

Do Reduced Tree Spacings Enhance Soil and Aboveground Carbon Storage? A Legume Tree Stand in Southeastern Brazil

Robert Gomes¹, Marcos V. W. Caldeira¹, Paulo A. Trazzi², Francielle S. de Oliveira¹, Gabriel S. L. Gomes¹, Victor B. R. Duarte¹, Mariana de A. Aragão¹, Adriano R. de Mendonça¹ & Otacilio J. P. Rangel³

¹ Departamento de Ciências Florestais e da Madeira, Universidade Federal do Espírito Santo. Jerônimo Monteiro, ES, Brazil

² Centro de Ciências Biológicas e da Natureza, Universidade Federal do Acre. Rio Branco, AC, Brazil

³ Instituto Federal de Educação, Ciência e Tecnologia do Espírito Santo, Campus de Alegre. Alegre, ES, Brazil

Correspondence: Robert Gomes, Av. Governador Lindemberg, 316, 29550-000, Departamento de Ciências Florestais e da Madeira, Jerônimo Monteiro, ES, Brazil. E-mail: robert_mrrg@hotmail.com

Received: April 4, 2025

Accepted: May 11, 2025

Online Published: May 13, 2025

doi:10.5539/jsd.v18n3p177

URL: <https://doi.org/10.5539/jsd.v18n3p177>

Abstract

The study aimed to describe the influence of different planting spacings in aboveground biomass and soil carbon stocks, in 7.5 years old *Anadenanthera peregrina* (L.) Speg. var. *peregrina* stands, hypothesizing that smaller spacings might enhance carbon storage. The stands are located in Espírito Santo, Brazil and were planted in 2011. Blocks were allocated in a randomized block design to evaluate three treatments: 3 m x 3 m, 4 m x 4 m and 5 m x 5 m tree spacings. Samples up to 100 cm were taken for carbon determination and soil bulk density. 10 trees were felled and their aboveground biomass measured. Soil and aboveground biomass C stocks were calculated. The aboveground biomass C stock did not change in different spacing. Soil C stock was not influenced by the spacings, with total C stock of 122.93, 106.09 and 97.08 Mg ha⁻¹ for 3 m x 3 m, 4 m x 4 m and 5 m x 5 m, respectively. The intensification of carbon storage in smaller spacings was not confirmed. The study reveals inedited information about carbon storage in *A. peregrina* var. *peregrina* stands and demands new investigations regarding different soil characteristics. The species do have potential for carbon storage regardless of tree spacing.

Keywords: *Anadenanthera peregrina*, carbon stock assessments, planting density

1. Introduction

Global climate changes have become one of today's main environmental concerns, with the exploitation of forests and the increasing greenhouse gases (GHG) emissions, impacting several ecosystems (Fawzy et al., 2020). The planted forest sector plays a major role in the atmospheric removal of GHG, and the removal is linked with the growth rate, whether reducing harvests to keep the biomass in the field or increasing the rotation frequency, to provide new plantations with early rapid growth and sequestration (Pukkala, 2018). Additionally, soil is one of the largest carbon storage compartments in forest ecosystems. Changes in soil carbon stock can influence carbon dioxide (CO₂) levels in the atmosphere and impact global climate change (Chen et al., 2015). The Brazilian forestry sector comprises around 1.82 billion tons of equivalent CO₂ stored in planted areas, natural conservation spots and soils (Ibá, 2023).

Forest plantation soils are directly influenced by specific characteristics of the chosen species, with deposition of organic matter on the soil surface and their chemical composition, which can facilitate or not microbial activity in the decomposition of the material and C increment to the soil (Balin et al., 2017). The silvicultural management decisions prior to planting such as the choice of planting spacing is crucial because it affects growth, production and allocation of biomass and dictates all post-planting management, according to its productive purpose (Páscoa et al., 2019). For some species, adequate spacing may increase carbon storage in biomass and influence the decomposition rate of the soil organic matter (Schwerz et al., 2020). The size of the trees and their dominance relationship are among the factors that can influence aboveground carbon stocks (Noulékoun et al., 2023).

