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Article

Growth and Carbon Accumulation of Pioneer and Non-pioneer Native Trees of the Atlantic Forest in Urban Afforestation

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RESUMO

O crescimento e a capacidade de sequestro de carbono (C) de árvores nativas dependem de fatores ambientais e características intrínsecas de cada espécie. Em ambientes urbanos, há uma lacuna no entendimento comparativo do potencial de crescimento e de sequestro de C entre espécies arbóreas pioneiras e não pioneiras. Assim, o objetivo deste estudo foi avaliar o crescimento e acúmulo de C na biomassa aérea de espécies arbóreas pioneiras e não pioneiras nativas da Mata Atlântica utilizadas na arborização urbana. O estudo foi conduzido na arborização do Campus de Nova Venécia do Instituto Federal do Espírito Santo, considerando oito espécies de árvores nativas, distribuídas igualmente entre os grupos de pioneiras e não pioneiras. A partir de dados de inventário florestal, os incrementos médios anuais em diâmetro (AAI_{DBH}), altura total (AAI_{H}) e C (AAI_{C}) foram calculados e comparados entre grupos ecológicos e espécies. O grupo das pioneiras apresentou maiores AAI_{DBH} e AAI_{C}, mas não houve diferença significativa entre grupos para AAI_{H}. Entre espécies, AAI_{DBH}, AAI_{H} e AAI_{C} variaram consideravelmente, sendo que as pioneiras *Cenostigma pluviosum*, *Enterolobium contortisiliquum* e *Schizolobium parahyba* demonstraram grande potencial em estocar C na biomassa acima do solo. Dada a variação interespecífica, é preciso considerar características intrínsecas na seleção de espécies para maximizar o sequestro de C em ambientes urbanos. Os resultados deste estudo destacam a influência do grupo ecológico e das características individuais das espécies no sequestro de C e podem orientar estratégias de plantio e manejo da arborização urbana visando a mitigação de emissões de gases de efeito estufa. A seleção de espécies para projetos de arborização urbana deve equilibrar o rápido crescimento e a capacidade de sequestro de C no curto prazo das espécies pioneiras com o potencial das espécies não pioneiras de contribuir para a biodiversidade e o sequestro de C no longo prazo.

Palavras-chave: incremento anual em carbono; florestas urbanas; grupos ecológicos; biomassa.

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ABSTRACT
The growth and carbon (C) sequestration capacity of native trees depend on environmental factors and the intrinsic characteristics of each species. In urban environments, there is a gap in the comparative understanding of the potential for growth and C sequestration between pioneer and non-pioneer tree species. Therefore, the objective of this study was to assess the growth and C accumulation in the aboveground biomass of pioneer and non-pioneer tree species native to the Atlantic Forest used in urban afforestation. The study was conducted in the afforestation of the Nova Venécia Campus of the Federal Institute of Espírito Santo, considering eight native tree species equally distributed between pioneer and non-pioneer groups. Using forest inventory data, the average annual increments in diameter (AAI_{DBH}), height (AAI_H), and C (AAI_C) were calculated and compared between ecological groups and species. The pioneer group exhibited higher AAI_{DBH} and AAI_C, but no significant difference was found between groups for AAI_H. Among species, AAI_{DBH}, AAI_H, and AAI_C varied considerably, with the pioneer species *Cenostigma pluviosum*, *Enterolobium contortisiliquum*, and *Schizolobium parahyba* showing great potential in storing C in aboveground biomass. Given the interspecific variation, intrinsic characteristics must be considered when selecting species to maximize C sequestration in urban environments. The results of this study highlight the influence of ecological group and the individual characteristics of species on C sequestration and can guide urban afforestation planting and management strategies aimed at mitigating greenhouse gas emissions. Species selection for urban afforestation projects should balance the rapid growth and short-term C sequestration capacity of pioneer species with the potential of non-pioneer species to contribute to biodiversity and long-term C sequestration.
Keywords: annual carbon increment; urban forests; ecological groups; biomass.

