^2*Ht)^{0{,}976} \quad \text{(Eq.1)}$$

$$AGB=\rho*EXP(-1{,}499+2{,}148*\ln(DBH))+0{,}207(\ln(DBH))^2-0{,}0281(\ln(DBH))^3 \quad \text{(Eq.2)}$$

$$AGB=EXP[(-3{,}1441+0{,}9719*\ln(DBH^2*Ht)] \quad \text{(Eq.3)}$$

In which: AGB = Biomass (kg); ρ = Wood density (g/cm^3); DBH = Diameter at breast height (cm), Ht = Total height of the individual (m), ln = Natural logarithm.

These equations have also been applied by Sharma et al. (2024), Da Silva et al. (2023), Arratia et al. (2020), and França (2017) in studies of urban forest carbon stocks. The choice of equations also considered the diameter ranges of the trees used by Chave et al. (2014) (5 to 212 cm), Chave et al. (2005) (5 to 156 cm), and Brown (1997) (5 to 130 cm DBH), which include the vast majority of individuals analyzed in CS/UEM. Besides that, a Pearson correlation analysis ($p < 0.05$) was conducted to evaluate the degree of association among carbon stock estimates obtained from the three allometric models.

To quantify the carbon stored in each tree or large palm, the aboveground biomass value (AGB) was multiplied by the constant 0.47, according to the estimate for tropical forests proposed by Thomas & Martin (2012) and IPCC (2006). Finally, the carbon values in Megagrams (Mg) were converted into carbon equivalent by multiplying by 3.67 Mg of CO_2, as described by Brianezi et al. (2014), and Lopes & Miola (2010), considering the following equation:

$$CO_2 = 3{,}67 * EC \quad \text{(Eq.4)}$$

In which: CO_2 = carbon dioxide equivalent (Mg); 3.67 = factor obtained from the ratio between the atomic mass of carbon (12) and the molecular mass of carbon dioxide (44), and EC = carbon stock.

3. RESULTS

In the study area, 842 trees and 156 large palms were recorded, totaling 998 specimens distributed across 27 botanical families, 68 genera, and 83 species (as shown in Table 1 and supplementary material). Of these, 45 are native to the northern region of Paraná, representing 49.40% of the total sampled individuals. The family with the highest species richness was Fabaceae (20), which also exhibited the highest abundance among the recorded specimens, with 428 individuals (42.88%), followed by Arecaceae, with 156 individuals (15.63%), and Bignoniaceae, with 137 individuals (13.73%).

The three most abundant species in the area were *Tipuana tipu* (148 individuals, 14.83%), *Cenostigma pluviosum* (146 individuals, 14.63%), both exotic to the northern region of Paraná and *Handroanthus heptaphyllus* (94 individuals, 9.42%), which is native to the region. In the study area, the exotic palm trees *Dypsis lutescens* (63 individuals, 6.31%) and *Roystonea oleracea* (49 individuals, 4.91%) also stood out (Table 1).

Regarding height (Figure 3), the majority of the specimens at CS/UEM fell within the 8.1-12 m class (41.58%), followed by individuals with heights between 4.1 and 8 m (33.47%), and only 0.70% had heights between 16.1 and 18 m. The site features single-story buildings (approximately four meters in height) shaded by the tree cover.

The analysis of trunk and stipe diameters at breast height (DBH, 1.30 m) revealed that 356 specimens (35.71%) had a DBH between 11 and 40 cm, while 313 (31.39%) had a DBH between 41 and 60 cm (Figure 4). In this second group, *Handroanthus heptaphyllus* (average DBH of 47.6 cm) and *Tipuana tipu* (average DBH of 59.5 cm) stood out.

The royal palms (*Roystonea oleracea*) and golden cane palms (*Dypsis lutescens*) had stipes with average DBH of 37.5 cm and 63 cm, respectively, considering all stipes in the clump. Large trees with more than 100

Table 1. Analysis of the 20 trees and largest palms at the Main Campus of the State University of Maringá with the highest carbon stock values. Number of individuals (N), wood density by species (ρ), mean total carbon stock, mean total carbon stock per specimen, mean carbon stock per hectare, according to Chave et al. (2014) (Eq.1), Chave et al. (2005) (Eq.2) and Brown et al. (1989) (Eq.3). Species native to the northern region of Paraná are marked with the symbol (*)

Tabela 1. Análise das 20 árvores e palmeiras de grande porte do Campus Sede da Universidade Estadual de Maringá com maiores valores de estoque de carbono. Número de indivíduos (N), densidade da madeira por espécie (ρ), média do estoque de carbono total, média do estoque total de carbono por espécime, média do estoque de carbono por hectare, segundo Chave et al. (2014) (Eq.1), Chave et al. (2005) (Eq.2) e Brown et al. (1989) (Eq.3). As espécies nativas da região norte do Paraná estão assinaladas com o símbolo (*)

