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EVALUATION OF AGROFORESTRY SYSTEMS AS ALTERNATIVES FOR TIMBER PRODUCTION AND CARBON STORAGE[1]

AVALIAÇÃO DE SISTEMAS AGROFLORESTAIS COMO OPÇÕES DE PRODUÇÃO DE MADEIRA E ESTOQUE DE CARBONO[1]

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ABSTRACT - In Agrossilvipastoril systems trees are cultivated together with agricultural crops or animals, aiming at multiple uses therefore constituting a viable option for better soil use. Thus, reversing the processes of degradation of natural resources, to increase the availability of wood, food and environmental services and emerging as a sustainable alternative to the currently used wood production systems. Here we investigate the effect of the Silvi-agricultural and Silvi-pastoral systems on dendrometric data, mean annual increment (MAI), CO_2 sequestration, wood density and anatomical features of *Croton floribundus* and *Guazuma ulmifolia* trees. The highest values of DBH (1.3 m from the ground), tree volume, volume per ha and MAI were observed in the silvi-agricultural system. Among the systems, *C. floribundus* presented higher values compared to *G. ulmifolia* in the silvi-agricultural system. While in the silvi-pastoral system, greater DBH and consequently greater volume of trees, volume per ha and MAI occurred in *G. ulmifolia* when compared to *C. floribundus*. CO_2 sequestration values corroborated the MAI, with higher values in the silvi-agricultural system. Wood properties are affected in part by the type of system. *C. floribundus* has lower wood density values and higher vessel element length values, regardless of the management system, and the reverse occurs for *G. ulmifolia*. In this study, we demonstrated that integrating short-cycle crop cultivation with timber tree production is a feasible approach, which not only enhances carbon storage but also aligns with Environmental, Social, and Governance (ESG) criteria. These findings highlight that agroforestry systems not only enhance timber production but also diversify farmers' income streams and make a significant contribution to carbon sequestration, establishing themselves as a sustainable and economically viable land management solution.

Keywords: Forest management; Wood properties; Mean annual increment; CO_2 sequestration.

RESUMO - Nos sistemas agrossilvipastoris, as árvores são cultivadas junto com culturas agrícolas ou animais, visando múltiplos usos, constituindo, portanto, uma opção viável para melhor uso do solo. Assim, esses sistemas revertem os processos de degradação dos recursos naturais, aumentam a disponibilidade de madeira, alimentos e serviços ambientais, surgindo como uma alternativa sustentável aos sistemas de produção de madeira atualmente utilizados. Investigamos o efeito dos sistemas silviagrícola e silvipastoril sobre dados dendrométricos, incremento médio anual (IMA), sequestro de CO_2, densidade da madeira e características anatômicas das árvores de *Croton floribundus* e *Guazuma ulmifolia*. Os maiores valores de DAP (1,3 m do solo), volume de árvores, volume por hectare e IMA foram observados no sistema silviagrícola. Entre os sistemas, *C. floribundus* apresentou valores superiores em comparação com *G. ulmifolia* no sistema silviagrícola. No sistema silvipastoril, maiores DAP e, consequentemente, maior volume de árvores, volume por hectare e IMA ocorreram em *G. ulmifolia* quando comparado a *C. floribundus*. Os valores de sequestro de CO_2 corroboraram com o IMA, com maiores valores no sistema silviagrícola. As propriedades da madeira são afetadas em parte pelo tipo de sistema. *C. floribundus* apresenta valores mais baixos de densidade da madeira e maiores valores de comprimento dos elementos do vaso, independentemente do sistema de manejo, e o inverso ocorre para *G. ulmifolia*. Além disso, demonstramos que é possível combinar o plantio de culturas de ciclo curto com a produção de árvores para madeira, ao mesmo tempo em que aumentamos o estoque de carbono e nos alinhamos aos critérios Ambientais, Sociais e de Governança (ESG). Essas descobertas destacam que os sistemas agroflorestais não apenas aumentam a produção de madeira, mas

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também diversificam os fluxos de renda dos produtores e contribuem significativamente para o sequestro de carbono, posicionando-se como uma solução sustentável e economicamente viável para a gestão de terras.

Palavras-chave: Manejo florestal; Propriedades da madeira; Incremento médio anual; Sequestro de CO_2.

1 INTRODUCTION

The Agrossilvipastoril systems encompass all production areas available in the integration, strategically uniting farming, livestock, and the forest. Integration systems provide considerable productive gains with low impact on the environment in which they are inserted, helping to maintain good soil conditions and environmental sustainability (Sousa et al. 2022). These systems aim at the joint development of all factors involved, according to spatial and temporal arrangements and with significant ecological and economic interactions between the components of the system using a scientific basis (Tsukamoto Filho and Medeiros 2022). Synergies are found between ecosystem services, such as livestock, wood production, and carbon sequestration targets. Such actions can support decision-making processes for the management of sustainable and multifunctional systems (Lecegui et al. 2022; Minini et al. 2024). Additionally, in the agroforestry systems there are co-benefits to bee populations for crop pollination services (Image et al. 2023). While in livestock systems, trees can provide thermal comfort for animals during warm days (Teixeira et al. 2022).

In this context, it is essential to identify combinations of tree crops associated with fast-cycling species, to transform low-input agriculture into land units with high economic returns, increasing the carbon storage capacity, nutrients, and acting to remedy environmental and social difficulties in achieving sustainable development goals (Verma et al. 2023). The correct choice of woody species and crop varieties that will make up the systems is essential, especially those adapted to the growing region and the competition promoted by the consortium (Alves et al. 2022).

There are some slightly different nomenclatures in the literature to designate ways of land-use and land-management, in which trees are used together with crops or animals in the same location. In this paper, we agree with the existing silvi-agricultural nomenclature to designate the planting of trees with agricultural crops, and with the existing silvi-pastoral nomenclature to designate the planting of trees combined animals and management of pastures.

Silvi-agricultural (agroforestry) systems can be defined as the cultivation of trees together with agricultural crops in the same unit of area. It aims at the joint development of all the factors involved, according to spatial and temporal arrangements and with significant ecological and economic interactions between the components of the system, and the scientific basis (Tsukamoto Filho and Medeiros 2022).