Introduction

The increase in greenhouse gas (GHG) concentrations in the atmosphere, particularly carbon dioxide (CO_2), has led to considerable changes in the global climate in recent decades. These changes include an increase in the frequency and intensity of extreme weather events, resulting in various environmental, economic, and social consequences (IPCC 2023). Numerous efforts have been made at national and global levels to reduce GHG emissions (Filonchyk et al. 2024). In parallel with emissions reduction, carbon (C) removal from the atmosphere is essential to achieving the targets set to limit global temperature rise (IPCC 2023; Morais Junior et al. 2024).

Forest ecosystems contribute to C removal by sequestering atmospheric CO_2 through the photosynthetic process and storing it in biomass and soil (Mendes et al. 2024; Nzabarinda et al. 2025). Notably, among Brazilian biomes, the Atlantic Forest stands out as a global biodiversity hotspot and an important C sink, exhibiting high C storage potential even under intense fragmentation (Milagre at al. 2024; Santana et al. 2025). In this context, one of the primary benefits of trees in urban environments is their ability to capture and store C, thereby helping to reduce atmospheric CO_2 levels (Brilli et al. 2022; Milagre et al. 2023). In addition to their C sequestration capacity, green areas contribute to improving urban quality of life by promoting thermal comfort, reducing air pollution, and conserving biodiversity (Ferreira et al. 2024; Soares et al. 2023; Souza et al. 2025).

The use of native forest species in urban afforestation contributes to the development of more resilient urban spaces and can reduce maintenance needs (Almas & Conway 2016). However, when native species are introduced into urban environments, they undergo morphological and physiological changes due to adverse conditions such as soil characteristics and limited growth space (Kulchetscki et al. 2006). The selection of native species for urban tree planting includes both pioneer and non-pioneer species (Santos et al. 2023). In natural ecosystems, these ecological groups play distinct roles. Pioneer species dominate the initial stage of ecological succession, promoting canopy closure, which creates favorable conditions for shade-tolerant species to develop. Non-pioneer species (secondary and climax species) tend to establish themselves later, taking advantage of the conditions created by pioneers, growing more slowly but contributing to the development of a more complex forest structure (Chazdon et al. 2010; Oliveira et al. 2023).

The selection of species to be planted is key for the C sequestration efficiency in urban green spaces. Different growth rates among species directly influence biomass accumulation, making it essential to consider this variability when planning urban afforestation (Zhao et al. 2023). Studies have shown that the biomass of urban trees can vary significantly among species, affecting the amount of C sequestered (Nowak & Crane 2002;

Sharma et al. 2020). Factors such as adult height, longevity, and growth rate directly impact C sequestration and storage in tree biomass (Nowak et al. 2002). Fast-growing species generally accumulate more biomass in urban areas than slow-growing species (Lind et al. 2023).

Previous research has explored the role of trees in C storage in different cities worldwide (Bherwani et al. 2022; Lind et al. 2023), but there remains a gap in the comparative understanding of the C sequestration potential of pioneer and non-pioneer species in urban environments. Therefore, understanding variations in C accumulation between pioneer and non-pioneer tree species can provide important information for the planning and management of urban afforestation. Therefore, this study aimed to assess the growth and C accumulation in the aboveground biomass of pioneer and non-pioneer tree species native to the Atlantic Forest used in urban afforestation.

Methodology

Study area

The study was conducted in an urban environment, using tree species from the afforestation of the Nova Venécia Campus of the Federal Institute of Education, Science, and Technology of Espírito Santo (Ifes) (Figure 1). Inaugurated in 2008, the Nova Venécia Campus is one of the 23 campuses of Ifes and is located in the urban area of the municipality of Nova Venécia, in the northwestern region of the Espírito Santo state (ES), Brazil.