Family	Species	N	ρ (g/cm³)	$\bar{x}$ 03 Eq. (Mg C)	$\bar{x}$ C/indiv. (Mg C)	$\bar{x}$ 03 Eq. (Mg C ha⁻¹)
Fabaceae	*Cenostigma pluviosum* (DC.) Gagnon & G.P.Lewis	146	0.652	111.009	0.760	9.715
Fabaceae	*Tipuana tipu* (Benth.) Kuntze	148	0.587	87.943	0.594	7.697
Bignoniaceae	*Handroanthus heptaphyllus* (Vell.) Mattos*	94	0.547	36.018	0.383	3.152
Fabaceae	*Delonix regia* (Bojer ex Hook.) Raf.	28	0.774	27.996	1.000	2.450
Arecaceae	*Dypsis lutescens* (H.Wendl.) Beentje & J.Dransf.	63	0.557	26.087	0.414	2.283
Cordiaceae	*Cordia trichotoma* (Vell.) Arráb. ex Steud.*	47	0.479	12.282	0.261	1.075
Fabaceae	*Holocalyx balansae* Micheli*	42	0.555	10.993	0.262	0.962
Arecaceae	*Roystonea oleracea* (Jacq.) O.F.Cook	49	0.557	10.216	0.208	0.894
Anacardiaceae	*Mangifera indica* L.	15	0.567	10.459	0.697	0.915
Fabaceae	*Schizolobium parahyba* (Vell.) Blake	21	0.389	10.722	0.511	0.938
Fabaceae	*Peltophorum dubium* (Spreng.) Taub.*	18	0.555	9.142	0.508	0.800
Moraceae	*Ficus elastica* Roxb.	1	0.618	3.694	3.694	0.323
Magnoliaceae	*Magnolia champaca* (L.) Baill. ex Pierre	16	0.497	4.065	0.254	0.356
Bignoniaceae	*Handroanthus impetiginosus* (Mart. ex DC.) Mattos	10	0.902	3.134	0.313	0.274
Combretaceae	*Terminalia catappa* L.	12	0.478	3.447	0.287	0.302
Phytolaccaceae	*Gallesia integrifolia* (Spreng.) Harms*	6	0.510	2.880	0.480	0.252
Proteaceae	*Grevillea robusta* A.Cunn. ex R.Br.	5	0.521	2.638	0.528	0.231
Fabaceae	*Libidibia ferrea* (Mart. ex Tul.) L.P.Queiroz	4	1.170	1.885	0.471	0.165
Meliaceae	*Cedrela fissilis* Vell.*	6	0.501	2.241	0.373	0.196
Moraceae	*Ficus guaranitica* Chodat*	1	0.412	2.153	2.153	0.188
Total		998	-	402.757	-	35.249

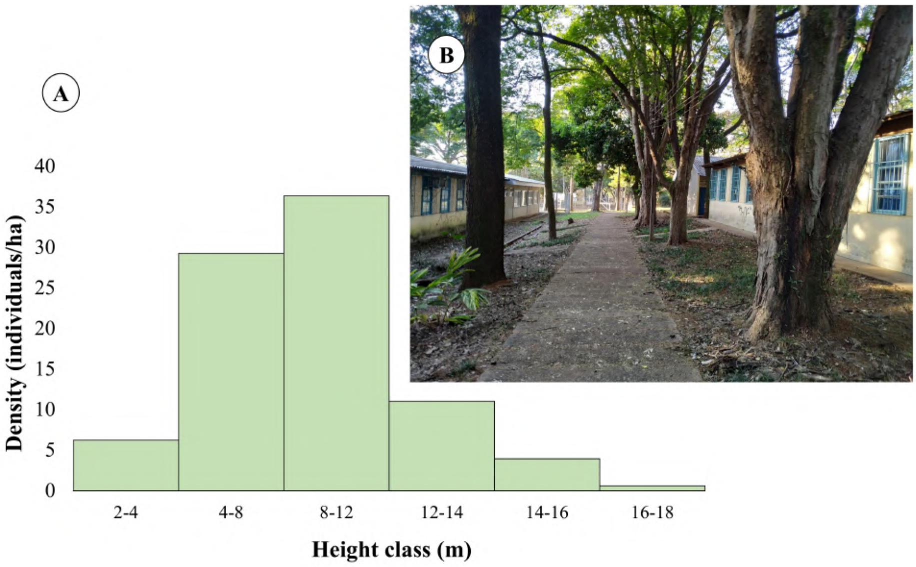

Figure 3. Distribution of the height classes of trees and large palms in urban forests (A) and a detailed view of the landscape (B) at the Main Campus of UEM, Maringá (PR)

Figura 3. Distribuição das classes de altura das árvores e palmeiras de grande porte presentes na arborização (A) e detalhe da paisagem (B) do Campus Sede da UEM, Maringá (PR)