Silvi-pastoral involves trees plus animals. The forest species used in these systems usually aim to bring thermal comfort to the animals, provide environmental services such as soil improvements, and in addition, supply rural properties with their timber needs. However, other uses could be given to these woods, thus expanding the supply of products on the market, which would provide added value to the species in these consortium arrangements (Oliveira et al. 2020).

To foster interest in the implementation of agroforestry systems based on the analysis of wood quality and to promote more efficient and sustainable end use, it is recommended to evaluate the species' anatomical variables, as they are strongly correlated with the wood's physical properties (Eloy et al. 2014).

In designing the present study, in addition to including some of the agricultural crops, which contribute to the basis of human and animal nutrition in the many countries of the world (*Sorghum bicolor* (L.) Moench, *Zea mays* L., *Cajanus cajan* (L.) Millsp and *Avena strigose* Schreb). The research evaluated two agroforestry systems: silvi-agricultural and silvi-pastoral, focusing on young plants of *Croton floribundus* Spreng (Euphorbiaceae family) and *Guazuma ulmifolia* Lam. (Sterculiaceae family). *C. floribundus* is a pioneer species, invasive in grasslands, known for its resilience to environmental changes. In contrast, *G. ulmifolia* is an early secondary or climax species that requires light and thrives in open environments such as logged forests and degraded areas. In the sequel, we hypothesized that planting systems interfere with the silvicultural data and mean annual increment, CO_2 sequestration, wood density, anatomical features in the two tree species. To test this hypothesis, the specific objectives of this study were: 1) Determine diameter at breast high, tree heigh, volume, volume/ha, mean annual increment; 2) Estimate the amount of carbon fixed and sequestered in the two woody species; 3) Determine anatomical features and wood density in the silvi-agricultural and silvi-pastoral systems. The key contribution and novelty of this study, relies in demonstrating that the use of multiple systems can provide a synergy of financial gain for the producer. This is an important management outcome because, it is possible to combine fast-growing species, animals, forages, and woody tree species, with a long-term production cycle, and ecosystem services with distinct financial resources, earned over decades.

2 MATERIAL AND METHODS

2.1 Description of study area

This study was conducted at Embrapa Pecuária Sudeste, São Carlos, SP (21° 57'S, 47° 50'W, elevation 860 m) (Figure 1). The region's climate is classified as Cwa-Awa (Köppen), with an average annual temperature of 21.2°C, an average annual rainfall of 1,435 mm and an average annual relative humidity of 75.6%, The relief is smooth, with slopes of 3% to 5% (Alvares et al. 2013).

Figure 1. Location of the Silvi-agricultural and Silvi-pastoral systems in the Embrapa Pecuária Sudeste, São Carlos, São Paulo State, and overview of Silvi-pastoral systems.

Figura 1. Localização dos sistemas Silviagrícolas e Silvipastoris na Embrapa Pecuária Sudeste, São Carlos, Estado de São Paulo, e visão geral dos sistemas Silvipastoris.

2.2 General experimental design of systems

In both studies, seedlings of the tree species were obtained from a local commercial nursery. These seeldings were produced from seeds collected from several matrix trees within an approximate radius of 150 kilometers from the nursery (Souza Junior and Bernardo 2006). The seedlings were considered suitable for planting in the field when they reached a size of 20 cm to 40 cm for 290 mL tubes, with a well-formed root system. The tree planting lines were subsoiled, and 30 cm deep furrows were opened with a sugarcane furrower.

The choice of tree species was due to adaptation to local conditions, rapid development, ability to fix nitrogen, provision of resources for fauna and timber production (Nicodemo et al. 2010). The forest species planted in the central line, randomly, were *Anadenanthera colubrina* (Vell.) Brenan, *Peltophorum dubium* (Spreng.) Taub., *Zeyheria tuberculosa* (Vell.) Bureau & K.Schum., *Cariniana estrellensis* (Raddi) Kuntze, *Piptadenia gonoacantha* (Mart.) J.F.Macbr., and for the staking of these species, to obtain larger stems, *C. floribundus* and *G. ulmifolia* were planted alternatingly in the marginal lines. All trees were fertilized for the first eighteen months. Cultural treatments involved combating leaf-cutter ants, mowing the grass, and crowning the seedlings. In the present study, we investigated *C. floribundus* and *G. ulmifolia*, as they were the species selected for thinning.

2.3 Silvi-agricultural system

The area was formed by *Brachiaria decumbens* Stapf (*Urochloa decumbens*) in a Red Yellow Oxisol (Embrapa 1999). The agroforestry system was implemented with five strips of trees interspersed with annual agricultural crops. The strips of trees were planted in three lines, following the level of the land and with a distance between trees of 2.5 m x 2.5 m, resulting in 600 trees ha^{-1}. The seventeen meters between the tree strips were planted with annual crops.

For the planting of agricultural crops, conventional soil preparation was carried out since implementation. Liming and fertilization were supported by annual soil analyses. The following agricultural crops followed: *Sorghum bicolor* (forage sorghum), fertilized with NPK 8-28-16, 500 $kg.ha^{-1}$ + zinc sulfate, 20 $kg.ha^{-1}$ + dolomitic limestone, 3.3 $t.ha^{-1}$ and NPK 25-00-25, 400 $kg.ha^{-1}$. Conducting sorghum regrowth, without fertilization, incorporated into the soil; cutoff: *Zea mays* (forage corn); soil amended with dolomitic limestone, 1.5 $t.ha^{-1}$, NPK 8-28-46 + Zn, 350 $kg.ha^{-1}$) and NPK 20-05-20+0.6%S, 400 $kg.ha^{-1}$. *Cajanus cajan* (L.) Millsp. (guandu-fava-larga); fertilized with simple superphosphate, 200 kg/ha + 50 kg of potassium chloride/ha. Forage sorghum, fertilized with NPK 10-20-20, 300 $kg.ha^{-1}$ and NPK 20-05-20+6% Zn, 500 kg/ha. Forage corn, soil correction with dolomitic limestone, 2.5 $t.ha^{-1}$; NPK 10-1-10 470 $kg.ha^{-1}$ and NPK 25-0-25, 500 $kg.ha^{-1}$. The pruning of *C. floribundus* and *G. ulmifolia* with the aim of controlling the established competition. The criteria for pruning were the conservation of at least 50% of the green crown, removing branches below the point where the trunk was 6 to 8 cm in diameter. After pruning, *Avena strigosa* (black oat) was planted at a depth of 2-3 cm, with a spacing of 20 cm between rows. The sowing density was 60-65 seeds/linear m, with a density of 55 kg of $seeds.ha^{-1}$. The oats received fertilization with 300 kg 8-28-16/ha at planting and 100 kg ammonium sulfate/ha as top dressing. Tree pruning was not enough to control the drop in agricultural production caused by competition with trees, justifying the recommendation for thinning to maintain agricultural productivity. Thinning was carried out (trees with 55 months, 4 and a half years). This initial study on the quality of the wood produced is part of the monitoring of the first 5 years of the implemented system.