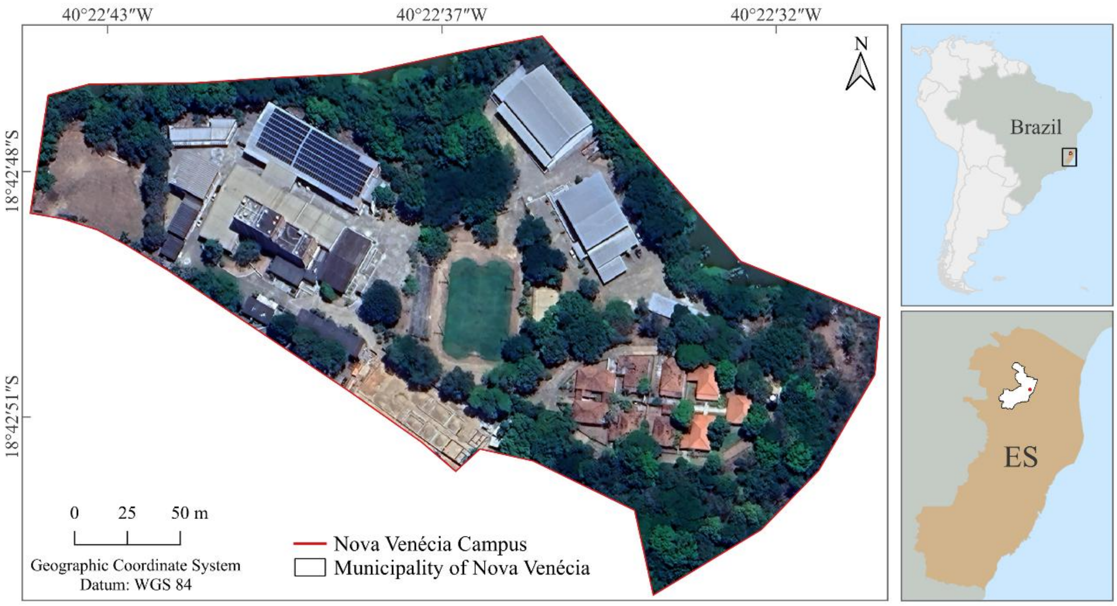

Figure 1 - Location of the Nova Venécia Campus of the Federal Institute of Education, Science, and Technology of Espírito Santo (Ifes), highlighting its afforestation. Source: Authors (2025).

The climate of Nova Venécia is classified by Köppen as Aw (tropical with a dry winter), with an average annual temperature of 23.1ºC and an annual precipitation of 1,255 mm (Alvares et al. 2013). The region belongs to the Atlantic Forest domain and is characterized by Dense Ombrophilous Forest vegetation, mainly represented by small forest fragments (Mendes et al. 2022). The campus topography is predominantly flat, with slight slopes near the Cricaré River. According to Cunha et al. (2016), the predominant soil type is Yellow Latosol.

The campus covers an area of 5.66 hectares along the banks of the Cricaré River, approximately 58% of which consists of green spaces. The tree-covered areas of the campus host both native and exotic tree species. This vegetation comprises trees planted by the Ifes administration, individuals present before the institution's establishment, and naturally regenerated trees.

Tree inventory

A tree census was conducted in November 2020 to assess the urban afforestation of the Nova Venecia Campus of Ifes. All tree individuals with a diameter at breast height (DBH) of at least 2.5 cm at 1.30 m above ground level were identified and measured. The 2.5 cm threshold was adopted to include a broader range of individuals compared to the commonly used 5 cm. It also excludes very small stems (< 2.5 cm), which may reduce the accuracy of C estimates. Species identification was conducted *in situ*, and for unidentified species, plant material was collected for further identification using specialized literature, virtual herbaria, and consultations with dendrology experts.

For each individual, DBH and total height (H) were measured using a diameter tape and a digital clinometer, respectively. The average annual increment in DBH (AAI_{DBH}, in cm individual^{-1} year^{-1}) and the average annual increment in height (AAI_H, in m individual^{-1} year^{-1}) were calculated based on DBH, H, and tree age. Tree age was determined using planting records, sequential satellite imagery (Google Earth Pro software), and annual volume increment values from literature.