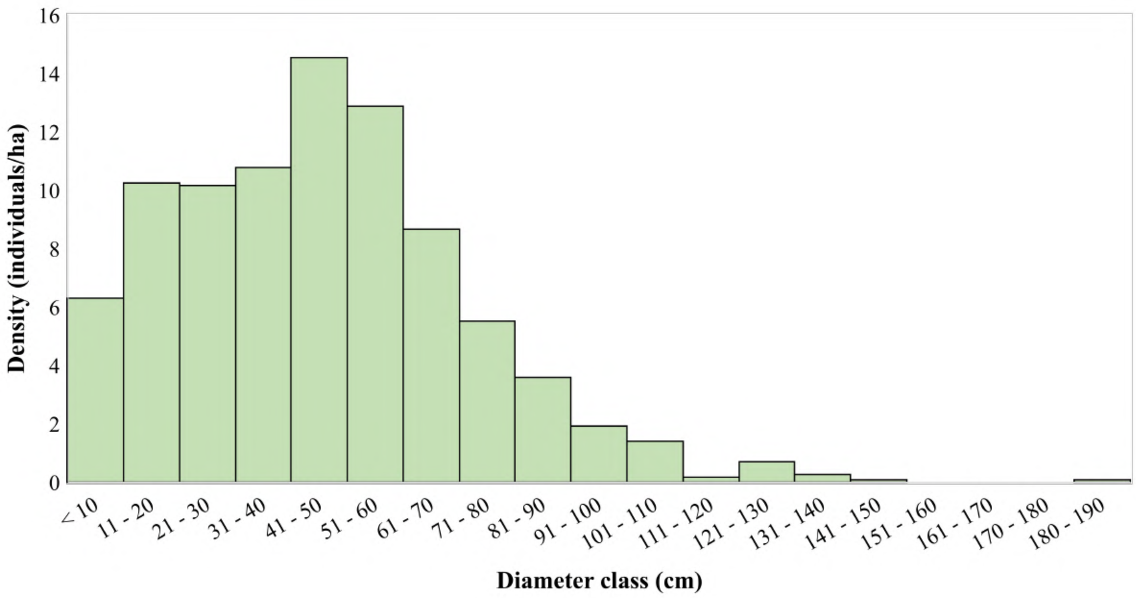

Figure 4. Distribution of trunk and stipe diameter classes at breast height (DBH) of trees and large palms on the Main Campus of the State University of Maringá (UEM), Maringá, Paraná State, Brazil
Figura 4. Distribuição das classes de diâmetro do tronco e estipes, à altura do peito (DBH), das árvores e palmeiras de grande porte da arborização do Campus Sede da UEM, Maringá (PR)

cm in diameter formed a group of only 31 individuals, and the largest were *Tipuana tipu* (DBH=215.81 cm), *Mangifera indica* (DBH=188.12 cm), *Ficus elastica* (DBH=139.74 cm), and *Delonix regia* (DBH=138.78 cm). The specimens of *M. indica* have been cultivated along the margins of BR 376 highway since the 1960's (Figures 2B-E).

Regarding wood density, 716 individuals (71.74%) had intermediate density values, followed by those with light density (157 individuals, 15.73%) and hard density (125 individuals, 12.53%) (Table 1).

According to Figure 5, carbon stock estimates for the study area, based on the three allometric models, were 436.80 Mg C, 326.40 Mg C, and 445.07 Mg C (average of 402.76 Mg C), respectively. In terms of wood density categories, the total carbon stock was distributed as follows: 322.07 Mg C for intermediate-density wood, 40.65 Mg C for softwood, and 40.04 Mg C for hardwood.

The application of the allometric models revealed that three of the 27 recorded botanical families accounted for 85.80% of the total carbon stock at CS/UEM. The leading contributor was Fabaceae, with an average of 264.69 Mg C (65.72%) (293.03 Mg C, Eq.1; 214.08 Mg C, Eq.2; 286.98 Mg C, Eq.3), followed by Bignoniaceae (41.69 Mg C, 10.23%) (46.31 Mg C, Eq.1; 29.38 Mg C, Eq.2; 49.39 Mg C, Eq.3), and Arecaceae (39.02 Mg C, 9.85%) (37.88 Mg C, Eq.1; 38.00 Mg C, Eq.2; and 41.19 Mg C, Eq.3) (see supplementary material).

The average carbon stock per hectare at CS/UEM was 35.25 Mg C ha^{-1} (38.23 Mg C ha^{-1}, Eq.1; 28.57 Mg C ha^{-1}, Eq.2; 38.95 Mg C ha^{-1}, Eq.3). The carbon equivalent in CO_2 for this stock was 1,602 Mg CO_2, 1,197 Mg CO_2, and 1,632 Mg CO_2, equivalent to 140.30 Mg CO_2 ha^{-1}, 108.51 Mg CO_2 ha^{-1}, and 142.94 Mg CO_2 ha^{-1} (average of 1,477 Mg C and 130.58 Mg CO_2 ha^{-1}), respectively, for the three allometric models used.

At CS/UEM, exotic species stood out in terms of carbon stock per hectare (Table 1), reaching an average of 27.45 Mg C ha^{-1} (77.89%) across the three allometric models (29.87 Mg C ha^{-1}, Eq. 1; 22.98 Mg C ha^{-1}, Eq.2; 29.53 Mg C ha^{-1}, Eq.3), while native species stored an average of 7.79 Mg C ha^{-1} (22.11%) (8.36 Mg C ha^{-1}, Eq. 1; 5.59 Mg C ha^{-1}, Eq.2; 9.43 Mg C ha^{-1}, Eq.3). Due to the large number of individuals present in the area, the exotic species that contributed most to the results were *Cenostigma pluviosum* with 11.18, 7.57, and 10.39 Mg C ha^{-1} (146 individuals) and *Tipuana tipu* with 8.34,