Further than growth behavior and spacing, the climatic adaptation of the chosen species is detrimental (Lázaro-Lobo et al., 2023). This argument makes the species choice one of the most important decisions for restoration and carbon storage (Thomas et al., 2007). Brazil has a wide diversity of native tree species, but around 95 % of planted

forest areas are composed by exotic species (Ibá, 2023). The smaller proportion of native forest plantations is not related to any kind of silvicultural unfeasibility but the lack of information and technologies regarding their characteristics of growth, survival, plant health and forestry practices (Mendonça et al., 2017). The market seeks alternative adapted high-quality material tied to the concept of low carbon and climate change mitigation, making native forest plantations a profitable option (Rolim et al., 2019).

Species such as *Anadenanthera peregrina* (L.) Speg. var. *peregrina* (angico-vermelho) are promising because of its commercial appeal to the timber sector. Native to Brazil, the pioneer to early intermediate trees grow to about 10 to 25 meters in height, in a branching form (De Souza et al., 2017). The species is known for its biomass energy potential, as well as non-timber use, such as the extraction of tannins in its bark (Athayde & Morellato, 2014). To reach their maximum potential, these plantations require adequate forestry treatments to facilitate their growth, production and carbon sequestration (Ferez et al., 2015).

Little is known about the silvicultural management of the species and its interactions with the environment, with carbon data limited to the early years of development of the trees (Souza et al., 2023). It is hypothesized that after years, the trees might experience canopy closure and increased competition in smaller spacings, enhancing soil and biomass carbon storage. Therefore, the study aimed to evaluate soil and biomass carbon stocks and the influence of planting spacing in such characteristics in 7.5 years old *A. peregrina* var. *peregrina* stands.

2. Methods

2.1 Site and Establishment

The study was developed in an area provided by the Federal Institute of Education, Science and Technology of Espírito Santo (Ifes), Alegre campus, located in Alegre, Espírito Santo, Brazil (Figure 1). The experimental plots are in an area with previous grazing pasture use and unfertilized pasture vegetation, mostly *Urochloa* sp. grasses.