The H and DBH data were used to estimate aboveground biomass C stock (E, in kg C) using the mathematical model fitted by Brianezi et al. (2013) (Equation 1). The model fitted by the authors was based on the model of Schumacher and Hall (1933) and selected for this study because it was successfully used for native urban tree species in the Atlantic Forest biome (Brianezi et al. 2013). Based on the C stock values and tree age, the average annual increment in C (AAI_C, in kg C individual^{-1} year^{-1}) was calculated.

$$\ln E = -0.906586+1.60421*\ln DBH+0.37162*\ln H \quad (1)$$

where:
ln = naperian logarithm
E = aboveground biomass C stock (kg C)
DBH = diameter at 1.30 m above ground level (cm)
H = total height (m)

For this study, eight native tree species from the Atlantic Forest with at least seven individuals in the campus afforestation were selected (Table 1). Of these, four species were classified as pioneer and four as non-pioneer (Barbosa et al. 2017). The selected pioneer species were *Cenostigma pluviosum* (DC.) Gagnon & G.P.Lewis, *Enterolobium contortisiliquum* (Vell.) Morong, *Schinus terebinthifolia* Raddi, and *Schizolobium parahyba* (Vell.) Blake. The selected non-pioneer species were *Byrsonima sericea* DC., *Handroanthus impetiginosus* (Mart. ex DC.) Mattos, *Inga laurina* (Sw.) Willd., and *Zeyheria tuberculosa* (Vell.) Bureau ex Verl..

Table 1 - Pioneer and non-pioneer tree species selected for the study.

Group	Scientific name	Common name	Acronym	No. of individuals
Pioneer	*Cenostigma pluviosum*	Sibipiruna	CP	17
	Enterolobium contortisiliquum	Timbaúva	EC	20
	Schinus terebinthifolia	Aroeira-vermelha	ST	12
	Schizolobium parahyba	Guapuruvu	SP	10
Non-Pioneer	*Byrsonima sericea*	Murici	BS	8
	Handroanthus impetiginosus	Ipê-roxo	HI	30
	Inga laurina	Ingá-branco	IL	14
	Zeyheria tuberculosa	Ipê-felpudo	ZT	7

Source: Barbosa et al. (2017) and Authors (2025).

Statistical analysis

The statistical analysis was performed using R software, version 4.2.1 (R Development Core Team 2022). Initially, the AAI_{DBH}, $AAI_{H,}$ and AAI_{C} data were subjected to the Shapiro-Wilk and Bartlett tests to verify error normality and homogeneity of variances, respectively. Since the data did not meet the assumptions of normality and homogeneity, nonparametric tests were applied. The two species groups (pioneer and non-pioneer) were compared based on their AAI_{DBH}, AAI_{H}, and AAI_{C} values using the Mann-Whitney U test at a 5% significance level. For species comparisons, AAI_{DBH}, AAI_{H}, and AAI_{C} values were analyzed using the Kruskal-Wallis test at a 5% significance level, followed by Dunn's test with a Bonferroni correction. A Spearman correlation at a 5% significance level was conducted to assess relationships between AAI_{DBH}, AAI_{H}, and AAI_{C}. The R packages ExpDes.pt, rstatix, and ggcorrplot were used for normality and homogeneity assumption tests, nonparametric analyses, and Spearman correlation, respectively.

Results

In the green areas of the Nova Venécia Campus of Ifes, 390 individual trees from 72 native and exotic species were recorded, with a density of approximately 119 trees per hectare. The eight native species selected for this study represented about 11% of the species and 30% of the total individuals with a DBH greater than 2.5 cm inventoried on campus. The average age of individuals from the selected species was 10.7 years.

The pioneer species group exhibited statistically higher AAI_{DBH} than the non-pioneer species group ($p < 0.0001$) (Figure 2A). The pioneer species *E. contortisiliquum* and *S. parahyba* stood out with the highest diameter increments (Figure 2B). The AAI_{DBH} values of these two species differed statistically only from the pioneer species *C. pluviosum* ($p = 0.0036$ for *E. contortisiliquum* and $p = 0.0496$ for *S. parahyba*) and the non-pioneer species *H. impetiginosus* ($p < 0.0001$ for *E. contortisiliquum* and $p = 0.0002$ for *S. parahyba*). No other species comparisons showed statistical differences in AAI_{DBH} values.