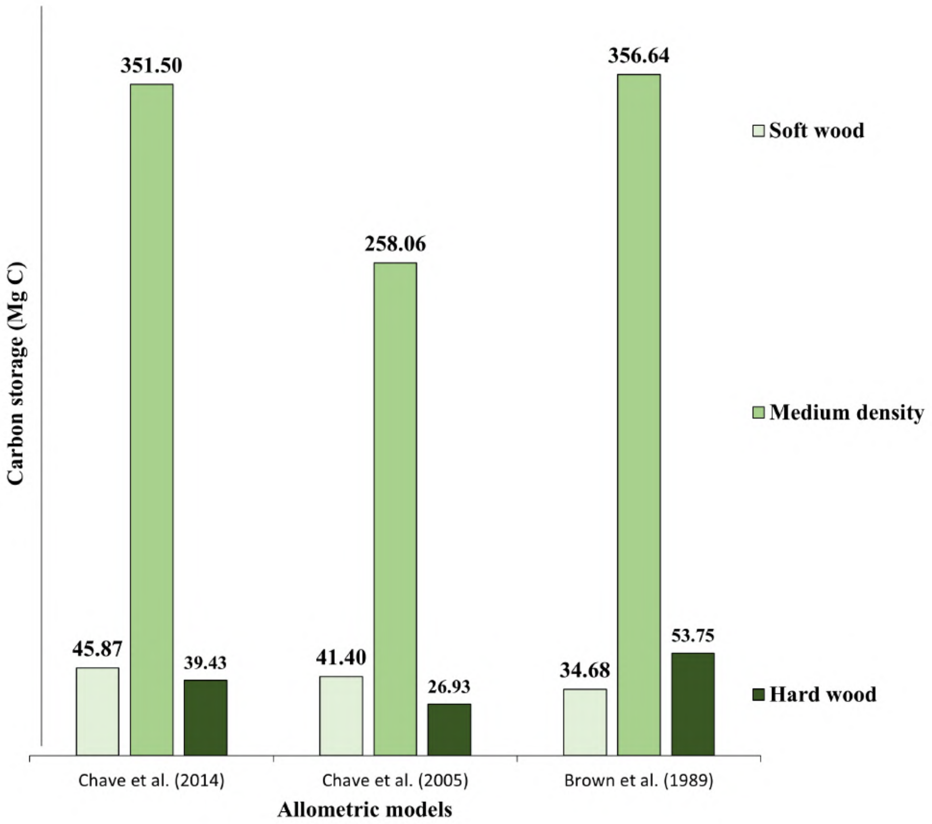

Figure 5. Carbon stock (Mg C) estimated using the allometric models of Chave et al. (2014), Chave et al. (2005), and Brown et al. (1989), based on wood density classes of trees and large palms in the urban forests of the Main Campus of the State University of Maringá (UEM), Maringá, Paraná State, Brazil

Figura 5. Estoque de carbono (Mg C) conforme os modelos alométricos de Chave et al. (2014), Chave et al. (2005) e Brown et al. (1989), de acordo com as classes de densidade da madeira das árvores e palmeiras de grande porte da arborização do Campus Sede da UEM, Maringá (PR)

6.17, and 8.58 Mg C ha^{-1} (148 individuals), *Delonix regia* with 2.68, 2.56, and 2.10 Mg C ha^{-1} (28 individuals), and *Dypsis lutescens* with 2.13, 2.40, and 2.32 Mg C ha^{-1} (63 individuals). Among the native species, *Handroanthus heptaphyllus* stood out with 3.47, 2.15, and 3.83 Mg C ha^{-1} (94 individuals), *Cordia trichotoma* with 1.14, 0.65, and 1.43 Mg C ha^{-1} (47 individuals), and *Holocalyx balansae* with 1.04, 0.71, and 1.14 Mg C ha^{-1} (42 individuals), respectively, for the three allometric models used (Table 1).

Concerning the average carbon stock per species and considering all sampled specimens (Table 1 and supplementary material), the single specimen of *Ficus elastica* at CS/UEM stood out, presenting 4.28, 2.64, and 4.17 Mg (average of 3.69 Mg C), respectively, for the three allometric models. It was followed by *Ficus guaranitica* (average of 2.15 Mg C), *Inga vera* subsp. *affinis* (average of 1.24 Mg C), *Delonix regia* (average of 1.00 Mg C), and *Cenostigma pluviosum* (average of 0.76 Mg C). *Mangifera indica*, *Pterogyne nitens*, *Cordia ecalyculata*, and *Tipuana tipu* presented average values between 0.60 and 0.70 Mg C. All of these species had intermediate wood density, except for *D. regia*, which featured hard wood. Among the large palms, *Dypsis lutescens*, with stipes that can reach seven meters in height, stood out with an average of 0.41 Mg C, *Aiphanes aculeata* (0.25 Mg C), and *Roystonea oleracea* (0.21 Mg C) regarding average carbon stock in their stipes (Table 1).

Figure 6 shows the comparison between the allometric models used, demonstrating that Brown et al. (1989) had the best fit (R^2=0.96), compared to the models of Chave et al. (2014) and Chave et al. (2005) (R^2=0.94