2.4 Silvi-pastoral systems

The experimental area was formed by *Brachiaria decumbens* Stapf in a Dark Red Oxisol (Embrapa 1997) of medium texture. The trees were planted in three lines, following the level of the land and with a distance between trees of 2.5 m x 2.5 m, resulting in around 600 trees/ha. Thirty (30) g of dolomitic limestone, 100 g of NPK 8-28-16 and 10 g of FTE BR12 were applied to the tree holes at planting. The seedlings were planted with 2 g of soil conditioner dissolved in 500 mL of water per hole, to minimize the need for irrigation in case of summer. Glyphosate was applied to desiccate the grass 15 days before planting the seedlings in the pasture strips and 4,519 tree seedlings were planted. The cultural treatments involved combating leaf-cutter ants, mowing the grass in the tree strips, and crowning the seedlings, to minimize competition from invaders, all trees received 100 g of NPK 08-28-16 in the crown. Annually pastures of *Brachiaria decumbens* cv. *marandu*, planted between strips of trees, receives maintenance fertilizer. The thinning operation carried out in this system aimed to enhance the growth of the remaining trees, increase light penetration into the pasture area, and control excessive shading, while also assessing the quality of the wood produced in the early years.

2.5 Sampling

For wood evaluation in two systems, 20 trees with 4 and a half years were collected, five trees of *C. floribundus* and five of *G. ulmifolia* managed by the silvi-agricultural system and 5 trees of *C. floribundus* and 5 of *G. ulmifolia* managed by the by the silvi-pastoral system.

2.5.1 Silvicultural data and mean annual increment

The diameter was measured with a caliper, and the height was measured with a hypsometer Vertex IV. Tree volumes were calculated using the DBH (1.3 m from the ground) and height values. Then, the volume per hectare was calculated according to the spacing (2.5 m x 2.5 m), by multiplying the number of plants by the average tree volume, and finally, the volume per hectare per year was calculated by dividing volume per hectare by the age of the plantation (4 and a half years).

2.5.2 Wood sampling and analyses

From each tree, a 7 cm thick disk was collected in the DBH region (diameter at breast height; 1.30 m from the ground). From each disk, three samples were taken representing the positions (pith, intermediate and bark), pith-bark direction corresponding to the log radius, from which the specific specimens for wood evaluation were removed to determination of wood properties.

Basic density was determined by the method of maximum moisture content, where samples of 2 cm x 2 cm x 3 cm were saturated by treatment with a vacuum system for 72 h to obtain saturated volume of wood. In sequence, the samples were dried in a laboratory kiln to determine the oven-dried mass at 103 ± 2°C (ABNT 2003). For the study of the anatomical wood features, small fragments were removed from each specimen, both groups of samples were prepared according to the Franklin method (Berlyn and Miksche 1976) to achieve cell dissociation and stained with alcoholic safranin. Slides were mounted with a solution of water and glycerin (1:1). Measurement of the fibers and vessels dimensions were according to terminology recommended by IAWA committee (1989). All measurements were obtained using an Olympus CX 31 microscope equipped with a digital camera (Olympus Evolt E 330) and image analyzer software (Image-Pro Plus 6.3).

2.5.3 CO_2 sequestration

After collecting the samples, the following procedures were performed by tree and species, according to Sousa et al. (2021): Calculation of trunk volume (Tv) or bole volume as Equation 1.

$$T_V = \frac{\pi}{4}\left[\left(\frac{(DBH)^2}{100}\right)HT\right]0.5 \qquad \text{Equation 1}$$

where: Tv = trunk volume (in m^3), DBH = diameter at breast height (in cm), and HT = tree height (in m).

Calculation of branch and root volume depends on such factors as species, age, and location. In this case, estimated 25% (1.25) over the trunk volume (Tv) and calculated the total volume (tv) as Equation 2.

$$t_v = (1.25)(T_V) \qquad \text{Equation 2}$$

where: t_v = total volume (in m^3).

Calculated tree weight (W) (in kg) as Equation 3.

$$W = (BD)(tv) \qquad \text{Equation 3}$$

where: BD = basic density (in kg m^{-3})

Basic density is the relationship between absolutely dry mass and saturated volume of wood, as described in the previous item. Then, to calculate fixed carbon, we applied a factor of 0.5 to tree weight, considering that 50% of the wood consists of carbon with the remainder constituted mainly by water and nutrients. We calculated absorbed CO_2 by multiplying the fixed carbon content by 3.67, as obtained from CO_2 / C, or a ratio of 44/12.

2.5.4 Statistical analyses

In the statistical evaluation of the experiment, initially the test of homogeneity of variance was performed and for that the Hartley test was used. Subsequently, the F test of analysis of variance was carried out according to the experimental design in a 4 x 3 factorial scheme (treatment x radial position) to study the properties. Tukey's test was applied whenever a significant difference was observed, at the 5% probability level of some treatment in the F test. Pearson's correlation test was applied between wood properties in each management system for each species. Statistical analyses were performed using the R software (R CORE TEAM 2019).