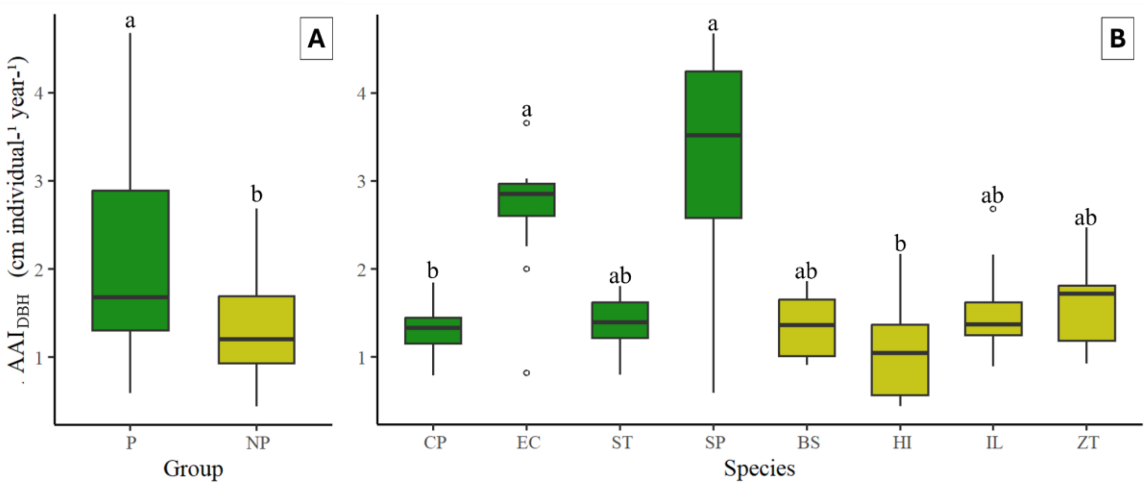

Figure 2 - Average annual increment in DBH (AAI_{DBH}, in cm individual^{-1} year^{-1}) for species groups (A) and species (B) in urban afforestation. Different lowercase letters indicate significant differences between groups (Mann-Whitney U test, $p < 0.05$) and species (Dunn's test, $p < 0.05$). P = pioneer species, NP = non-pioneer species, CP = *Cenostigma pluviosum*, EC = *Enterolobium contortisiliquum*, ST = *Schinus terebinthifolia*, SP = *Schizolobium parahyba*, BS = *Byrsonima sericea*, HI = *Handroanthus impetiginosus*, IL = *Inga laurina*, ZT = *Zeyheria tuberculosa*. Source: Authors (2025)

There was no significant difference between groups in terms of AAI_H (Figure 3A). However, significant differences were observed for this variable among species, with *S. parahyba* standing out with the highest AAI_H values (Figure 3B). A statistically significant difference was found between *S. parahyba* and *C. pluviosum* ($p < 0.0001$), as well as between *S. parahyba* and *H. impetiginosus* ($p = 0.0184$). Contrary to expectations, the pioneer species *C. pluviosum* exhibited a statistically lower AAI_H compared to the other species, except for the non-pioneer species *I. laurina* ($p = 0.1800$). No other species comparisons showed statistical differences for AAI_H values.