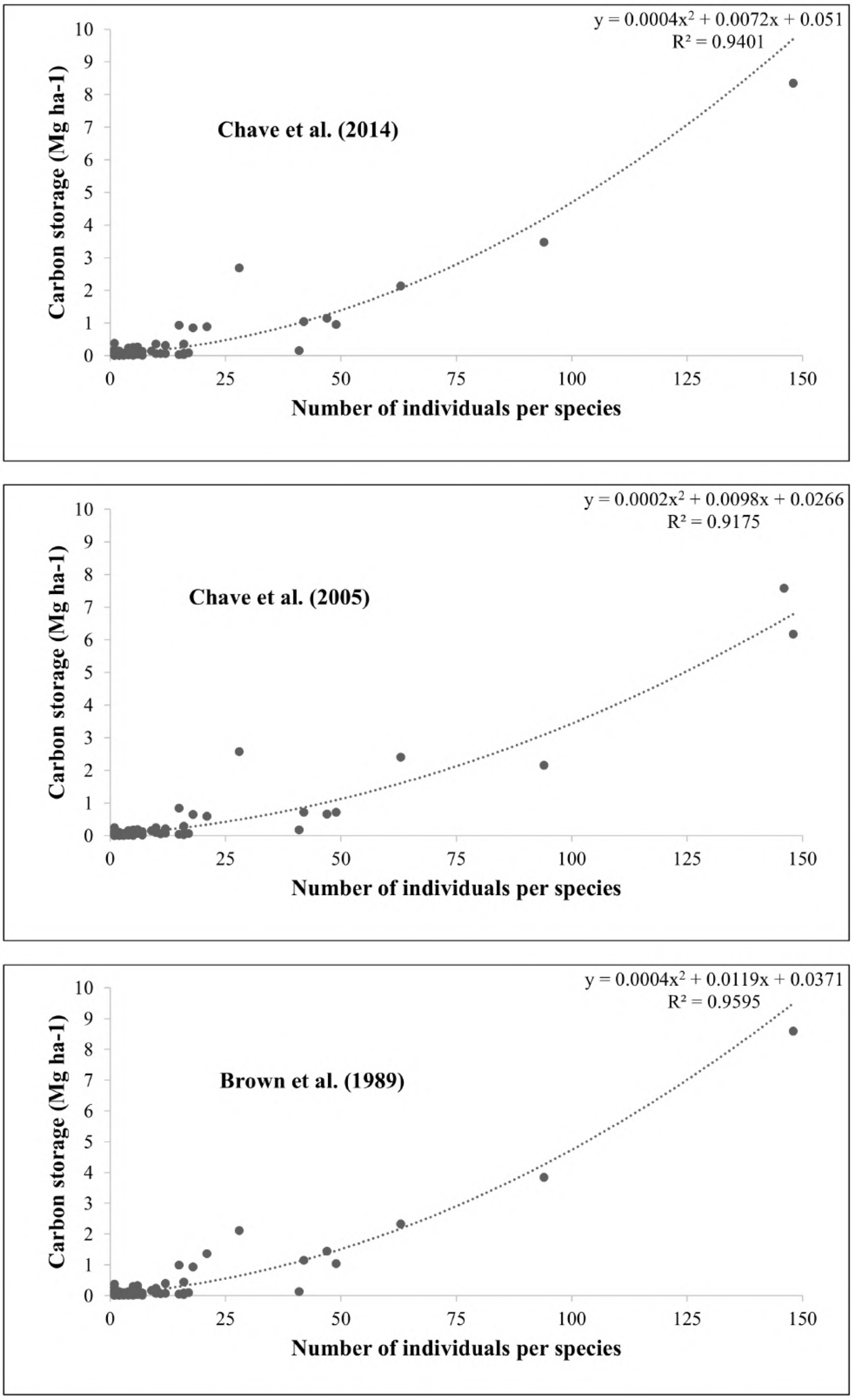

Figure 6. Relationship between the number of individuals per species and carbon stock per hectare in the urban forests of the Main Campus of the State University of Maringá (UEM), Maringá, Paraná State, Brazil, based on three allometric models: Chave et al. (2014), Chave et al. (2005), and Brown et al. (1989). Dotted lines represent the model fits, with their respective coefficients of determination (R^2), indicating model quality

Figura 6. Relação entre o número de indivíduos, por espécie, e o carbono estocado por hectare na arborização do Campus Sede da UEM, Maringá (PR), com base em três modelos alométricos utilizados: Chave et al. (2014), Chave et al. (2005) e Brown et al. (1989). As linhas pontilhadas representam os ajustes dos modelos, com os respectivos coeficientes de determinação (R^2), que indicam sua qualidade and R^2=0.92, respectively). Despite these differences, all models confirm the same general trend of higher carbon stock in relation to the number of individuals sampled. This pattern is further supported by the positive correlations among the carbon estimates from the three models ($r > 0.95$; $p < 0.05$), as shown in Figure 7. The results indicate that the number of individuals per species is a relatively accurate predictor for estimating stored carbon.

A positive correlation was observed among the three allometric models used to calculate the amount of carbon stored in the CS/UEM, showing relatively similar values. However, as already seen in Figure 6, the model by Brown et al. (1989) presented the highest R^2 value (0.95). The correlation matrix among the three allometric models reveals a strong similarity in the predictions of carbon stored in the CS/UEM area, with