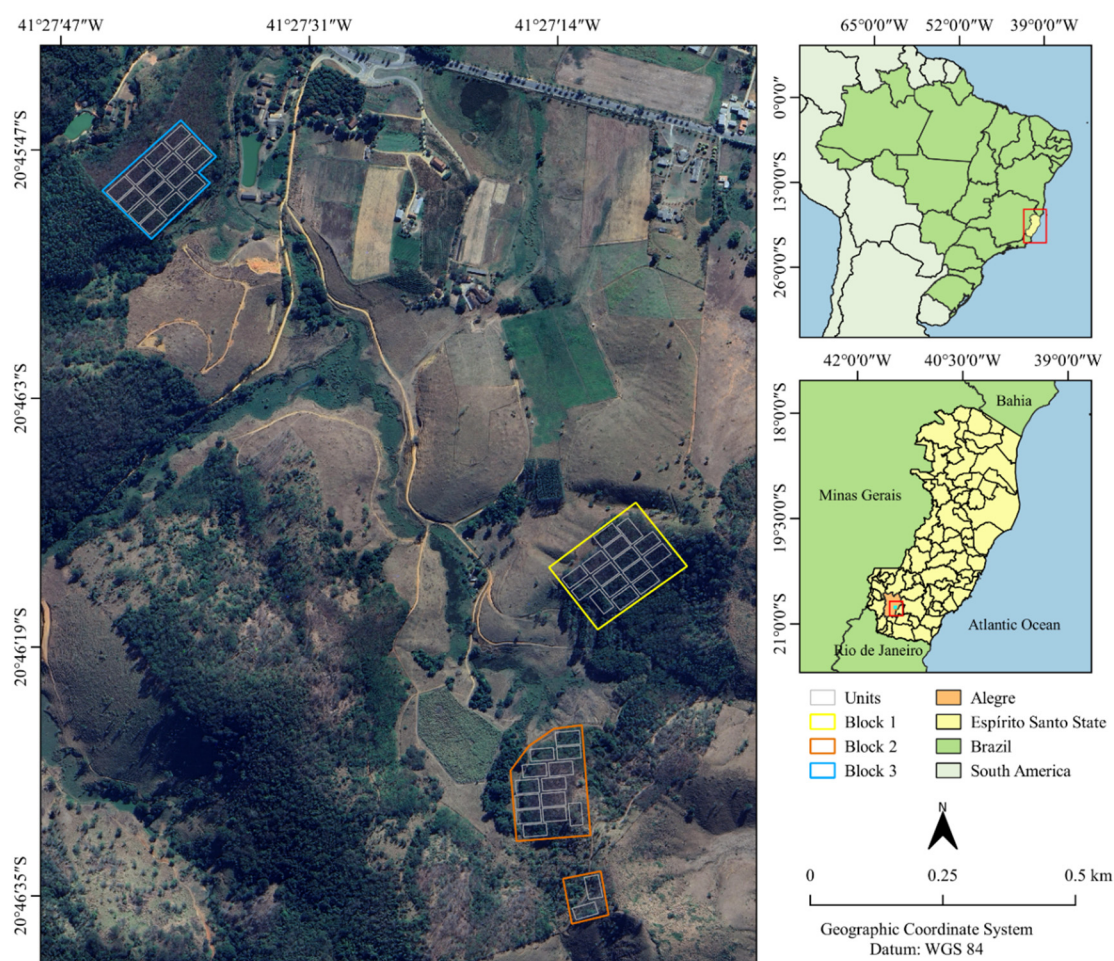


Figure 1. *Anadenanthera peregrina* stands location in Alegre, Espírito Santo, Brazil

The climate is classified as Aw in the Köppen classification system, with dry winter and rainy summer (Alvares et al., 2013). The local altitude of the study site varies between 120 and 235 meters to sea level (Figure 2) and the difference between the experimental blocks presents 51 % variation (Souza et al., 2023).

Soil type was classified by Cunha et al. (2016) with the revised Brazilian nomenclature system, according to Embrapa (Dos Santos et al. 2018). Different soil type combinations occur throughout the experimental area (Figure 2), with Latossolo Amarelo distrófico (Ferralsols) alone (LAd1) or combined with Argissolo Vermelho-Amarelo distrófico (Acrisols) (LAd7) or Cambissolo Háplico Distrófico (Cambisols) (LAd9). The soils' chemical and physical characteristics for the 0 – 20 and 20 – 40 cm layers were evaluated in 2010, before planting. They were classified as clayey textured soils with medium organic matter content, regardless of the locations. The Atlantic Forest is the local biome and the main forest formation in the region is classified as Semideciduous Seasonal Forest (IBGE, 2012).