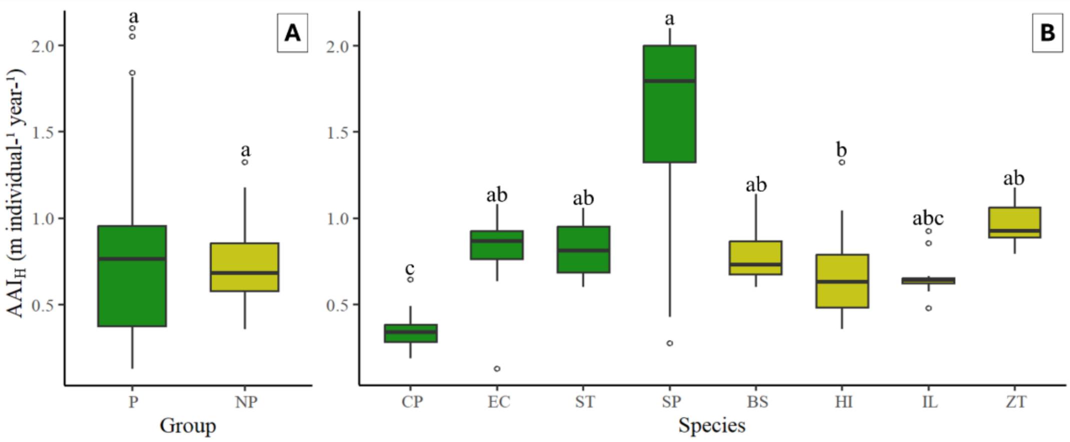

Figure 3 - Average annual increment in height (AAI_H, in m individual^{-1} year^{-1}) for species groups (A) and species (B) in urban afforestation. Different lowercase letters indicate significant differences between groups (Mann-Whitney U test, $p < 0.05$) and species (Dunn's test, $p < 0.05$). P = pioneer species, NP = non-pioneer species, CP = *Cenostigma pluviosum*, EC = *Enterolobium contortisiliquum*, ST = *Schinus terebinthifolia*, SP = *Schizolobium parahyba*, BS = *Byrsonima sericea*, HI = *Handroanthus impetiginosus*, IL = *Inga laurina*, ZT = *Zeyheria tuberculosa*. Source: Authors (2025)

The pioneer species group exhibited a statistically higher AAI_C than the non-pioneer species group ($p < 0.0001$) (Figure 4A). The species *C. pluviosum* showed significant differences when compared with *H. impetiginosus* ($p < 0.0001$), *I. laurina* ($p < 0.01$), and *Z. tuberculosa* ($p < 0.01$) (Figure 4B). The species *E. contortisiliquum* also exhibited significant differences compared to *H. impetiginosus* ($p < 0.0001$), *I. laurina* ($p =$

0.0045), and *Z. tuberculosa* (p = 0.0181). The species *S. parahyba* showed significant differences compared to *H. impetiginosus* (p < 0.0001) and *I. laurina* (p = 0.0235). The comparison between *S. parahyba* and *Z. tuberculosa* indicated a non-significant trend, with the p-value near the significance threshold (p = 0.0563). A similar result was observed between *S. terebinthifolia* and *H. impetiginosus*, with a p-value also close to the significance threshold (p = 0.0609).

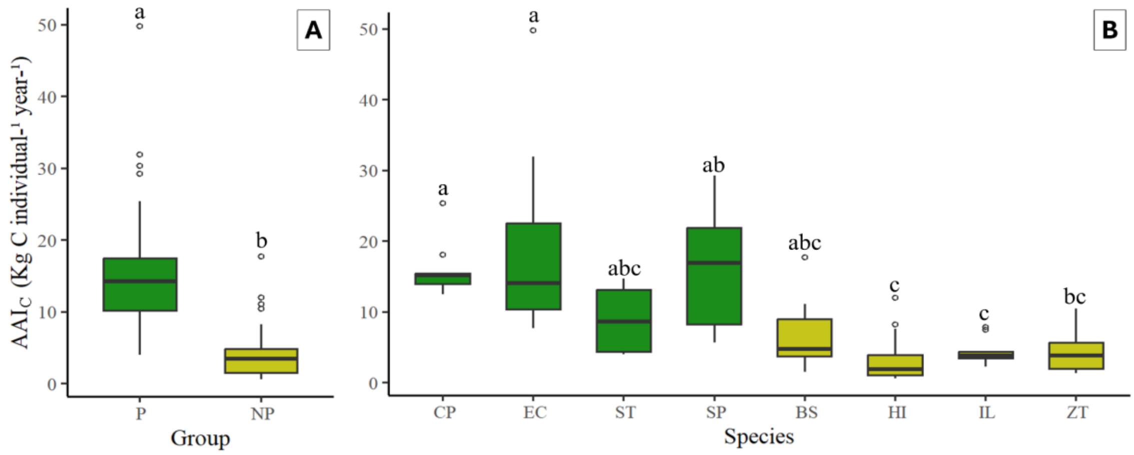

Figure 4 - Average annual increment in carbon (AAI_C, in Kg C individual^{-1} year^{-1}) for species groups (A) and species (B) in urban afforestation. Different lowercase letters indicate significant differences between groups (Mann-Whitney U test, p < 0.05) and species (Dunn's test, p < 0.05). P = pioneer species, NP = non-pioneer species, CP = *Cenostigma pluviosum*, EC = *Enterolobium contortisiliquum*, ST = *Schinus terebinthifolia*, SP = *Schizolobium parahyba*, BS = *Byrsonima sericea*, HI = *Handroanthus impetiginosus*, IL = *Inga laurina*, ZT = *Zeyheria tuberculosa*. Source: Authors (2025)