3 RESULTS

3.1 Silvicultural data and mean annual increment

Concerning the growth and volume increase, the species presented different results depending on the system. In general, the highest values of DBH, tree volume, volume per ha, and MAI were observed in the silvi-agricultural system. Between systems, we observed a notable difference, with *C. floribundus* showing higher values in the silvi-agricultural system compared to both *G. ulmifolia* and *C. floribundus* in the silvi-pastoral system. In the silvi-pastoral system, there were no significant differences between species for the growth variables (Table 1). In Table 2, the mean values and standard deviations of the wood properties for each treatment are presented.

Table 1. Silvicultural data and mean annual increment of 4 and a half years *Croton floribundus* and *Guazuma ulmifolia* in different planting systems

Tabela 1. Dados silviculturais e incremento médio anual de *Croton floribundus* e *Guazuma ulmifolia* aos 4 anos e meio em diferentes sistemas de plantio.

	Treatments	DBH (cm)	HT (m)	Tree volume (m^3)	Volume per ha (m^3.ha^{-1})	MAI (m^3.ha^{-1}.year^{-1})
1	SA - *Croton floribundus*	16.0^{a}	9.1^{a}	0.19909^{a}	119.45	26.54
2	SA - *Guazuma ulmifolia*	12.5^{ab}	7.6^{ab}	0.11689^{ab}	70.13	15.58
3	SP - *Croton floribundus*	11.1^{b}	7.8^{b}	0.09047^{b}	54.28	12.06
4	SP - *Guazuma ulmifolia*	11.6^{b}	6.8^{b}	0.09949^{b}	59.69	13.26

SA = Silvi-agricultural systems; SP = Silvi-pastoral systems; MAI = Mean annual increment
SA = Sistemas Silvi-agrícolas; SP = Sistemas Silvi-pastoris; MAI = Incremento Médio Anual

Different letters indicate statistical significance at $p < 0.05$ level (TUKEY test).
Letras diferentes indicam significância estatística ao nível de $p < 0,05$ (teste de TUKEY).

Table 2. Summary analysis of variance for basic density (BD), fiber length (FL), fiber wall thickness (FWT) and vessel element length (VEL) as a function of management systems and species.

Tabela 2. Análise de variância resumida para densidade básica (BD), comprimento da fibra (FL), espessura da parede da fibra (FWT) e comprimento dos elementos de vaso (VEL) em função dos sistemas de manejo e das espécies.

Causes of variation	DF	Mean squares			
		BD (g.cm^{-3})	FL (µm)	FWT (µm)	VEL (µm)
Treatment (T)	3	0.0191**	84061**	0.8191$^{n.s.}$	490741**
Radial Position (RP)	2	0.0125**	113392**	0.4673$^{n.s.}$	2082$^{n.s.}$
(T) x (RP)	6	0.0008$^{n.s.}$	12455$^{n.s.}$	0.2028$^{n.s.}$	769$^{n.s.}$
Treatments					
silvi-agricultural	*Croton floribundus*	0.36 (0.04)	1058 (160)	4.78 (0.73)	630 (70.25)
silvi-agricultural	*Guazuma ulmifolia*	0.42 (0.03)	1223 (181)	4.93 (0.79)	341 (38)
silvi-pastoral	*Croton floribundus*	0.36 (0.04)	1112 (99)	4.54 (0.66)	656 (44)
silvi-pastoral	*Guazuma ulmifolia*	0.43 (0.05)	1190 (149)	5.09 (0.40)	321 (22)
mean		0.39	1146	4.83	487
CV$_e$ (%)		9.53	12.26	14.08	10.05

Note: standard deviations in parentheses
**Significant at 5% level of significance; n.s. = not significant and CVe= coefficient of experimental variation. DF= degrees of freedom.

Nota: desvios padrão entre parênteses
**Significativo ao nível de 5% de significância; n.s. = não significativo e CVe = coeficiente de variação experimental. GL = graus de liberdade

The values for carbon fixed and carbon sequestered corroborated the MAI, with higher values in the silvi-agricultural system (Figure 2).

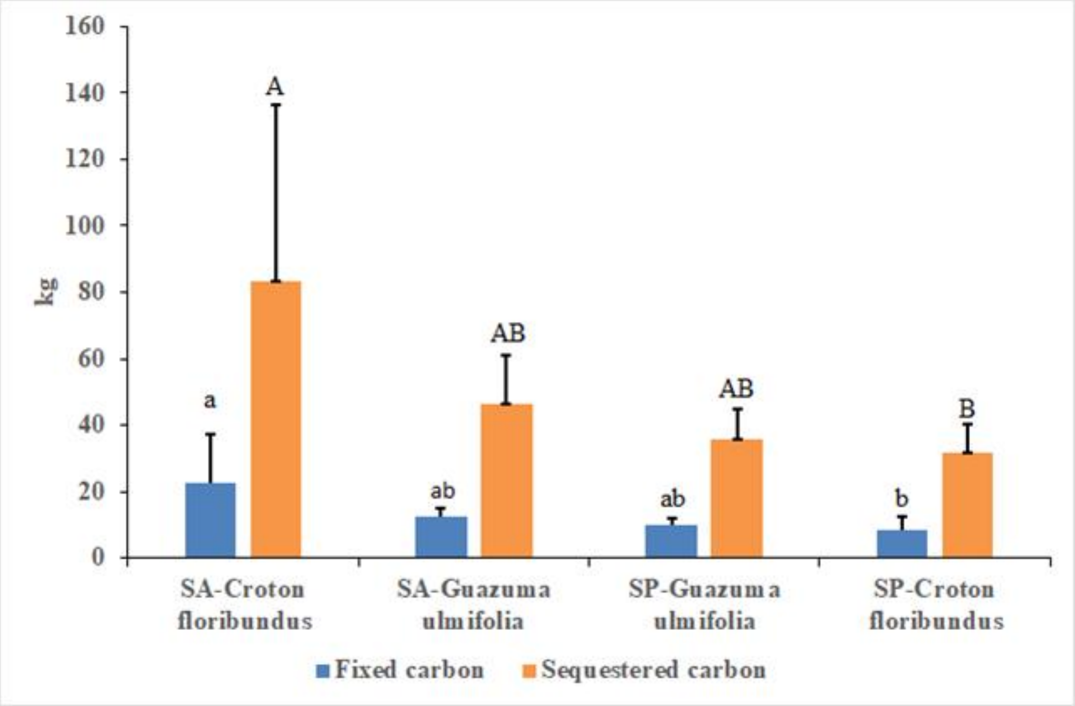

Figure 2. Variation in fixed and sequestered carbon in 4 and a half years *Croton floribundus* and *Guazuma ulmifolia* in silvi-agricultural (SA) and silvi-pastoral (SP) systems. Different letters indicate statistical significance at $p < 0.05$ level (TUKEY test).