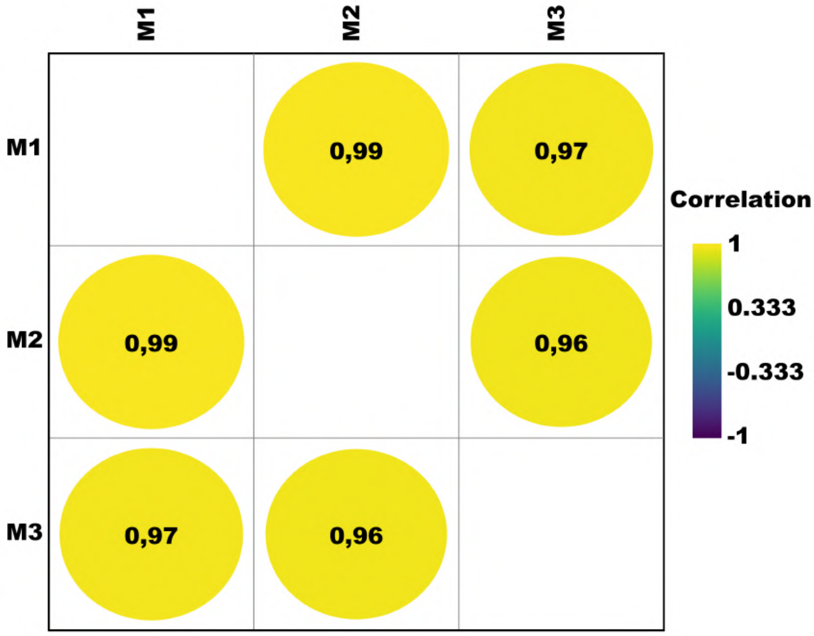

Figure 7. Pearson correlation matrix ($p < 0.05$) between carbon stock estimates obtained from three different allometric models: M1 (Chave et al., 2014), M2 (Brown et al., 1992), and M3 (Chave et al., 2005). The strong correlations ($r > 0.95$) indicate high agreement among the estimates, supporting the consistency and applicability of the models within the context of this study. Analysis performed using PAST software

Figura 7. Correlação de Pearson ($p < 0,05$) entre os estoques de carbono estimados pelos três modelos alométricos: M1 (Chave et al., 2014), M2 (Brown et al., 1992) e M3 (Chave et al., 2005). As correlações elevadas ($r > 0,95$) indicam forte associação entre os valores estimados pelos diferentes modelos, validando sua consistência para aplicação no contexto deste estudo. Análise realizada no software PAST

correlation coefficients ranging between 0.96 and 0.99. These results indicate that, despite small methodological differences, the models follow very similar patterns for estimating carbon stored in the analyzed urban area.

When comparing carbon stock values from CS/UEM to those reported in native and urban forests (Table 2), the site ranks tenth overall. However, among studies conducted specifically in urban areas, CS/UEM holds the fourth position.

4. DISCUSSION

Urban trees are important for reducing the effects of climate change, functioning as sinks for atmospheric carbon. They also contribute to carbon sequestration and enhance biodiversity, thus offering ecological and public health benefits. In this study, we estimated that 35.25 Mg C ha^{-1} was stored in 11.5 ha, which is comparatively larger than other urban regions and some natural environments.

Table 2. Studies on the theme of carbon stock/sequestration conducted in Brazil. in different forest types or urban areas. using allometric equations. Biomass per hectare (AGB Mg ha^{-1}). Chave et al. (2014) (Eq.1). Chave et al. (2005) (Eq.2). Brown et al. (1989) (Eq.3). hectare (ha). carbon stock per hectare (Mg C ha^{-1}). number of individuals (Ni). other allometric equations (*)
Tabela 2. Estudos com o tema estoque/sequestro de carbono realizados no Brasil. em diferentes tipos florestais ou áreas urbanas. com o uso das equações alométricas. Biomassa por hectare (AGB Mg ha^{-1}). Chave et al. (2014) (Eq.1). Chave et al. (2005) (Eq.2). Brown et al. (1989) (Eq.3). hectare (ha). estoque de carbono por hectare (Mg C ha^{-1}). número de indivíduos (Ni). outras equações alométricas (*)

Ranking	Author/year	Forest type	City/State	Area (ha)	Ni	AGB Mg ha^{-1}	Mg C ha^{-1}
1	Rolim et al. (2005)	Seasonal Semideciduous Forest	Linhares/ES	2.5	-	334.5	167.25 (*)
2	Alves et al. (2010)	Seasonal Semideciduous Forest	Several municipalities/SP	13	1576	283.2	141.6 (Eq.3)
3	Arratia et al. (2020)	Urban	Square Júlio Prestes/SP	7.1	-	250	125 (Eq.1 and Eq.3)
4	Caldeira (2013)	Mixed Ombrophilous Forest	General Carneiro/PR	4	-	210.5	98.9 (*)
5	Dantas et al. (2021)	Cerrado	Lavras/MG	1.2	-	188.5	94.25 (Eq.1)
6	Ribeiro et al. (2009)	Seasonal Semideciduous Forest	Viçosa/MG	35	319	166.67	83.34(*)
7	França (2017)	Urban	São Paulo/SP	7.13	1510	130.4	65.2 (Eq.2)
8	Da Rocha et al. (2019)	Seasonal Semideciduous Forest	Viçosa/MG	14.8	1376	127.42	63.71 (*)
9	Brianezi (2012)	Urban	Viçosa/MG	1.359	3683	108	54(*)
10	**CS/UEM**	**Urban**	**Maringá/PR**	**11.5**	**998**	**81.34**	**38.23 (Eq.1) 28.57 (Eq.2) 38.95 (Eq.3) $\bar{x}$ = 35.25**
12	Dias (2014)	Dense Cerrado	03 municipalities/MG	11.83	1039	54.42	27.21(*)
13	Veres et al. (2020)	Seasonal Semideciduous Forest	São José das Palmeiras/PR	0.5	779	56.25	25.88(*)
14	Nunes (2018)	Urban	Catolé da Rocha/PB	-	3085	44.54	20.04(*)
15	Da Silva et al. (2023)	Urban	Sete lagoas/MG	1.4	106	9.74	4.87 (Eq.2)
16	Lopes & Miola (2010)	Wooded Savanna	Pará de Minas e Maravilhas/MG	0.4	124	7.7	3.85 (Eq.2)

According to Sharma et al. (2020), urban trees are important for aesthetic and ornamental purposes and could contribute to the adaptation of urban environments to changing climatic conditions. Kurtz et al. (2024) and Keenan & Williams (2018) highlight that tropical areas inside the urban matrix can function as important carbon sinks which are systems that absorb more carbon than they emit, primarily through biological processes such as photosynthesis.