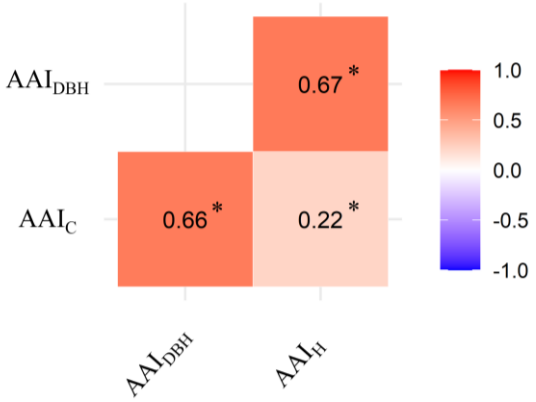

Figure 5 - Spearman correlation for growth and carbon accumulation variables. Asterisk (*) indicates a significant difference (p < 0.05). AAI_{DBH} = average annual increment in DBH, AAI_H = average annual increment in height, AAI_C = average annual increment in carbon. Source: Authors (2025)

Discussion

The differences in ecological strategies between pioneer and non-pioneer species were reflected in the growth patterns and C accumulation observed in the urban afforestation at the Nova Venécia Campus of Ifes. The higher AAI_{DBH} and AAI_C in the pioneer species group (Figures 2 and 4) are associated with the faster growth rate of these species during the early years after planting. Pioneer species, characterized by rapid growth and shorter longevity, accumulate more biomass in a shorter period, whereas non-pioneer species accumulate biomass at a slower rate over their life cycle (Shimamoto et al. 2014). Thus, pioneer species of the Atlantic Forest contribute more to C stock in the early years after planting, while non-pioneer species have a greater impact in the long term (Oliveira et al. 2023; Shimamoto et al. 2014). In the present study, the evaluated species had an average age of 10.7 years, a period in which C accumulation is still more pronounced in pioneer species.

The pioneer species *C. pluviosum*, *E. contortisiliquum*, and *S. parahyba* stood out for their high AAI_C values (averaging around 14.3 kg C individual^{-1} year^{-1}). Studies have demonstrated the potential of these species to store C in aboveground biomass due to their high photosynthetic rates and rapid growth (Lisboa et al. 2024; Paula et al. 2022; Rodrigues-Leite et al. 2024; Souza et al. 2020). Although smaller pioneer species like *S. terebinthifolia* accumulate less C, they are highly relevant in urban tree planting. Besides contributing to urban biodiversity, their small to medium size allows them to be planted in areas with limited space.

The lower C accumulation in the non-pioneer species group, especially *H. impetiginosus*, *I. laurina*, and *Z. tuberculosa* (Figure 4), is consistent with the literature, which indicates that these species tend to grow more slowly and contribute more significantly to C storage in later stages of development (Oliveira et al. 2023; Shimamoto et al. 2014). Planting native non-pioneer tree seedlings in urban areas is essential for diversifying species and enhancing ecosystem services (Hardberger et al. 2025). Additionally, these species with longer life cycles generally exhibit greater efficiency in resource use and higher tolerance to environmental stresses (Paula et al. 2022), reducing the need for maintenance and replacement of individuals in urban afforestation.