Figura 2. Variação no carbono fixo e sequestrado em *Croton floribundus* e *Guazuma ulmifolia* em 4 anos e meio em sistemas silvi-agriculturais (SA) e silvi-pastoris (SP). Letras diferentes indicam significância estatística ao nível de $p <$ 0,05 (teste de TUKEY).

3.3 Wood features

The analysis of variance performed is shown in Table 2. According to the obtained results, the treatments adopted did influence the wood properties, except for fiber wall thickness. Basic density and fiber length differed between radial positions from pith to the bark, however, for vessel length and fiber wall thickness, there were no significant differences between radial positions. It was also found that there were no significant interactions between treatments and radial position for all properties studied, which demonstrated that there is no dependency between these three factors.

We verified that when we compared the treatment, there were significant differences in the wood properties up to the age of 4 and a half years for the studied species, except for fiber wall thickness (Figures 3A-D). The basic wood density of *G. ulmifolia* was higher in both systems: Silvi-agricultural and silvi-pastoral, while *C. floribundus* presented the lowest values in both systems. The fiber length of *G. ulmifolia* wood in the Silvi-agricultural system significantly differed from the fiber length of *C. floribundus* in the same system. The fiber wall thickness of the two species did not differ significantly in the two evaluated systems. However, the vessel element length of *C. floribundus* was significantly greater than that of *G. ulmifolia* in both systems.

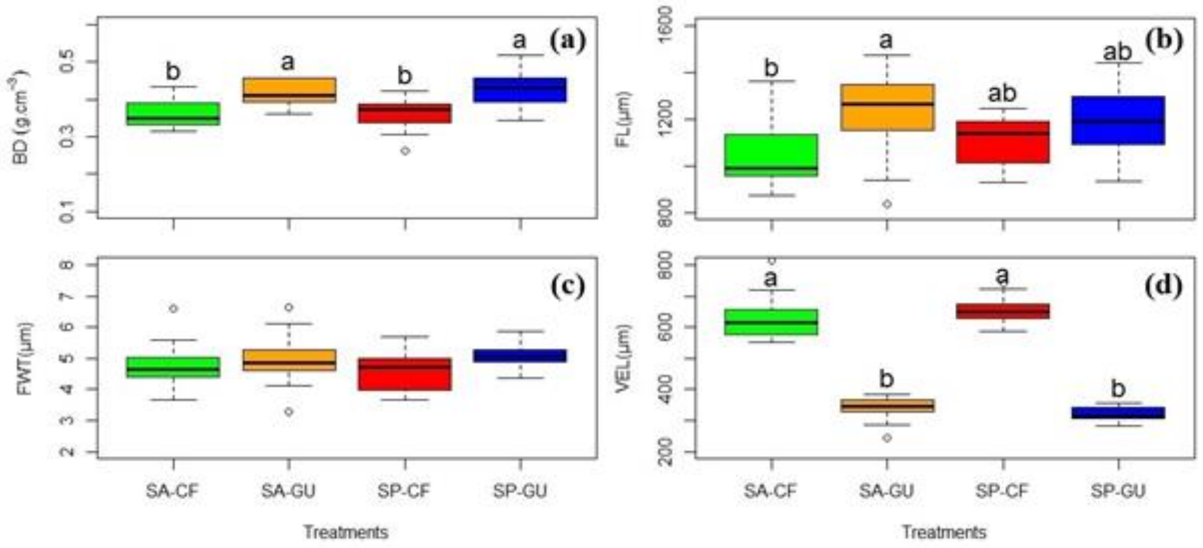

Figure 3. Basic density [BD] (A), fiber length [FL] (B), fiber wall thickness [FWT] (C) and vessel element length [VEL] (D) as a function of the treatment.

Figura 3. Densidade básica [BD] (A), comprimento da fibra [FL] (B), espessura da parede da fibra [FWT] (C) e comprimento dos elementos de vaso [VEL] (D) em função do tratamento.

Where: SA-CF = Silvi-agricultural systems for *Croton floribundus*; SA-GU = Silvi-agricultural systems for *Guazuma ulmifolia*;SP-CF = Silvi-pastoral systems for *Croton floribundus*; SP-GU =Silvi-pastoral systems for *Guazuma ulmifolia*. Different letters indicate statistical significance at $p < 0.05$ level (TUKEY test).

Em que: SA-CF = Sistemas silvi-agriculturais para *Croton floribundus*; SA-GU = Sistemas silvi-agriculturais para *Guazuma ulmifolia*; SP-CF = Sistemas silvi-pastoris para *Croton floribundus*; SP-GU = Sistemas silvi-pastoris para *Guazuma ulmifolia*. Letras diferentes indicam significância estatística ao nível de $p < 0,05$ (teste de TUKEY).

Comparing pith-bark variation of wood properties of two species, in each separate system, we can see that fiber length and basic density increased from pith to the bark in both systems (Figures 4A, 4B, 4E and 4F). The fiber thickness of the two species in the silvi-pastoral system increased in the pith-bark direction (Figure 4G). However, in the silvi-agricultural system, this same trend did not occur, with a decrease in the pith for the intermediate position and an increase in the intermediate pith for the bark position (Figure 4C).

The vessel element length of both species in the silvi-agricultural system increased in the pith-bark direction (Figure 4D). In the case of the silvi-pastoral system, there was a decrease from the pith to the intermediate position and an increase from the intermediate to the bark position for the species C. floribundus, for the species G. ulmifolia there was an increase in the direction from the pith to the bark (Figure 4H).