Forest environments generally exhibit larger carbon stock compared to urban environments, because of higher tree density (Nowak & Crane, 2002). In this context, tree density and structure of plant communities could influence the efficiency of carbon sequestration (Zhang et al., 2024). Despite their proven benefits, urban trees continue to face challenges related to equitable access and long-term maintenance. These factors reinforce the need to incorporate broader sustainable planning strategies related to urban forestry (Athokpam et al., 2024). To better understand the carbon sequestration capacity of urban environments, additional studies should explore the carbon present in carbon pools beyond aboveground biomass.

Cenostigma pluviosum and *Tipuana tipu*, planted approximately 50 years ago, stood out at the CS/UEM in terms of the number of individuals (29.46% of the total sampled) and, due to their high DBH and intermediate wood density, both species had the highest carbon stock (111.01 and 87.94 Mg C, respectively). These species are abundant in the urban forests of Maringá (PGAU, 2019; Sampaio & De Angelis, 2008), contributing to the early-stage initiatives implemented in the 1950's. In addition to the eight exotic species of Fabaceae, the occurrence of 12 native species of this family at the study area aligns with the results obtained in different areas of the Submontane Semideciduous Seasonal Forest in northern (Rossetto & Vieira, 2013) and northwestern regions of Paraná (Souza et al., 2009), where the family stands out for its species richness.

In addition to the 12 native Fabaceae species, there are 33 other native species at the CS/UEM. According to Martins Neto et al. (2016), the incorporation of native species in urban forests should be encouraged by public managers and urban planners, ensuring the preservation of biodiversity, the maintenance of ecosystem services, and the improvement of quality of life in cities. To these ecosystem services, the possibility of planting native species that guarantee good carbon stocks per hectare should be added, such as *Handroanthus heptaphyllus* and *Holocalyx balansae*, which are recognized as suitable and already used in the afforestation of Maringá (PGAU, 2019). Other native species can also be employed in afforestation, contributing to carbon stock, such as *Cordia ecalyculata, Pterogyne nitens*, and *Cordia trichotoma*, while *Inga vera* subsp. *affinis*, although storing significant amounts of carbon, is not suitable for urban forests due to its low wood density and consequent risk of branch fall over time.

Regarding exotic species with a high capacity for average carbon stock per individual, *Ficus elastica, F. guaranitica* and *Delonix regia*, due to their extensive superficial root systems, should only be planted in compatible urban environments, such as wide central medians and squares. However, Sharma et al. (2020) also indicate the great capacity of some *Ficus* species to store carbon in the afforestation of Amity University, Noida (India). However, the introduction of exotic species that contribute to increasing carbon stocks and other ecosystem services should be approached with caution (Sjöman et al., 2016).

The work of Sjöman et al. (2016) states that the use of native species in urban forestry is appropriate, however, where the availability of native species is limited, non-invasive exotic species that effectively provide essential ecosystem services can serve as viable alternatives.

In this context, Chalker-Scott (2015) notes that many exotic species introduced into urban environments may offer advantages over native species, but exotic species with invasive potential should be avoided. Regarding disadvantages, the author above mentions that native species may be more sensitive to soil changes and the effects of global warming. According to Bellard et al. (2016), exotic species are the second leading cause of biodiversity loss.

Therefore, we emphasize that, in the context of urban forestry, managers should select species that provide ecosystem and environmental services but do not promote degradation. In our study, only two invasive alien species were found, both of which contribute little to carbon storage (Table 1): *Psidium guajava* and *Eriobotrya japonica*. They were also found by Blum et al. (2008) in the urban forestry of Maringá.

Regarding palms, it was expected that the species at the study area would not represent large volumes of stored carbon, as verified by Das et al. (2021) when estimating carbon stocks in the stipes of *Areca catechu* (a commercial species in India). In their study, the store carbon volume reached only 20.5 Mg C ha^{-1} in 35-year-old plantations, a result considered very low by the authors. However, the Arecaceae at CS/UEM occupied the third position among the sampled families (average of 39.02 Mg C and 3.41 Mg C ha^{-1}), which is due to the high number of individuals (156) and the DBH of the stipes (*Roystonea oleracea*), or the sum of stipes per clump (*Dypsis lutescens*).

The three equations used to calculate carbon stock at CS/UEM were similar to the Pearson correlation, showing a positive correlation among the three models, especially the equations by Chave et al. (2014) and Brown et al. (1989). These similarities were expected, as the three models employ allometric principles to estimate carbon stock based on the number of individuals and characteristics of tree species (wood density, DBH, and total height). Guo et al. (2024) and Chave et al. (2006) stated that genetic variations and wood density directly affect carbon estimates in tropical forests. It is worth noting that the three equations were developed for forest areas and, as suggested by Nowak et al. (2013), only the development of new studies in urban (non-forest) landscapes can help improve carbon stock estimates in cities. The high R^2 values in the regression equations in Figure 6 suggest that the abundance of individuals is a

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significant factor in determining carbon stock. However, it is important to note that this approach, although useful, can be considered simplistic, as other factors such as individual size and wood density are also important for carbon storage.