In contrast to this study, *H. impetiginosus* exhibited the highest annual growth among native pioneer species (*Inga vera*, *Peltophorum dubium*, *Cordia superba*, and *Senna multijuga*) and non-pioneer species (*Inga edulis*, *Pterocarpus violaceus*, *Jacaranda cuspidifolia*, and *Stifftia chrysantha*) of the Atlantic Forest planted in the urban area of Lavras, Minas Gerais, southeastern Brazil. Over a five-year period, *H. impetiginosus* reached average values of 8.7 m in height (AAI_H = 1.74 m individual^{-1} year^{-1}) and 32.0 cm in DBH (AAI_{DBH} = 6.4 cm individual^{-1} year^{-1}) (Paiva et al. 2022). *H. impetiginosus* also showed significant potential for C accumulation (1.3 t C individual^{-1}) in urban squares in Ceará (northeastern Brazil), but this value is much lower than that of the pioneer species *E. contortisiliquum* (8.6 t C individual^{-1}), which exhibited the largest diameter and C stock among the native species evaluated (Lisboa et al. 2024). On the other hand, the initial height growth of *H. impetiginosus* in riparian forest restoration areas in the Cerrado (AAI_H = 0.2 m individual^{-1} year^{-1}) was the lowest among native species, including non-pioneer species like *I. laurina* (AAI_H = 0.7 m individual^{-1} year^{-1}) (Lima et al. 2016).

Tree growth is influenced by a range of biotic and abiotic factors acting both above and below ground (Gull et al. 2019). Besides differences in growth and C accumulation between distinct species, variations may also occur among individuals of the same species due to environmental factors. For example, *C. pluviosum* trees showed variations in growth and CO_2 removal capacity depending on soil conditions and microclimate in urban environments of São Paulo, southeastern Brazil (Rodrigues-Leite et al. 2024). The authors noted that the growth of this species was greater in soils with better moisture conditions. Moreover, management practices such as fertilization and weed control can also enhance C sequestration in native tree plantations (Ferez et al. 2015).

The absence of a significant difference in AAI_H between the ecological groups evaluated (Figure 3) was unexpected, as previous studies in forest restoration areas indicated greater height growth for pioneer species in the early years after planting (Morais Junior et al. 2020; Oliveira et al. 2023). Correlations between growth variables and C accumulation showed that trunk diameter growth had a greater influence on C accumulation in aboveground biomass compared to height growth (Figure 5). In fact, DBH is commonly used in mathematical models to estimate C accumulation in forest species due to its strong relationship with tree volume and biomass, as well as its greater ease of measurement in tree inventories. However, although accurate estimates can be obtained using DBH alone, combining DBH and height in mathematical models can yield even more accurate results for biomass and C in Atlantic Forest species (Gaui et al. 2024).

Studies emphasize the need to carefully select species that are appropriate for each urban context, considering not only growth characteristics but also environmental quality benefits (Conway & Vecht 2015;

Nowak et al. 2002; Ornelas et al. 2023; Shaamala et al. 2024). Among the species analyzed in this study, the pioneer species *C. pluviosum*, *E. contortisiliquum*, and *S. parahyba* demonstrated great potential for maximizing C sequestration in urban environments. Non-pioneer species, in contrast, exhibited more uniform growth, likely due to their biomass allocation strategy over time (Shimamoto et al. 2014). These distinct behaviors between ecological groups highlight the importance of using both pioneer and non-pioneer species in urban afforestation projects, ensuring benefits for C sequestration and other ecosystem services in both the short and long term.

The selection of species in this study was constrained by the availability of at least seven individuals per species, a criterion adopted to ensure minimum sample representativeness and the feasibility of comparative analyses among species. As a result, the analysis was limited to eight species, which reduces the taxonomic breadth of the study and may limit the generalization of the findings to other urban afforestation contexts. Due to the impossibility of applying destructive methods, C increment estimates were obtained using allometric equation from literature. This approach introduces uncertainties associated with the use of indirect models and the adaptation of these equations to local growth conditions. In addition, the study was conducted in a single urban environment, which should also be considered when interpreting the results, given site-specific conditions and management practices.

Conclusion

The results of this study demonstrate the influence of ecological group and individual species characteristics on tree growth and C accumulation in urban areas. Pioneer species exhibited higher diameter growth and biomass accumulation rates, underscoring their importance in C capture during the early stages of urban tree planting. However, the variation in species performance highlights the need to consider both environmental factors and intrinsic characteristics when selecting species for urban planning. The absence of significant differences among non-pioneer species for the variables analyzed suggests a more uniform growth pattern in this group, likely associated with their long-term biomass allocation strategy. Thus, species selection for urban afforestation projects should balance the rapid growth and short-term C sequestration capacity of pioneer species with the potential of non-pioneer species to contribute to biodiversity and long-term C sequestration.

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