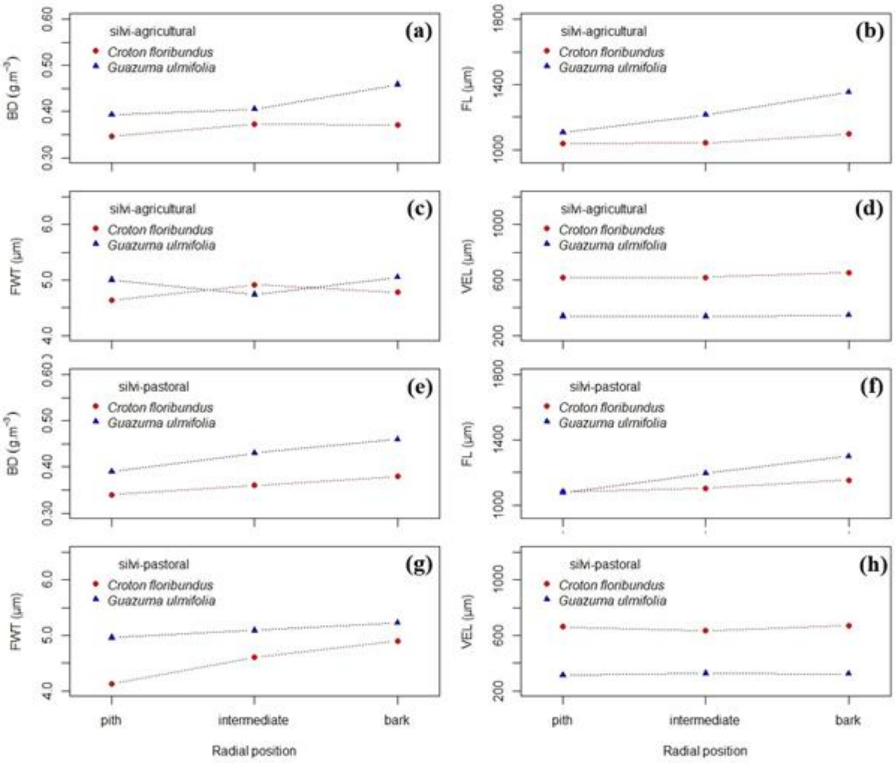

Figure 4. Radial variation of basic density (BD) [A], fiber length (FL) [B], fiber wall thickness (FWT) [C] and vessel element length (VEL) [D] in the silvi-agricultural system and Radial variation of basic density (BD) [E], fiber length (FL) [F], fiber wall thickness (FWT) [G] and vessel element length (VEL) [H] in the silvi-pastoral system.

Figura 4. Variação radial da densidade básica (BD) [A], comprimento da fibra (FL) [B], espessura da parede da fibra (FWT) [C] e comprimento dos elementos de vaso (CEL) [D] no sistema silvi-agricultural e variação radial da densidade básica (BD) [E], comprimento da fibra (FL) [F], espessura da parede da fibra (FWT) [G] e comprimento dos elementos de vaso (VEL) [H] no sistema silvi-pastoril.

To better explain the relationships between the properties of the wood of *C. floribundus* and *G. ulmifolia*, Pearson's correlation analyses were performed, separately by agroforestry systems (Figures 5A-D). Negative and positive correlations are represented by red and blue, respectively. The magnitude of all correlations is represented by color intensity. basic density (BD), fiber length (FL), fiber wall thickness (FWT) and vessel element length (VEL).

In the silvi-agricultural system for *C. floribundus*, all properties had high positive corrections, with the vessel element length and fiber length relationship being the highest, and for *G. ulmifolia* only the basic density x fiber length relationship had high positive correction (Figures 5 A-B). In the silvi-pastoral system for *C. floribundus* only the basic density x fiber length relationship was high and positive, while for *G. ulmifolia* only the vessel element length and fiber length relationship were high and positive (Figures 4 C-D).

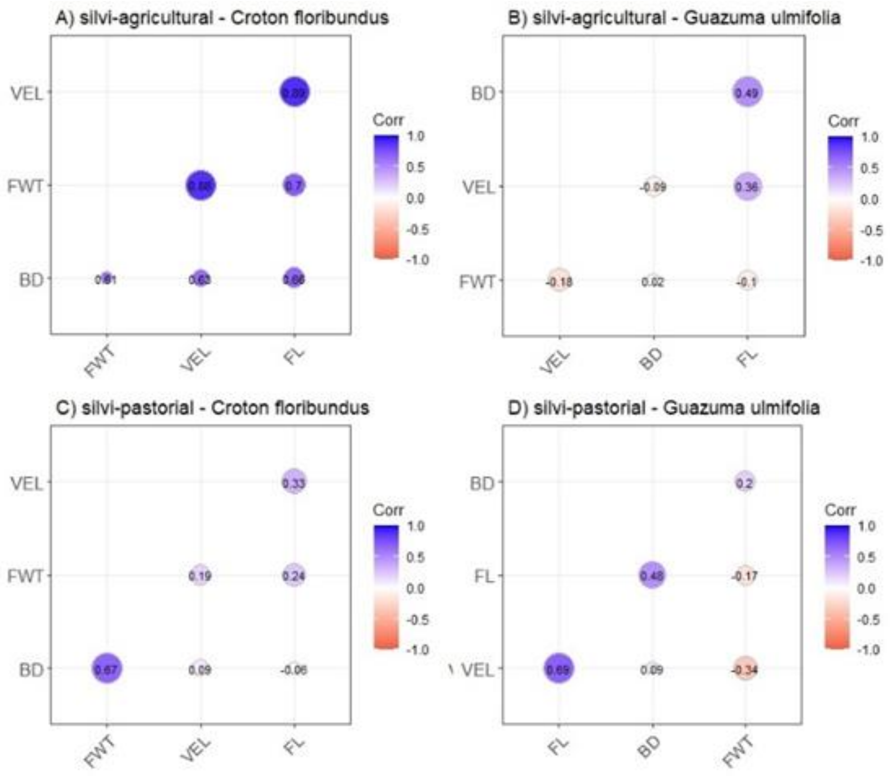

Figure 5. Pearson’s Correlation Coefficient between the properties of the wood of *Croton floribundus* in the silvi-agricultural system (A), *Guazuma ulmifolia* in the silvi-agricultural system (B), *Croton floribundus* in the silvi-pastoral system (C), *Guazuma ulmifolia* in the silvi-pastoral system (D).