In this study, the equation by Brown et al. (1989) presented the highest carbon storage values in this study, but the model by Chave et al. (2014) is more accurate as it incorporates climatic and regional variables, increasing the precision of estimates. The discussions available in the studies by Chave et al. (2005) and Chave et al. (2014) show that Brown et al. (1989) tends to overestimate biomass, directly impacting carbon storage. Although our study focused exclusively on aboveground biomass, the lack of estimates for belowground biomass and soil carbon is recognized as a limitation. These components can contribute to total carbon stocks, especially in urban ecosystems, and should be considered in future research.

4.1 Performance of Urban Areas in Carbon Storage

The carbon stock at CS/UEM (38.23 Mg C ha^{-1}; 38.95 Mg C ha^{-1}; 28.57 Mg C ha^{-1}, average of 35.25 Mg C ha^{-1}) can be considered intermediate compared to other analyzed areas, mainly due to its high number of species (71.74%) with intermediate wood density values and DBH. This indicates that the trees are of medium size, and the area is not dominated by mature trees.

Unwin & Kriedemann (2000) state that, in trees between 15 and 45 years old, CO_2 sequestration increases drastically and remains constant once they reach maturity. According to Nowak et al. (2002), the life span of urban tree species is crucial for the urban carbon cycle, since increased longevity postpones carbon emissions associated with planting, maintenance, and eventual removal processes. In recent years, individuals of *C. pluviosum, D. regia,* and *T. tipu* at the CS/UEM area have begun to exhibit carbon loss, likely associated with inadequate pruning practices. These interventions appear to be contributing to serious phytosanitary issues and, in some cases, tree mortality. However, studies confirming this correlation within the region are currently lacking.

In terms of height, the individuals within the CS/UEM area can be classified as low to medium size (75% with heights between 4 and 12 m), compared to the data presented by Roderjan et al. (2002) for the Submontane Semideciduous Seasonal Forest, the phytophysiognomy of the Maringá region, where the canopy of 30 to 40 m includes *Aspidosperma polyneuron, Tabebuia heptaphylla, Peltophorum dubium, Balfourodendron riedelianum, Ficus luschnathiana, Gallesia gorazema, Holocalyx balansae, Astronium graveolens, Pterogyne nitens, Ceiba speciosa* and *Cordia trichotoma*, among others.

According to Wu et al. (2022), urban trees have limited space to grow due to urban structures, reducing their development compared to those in natural areas, which directly influences carbon storage. Since total height and DBH of trees are variables directly correlated with the amount of carbon stored, forests and urban areas composed of medium-sized trees have lower total biomass and, consequently, lower carbon stock (Duangsathaporn et al., 2023; Khan et al., 2020).

Studies on university campuses are important, as they reveal the interest of higher education institutions in urban forestry. Cox (2012) found 8.53 Mg C ha^{-1} and 31.33 Mg CO_2 ha^{-1} in trees on the campus of California State University (USA, 101 ha). De Villiers et al. (2014) obtained carbon stocks of 24.38 Mg C ha^{-1} and 89.36 Mg CO_2 ha^{-1} at Kiwi University (Australia) and Sharma et al. (2020) found that 15.74 Mg C ha^{-1} are stored in the trees at Amity University campus Noida (India). These findings demonstrate that CS/UEM's afforested area holds a higher carbon stock than other international university campuses worldwide. Such results highlight the value of urban trees on campus in contributing significantly to carbon sequestration and urban ecological resilience.

5. CONCLUSION

Considering the average among the three allometric models used, the carbon stocks, accumulated over 50 years of urban forests at CS/UEM, reached 402.76 Mg C and 35.25 Mg C ha^{-1}. These results are higher in comparison to other Brazilian urban areas. Among the botanical families, Fabaceae stood out by contributing 65.72% of the total carbon stock, followed by Bignoniaceae and Arecaceae. The species that contributed the most to the carbon stock at CS/UEM were *Cenostigma pluviosum*, *Tipuana tipu*, *Delonix regia*, and *Dypsis lutescens* (exotic), as well as *Handroanthus heptaphyllus*, *Cordia trichotoma* and *Holocalyx balansae* (native), both in terms of the number of individuals and their DBH and total height. However, only *D. regia* has wood with a hard density, and the others have wood with intermediate density.

These results highlight the need for careful planning to maximize carbon sequestration in urban areas, further emphasizing urban forests as an ecosystem service of great importance to society. The use of species with high carbon storage capacity (particularly those with intermediate or hard wood density), combined with management practices that allow for the full growth of trees, is essential to enhance the ecological and climatic benefits of urban forests.

It is expected that further studies will be conducted in Paraná and other Brazilian states to expand the understanding of tree growth patterns and their carbon storage capacity in urban areas.

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AUTHOR CONTRIBUTIONS

Broi Junior, C. C.: Data curation, Formal analysis, Investigation, Project administration, Supervision, Writing – review & editing; Sampaio, M. B.: Conceptualization, Methodology, Writing – review & editing; França, N. A.: Investigation, Writing – review & editing; Batista, V. S.: Investigation, Writing – review & editing; Oliveira, B. L.: Investigation, Writing – review & editing; Milaneze-Gutierre, M. A.: Conceptualization, Investigation, Project administration, Supervision, Writing – review & editing.

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