Figura 5. Coeficiente de Correlação de Pearson entre as propriedades da madeira de *Croton floribundus* no sistema silvi-agricultural (A), *Guazuma ulmifolia* no sistema silvi-agricultural (B), *Croton floribundus* no sistema silvi-pastoril (C), *Guazuma ulmifolia* no sistema silvi-pastoril (D).

4 DISCUSSION

This study investigated the effect of the silvi-agricultural and silvi-pastoral systems on silvicultural data, mean annual increment, CO_2 sequestration, basic density, and wood features in *C. floribundus* and *G. ulmifolia*. Our results are significant and can provide valuable insights into the potential benefits of both types of systems. In addition to serving as examples for similar plantations around the world and, at the same time, showing that it is possible to align the production of native Brazilian wood, reducing the impact on native forests. The results show that species growth and volume increase presented different results depending on the system. The values for carbon fixed and carbon sequestered corroborated the MAI, with higher values in the silvi-agricultural system. Species differed significantly in basic density and vessel element length in the two evaluated systems. The species differed significantly in fiber length only in the Silvi-agricultural system. There was no difference between species in fiber wall thickness in both systems. Basic density and anatomical dimensions varied in the pith-bark direction, where the lowest values are in the position close to the pith, and the highest near the bark. It was found that there were no significant interactions between management, species, and radial position for all properties under study, which demonstrated that there is no dependency between these three factors. The relationships between the properties of *C. floribundus* and *G. ulmifolia* wood varied depending on the management system.

4.1 Silvicultural data and mean annual increment

Our results indicated a better performance of the trees and consequently of the MAI in the silvi-agricultural system compared with silvi-pastoral system. In *Pinus taeda* it was observed that trees grown under uniform and fertilized conditions showed the highest growth (height, DBH), productivity (IMA and stem volume) and biomass (stem, trunk, branches, thick and total roots) compared to trees grown in heterogeneous and unfertilized conditions (Kulmann et al. 2023). Wound inflicted by livestock to trees may include branch breakage, trunk breakage, leaves browsing and bark stripping, causing severe damage to the trees, which can lead to plant death and depression in the wood quality (Nicodemo et al. 2010). In our study, both systems received fertilization, however, even though cattle are restricted to grazing in the paddocks, therefore, no barkstripping damage was inflicted by livestock, we wonder if just the grazing may explain the lower performance of the silvi-pastoral system compared to the silvi-agricultural system.

Another possible explanation would be soil variation, since the silvi-agricultural system is in Red Yellow Oxisol, which are soils associated with flat, gently undulating, or wavy relief. They occur in well-drained environments, being very deep and uniform in terms of color, texture and structure in depth; and the silvi-pastoral system is in dark Red Oxisol, which are soils with accentuated red colors, due to the higher levels and nature of iron oxides present in the material originating in well-drained environments, and characteristics of uniform color, texture and structure in depth, however, if the texture is clayey there will be a low amount of water available to plants and susceptibility to compaction (Santos et al. 2018). We suggest that soil type better explains the difference in performance between systems than livestock grazing.

Another suggestion for the differences found in the trees between the system could be the evaluation time of our experiment (4 and a half years) or the species used and their different development. In a study with Eucalyptus trees in agroforestry systems, it was reported that pasture renewal in the first years after system implementation promoted greater initial tree growth, which led to higher values of stem volume and biomass in the system with pasture renewal when compared to system without pasture renewal (Pezzopane et al. 2021). In our study, there was renewal of the pasture with *Brachiaria decumbens* cv. *marandu*, plus the addition of maintenance fertilizers, even so the performance of the silvi-pastoral system was inferior to that of the silvi-agricultural system.

We emphasize that *C. floribundus* and *G. ulmifolia* are shade-forming species well used in agroforestry systems in Brazil. However, it is important to clarify that *C. floribundus* is a classic pioneer species (Durigan and Nogueira 1990), while *G. ulmifolia* is cited as a pioneer (Rozza, 1997) or non-pioneer (Ferretti et al. 1995). Which partly explains the volume and MAI results, since the results were different between species for each system (Table 2). It is suggested that in the system with cattle, even though the trunks are far from the animals, they could have access to the tree crown, the most susceptible or most preferred being the leaves of *C. floribundus*, which could reduce their photosynthetic area and consequently interfere in growth. In silvi-pastoral systems, special attention must be paid to the crown area, due to the shading caused by the tree component over the pasture. In this system, therefore, pruning must be carried out to reduce the shading caused by the trees, with the crown area being a variable to be observed with greater care (Almeida et al. 2022). In silvi-pastoral systems, it is recommended that animals have access only to older trees with greater total height and DBH, as animals can damage smaller trees, thereby affecting wood quality (Gonçalves et al. 2022).

4.2 CO_2 sequestration

Here we notice that values for CO_2 sequestration corroborated the silvicultural data and mean annual increment with higher values in the silvi-agricultural system. Studies with agroforestry systems are essential to meet the needs of the growing world population, however, the environmental impact of these systems must be considered. In a study with four types of system, it was reported that over four years, the system with livestock and forestry was more efficient, with a more negative net balance C (i.e., C storage) when expressed as ha. Additionally, the association of crops and forestry in livestock systems increases environmental benefits, emphasizing the potential of integrated systems to offset greenhouse gas emissions (Monteiro et al. 2024). For a few decades, especially in the last few decades, the topic of carbon capture has gained importance around the world, due to its influence on climate change. Therefore, specific studies on carbon capture calculations by forests are essential (Arevalo et al. 2022). We understand that more studies must be registered so that wood producers are aware and can price the possibilities that ecosystem services can add to tree plantings.

However, regardless of the results of our study, there is an urgency to increase forest cover. Planting trees continues to be one of the most effective strategies for mitigating climate change, as trees could store many gigatons of carbon (Bastin et al. 2019).

4.3 Wood properties

Guazuma ulmifolia presented an average value of 0.36 g cm^{-3} of basic density, a value lower than the 0.51 g cm^{-3} that was obtained by Sousa et al. (2021) for 10-year-old wood. For *C. floribundus*, an average value of 0.42 g cm^{-3} of basic density was found, a lower value (0.48 g cm^{-3}) than that found by Lima et al. (2010). It is widely known that anatomical variations directly influence wood density (Wiedenhoeft and Eberhardt 2021), and that density, a key physical property in wood quality investigations, in turn influences and is used to estimate mechanical properties (Senalik and Farber 2021), wood chemicals and energetics (Rowell 2013). It was verified that for basic density and vessel element length, the two species had the same behavior in both systems. Since *G. ulmifolia* had the highest basic density values and the smallest vessel element length, and *C. floribundus* had the lowest basic density values and the largest vessel element length.

Some studies evaluate wood quality from species managed by the agroforestry system, mainly using species native to Brazil. In a study on agroforestry system on wood quality of *Schizolobium parahyba* var. *amazonicum*, it was found that the timber produced had vessels with a smaller tangential diameter and fewer rays in the juvenile wood, and the wood also showed lower values of basic density and resistance to compression parallel to the fibers, when compared to the monocultural system (Silva et al. 2020).

In another study on agrosilvi-pastoral systems using the species *Myracrodruon urundeuva* and *Peltophorum dubium*, it was found that this system can be used successfully, as they produce wood with greater mechanical resistance and better quality for energy (Longui et al. 2021). In a study with *Tectona grandis* wood from an agrosilvi-pastoral system, it was found that when compared with literature results referring to homogeneous plantations, teak wood from an agrosilvi-pastoral system maintained its technological qualities in terms of basic density, which is a favorable option for the use of this species in the format of associated plantations (Oliveira et al. 2020). Also, the biomass values found in *Cordia goeldiana* wood were consistent with the expected characteristics for species used in an agroforestry system (Mascarenhas et al. 2020).

The basic density and charcoal ash content of *Mimosa scabrella* introduced in an agroforestry system far from its natural occurrence site of the species, show few differences compared to those found for the species in natural occurring sites (Friederichs et al. 2015).

A similar result of radial variation was obtained for basic density, length of vessel elements, fiber length and fiber wall thickness, for wood from trees derived from natural population of *C. floribundus* by (Lima et al. 2010). *C. floribundus* showed mean values of 1085, 4.66 and 643 µm for fiber length, fiber wall thickness and vessel element length, respectively, with these values being lower than that was observed by Lima et al. (2010), which were 1360, 5.3 and 751 µm, for wood from *C. floribundus* trees, originating from natural populations.

For fiber length, it was found that in the silvi-agricultural system, *G. ulmifolia* presented the highest values, differing significantly from the lowest values of *C. floribundus* in the silvi-pastoral system. In the case of fiber wall thickness, in both the silvi-agricultural system and silvi-pastoral system, it was found that there is no significant difference between species (Table 2 and Figure 3D).

When compared with other works with native species from Brazil managed by the agroforestry system, we must consider the fact that the wood analyzed in this research is considered still young (4 and a half years), and this is a factor that has a lot of influence on the quality of the wood produced for certain uses.

A similar result was verified for the fiber length of *Ocotea porosa* wood, where variation occurred in the direction of the bark pith, where the fiber length was smaller close to the pith, tending to increase towards the bark region (Vivian et al. 2021).

For the species *Caryocar brasiliense*, there is a positive correlation between basic density and fiber length (Abrahão et al. 2020). Therefore, we can consider that the relationships between the wood properties of the two species varied depending on the management system.

In general, it was found that we have few studies that assess the quality of wood produced by agrossilvi-pastoril systems. The results are still incipient, and many factors still must be considered to define the ideal management that produces wood in quantity and quality managed. Incorporating trees into agricultural landscapes represents a promising approach to sustainably supply goods for society, simultaneously enhancing biodiversity, ensuring animal welfare, and generating profits for stakeholders (Kruchelsk et al. 2021). Therefore, considering the adaptation of the species to the two soils under study, we can infer that *C floribundus* exhibited greater initial growth and lower wood density, which is typical of traditional pioneer species. In contrast, *G. ulmifolia* demonstrated slower initial growth but higher wood density, a trait commonly associated with non-traditional pioneer species.

In summary, agrossilvi-pastoril systems have shown to be promising in several aspects, being possible to successfully combine fast-growing shrub species, resistant grasses consumed by animals and tree species that can produce different products with a cycle of more than 50 years, for example, ornamental plants, hearts of palm, landscaping, fruits, seeds, bee pasture and wood with different properties (Longui et al. 2021).

4 CONCLUSIONS

The highest values of DBH, tree volume, volume per hectare, and MAI were observed in the silvi-agricultural system. Among the systems, *Croton floribundus* exhibited higher values compared to *Guazuma ulmifolia* within the silvi-agricultural system. The tree growth results may be attributed to the successional group of the two species or to cattle access and preference for *C. floribundus* leaves in the silvi-pastoral system. CO_2 sequestration values aligned with the MAI results, showing higher values in the silvi-agricultural system. However, regardless of the system, it is concluded that the arboreal component is essential for contributing to carbon stock. Wood properties were partially influenced by the type of system. *G. ulmifolia* displayed higher wood density and shorter vessel elements, irrespective of the management system. Conversely, *C. floribundus* exhibited lower wood density and longer vessel elements, also independent of the management system. These findings encourage the adoption of agroforestry systems that provide multiple income sources. The results related to wood quality are particularly significant, even in trees with diameters around 12 cm. As the trees grow in height and diameter, much of this 12 cm will form the heartwood, which can be utilized in sawmills with quality unaffected by cattle presence in the system. As expected, the wood of both species showed radial variation, with basic density and anatomical dimensions changing from the pith to the bark. Lower values were observed near the pith, and higher values near the bark. The data confirm the feasibility of combining short-cycle crop planting with tree production for wood.

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