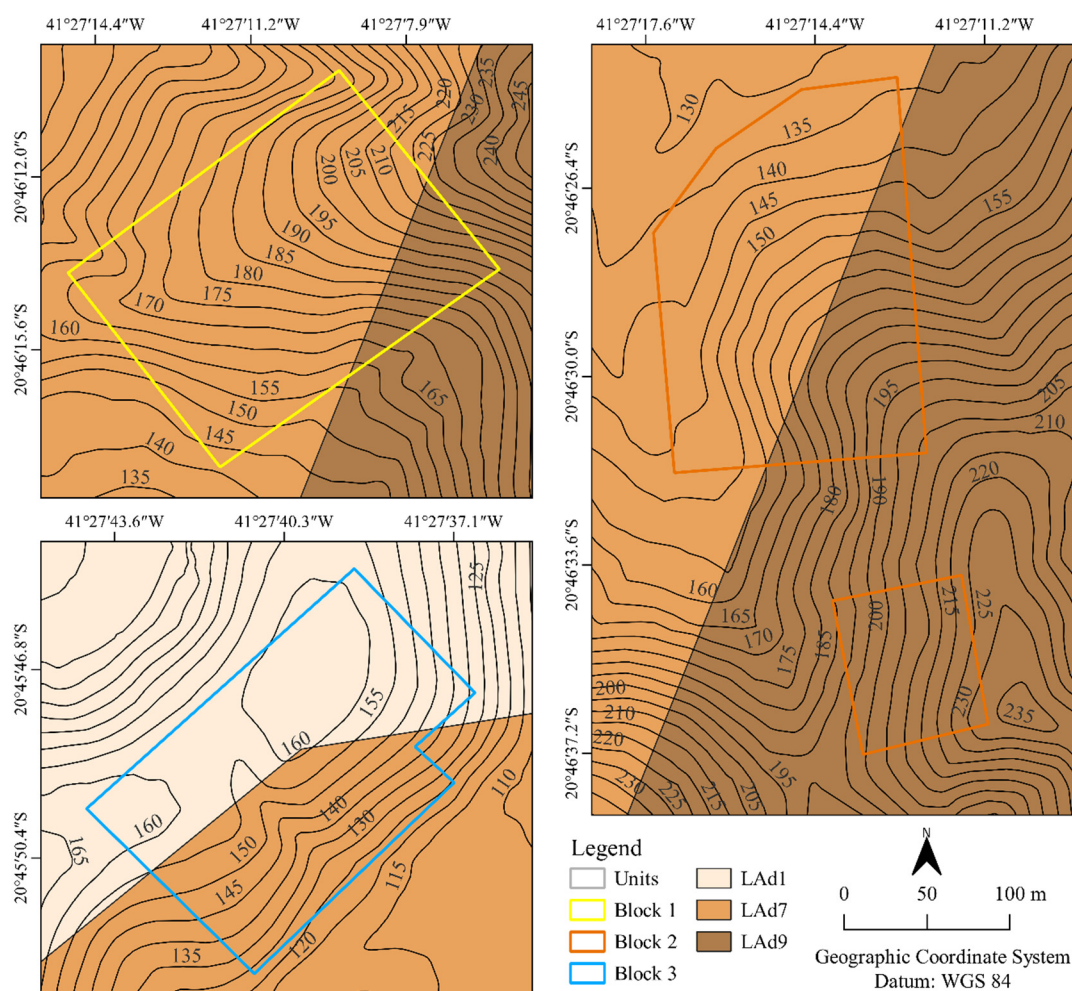


Figure 2. Soil type classification and site level curves in *Anadenanthera peregrina* stands located in Alegre, Espírito Santo, Brazil

Note. LAd1 - Latossolo Amarelo distrófico (Ferralsols); LAd7 - Latossolo Amarelo distrófico (Ferralsols) + Argissolo Vermelho-Amarelo distrófico (Acrisols); LAd9 - Latossolo Amarelo distrófico (Ferralsols) + Cambissolo Háplico Distrófico (Cambisols).

The stands of *A. peregrina* var. *peregrina* were planted in June 2011. The cattle were removed from the site and glyphosate-based chemicals used to dry out the weeds. Planting was carried out in pits and initial fertilization was made using 220 grams per plant of formulated NPK 02-30-06 fertilizer. The maintenance was carried out during the first year, with replanting, mowing and manual weeding operations. In each of the blocks, experimental units

of 30 m x 50 m were allocated, according to the treatments (3 m x 3 m, 4 m x 4 m and 5 m x 5 m spacings).

2.2 Aboveground Biomass C Stock

The biomass was quantified at 7.5 years after planting, using 10 trees per treatment, according to the mean diameters. The trees were felled and segmented into fractions (Stemwood, Stembark, leaves and branches). All the fractions were entirely weighed in the field using a digital scale to obtain the individual fresh biomass. Stemwood was sampled in discs with bark approximately 5.0 cm thick, removed at the 0.10 m, d (1.30 m), $\frac{1}{2}$ of the stem length and top positions. The stembark samples were extracted from the disks. Leaf samples were taken from the lower, middle and upper positions of the crown. The branches were sampled in portions from the lower, middle and upper third of the tree's crown. The dry weight of the biomass was obtained by weighing the fresh samples and drying them in a forced air circulation oven at 65 °C, until they reached a constant weight. The dry biomass of the fractions and the stand's total biomass was determined (Table 1).

Table 1. Mean diameter at breast height (DBH) and mean aboveground biomass in *A. peregrina* var. *peregrina* planting 7.5 years after planting

Treatment	DBH cm	Trunk	Bark	Leaves Mg ha ⁻¹	Branches	Total
3 m x 3 m	10.37	13.80	2.93	5.52	23.42	44.83
4 m x 4 m	12.18	17.20	2.38	5.65	27.68	52.06
5 m x 5 m	14.41	15.99	2.07	5.02	27.28	49.26
SD	1.93	2.97	0.53	0.72	5.46	8.88
CV (%)	15.71	18.96	21.46	13.40	20.88	18.23

Source: Gomes, unpublished data.

The carbon stocks in the aboveground biomass were quantified according to the carbon concentration per compartment (Table 2) reported by Souza et al. (2023), for the same stand at 56 months of age. Carbon concentration at young age was used to estimate the stocks, since they usually do not change with the stand age (Sanquetta et al., 2014, Martins et al. 2020).

Table 2. Carbon concentration (%) in *A. peregrina* var. *peregrina* compartments 56 months after planting

Compartment	Carbon concentration (%)
Trunk	44.22
Bark	44.31
Leaves	43.97
Branches	44.25

Source: Adapted from Souza et al. (2023).

Considering the percentage of carbon in the compartment of each tree and the survival rate of the stand, the stocks were calculated.

$$\text{BioC stock (Mg ha}^{-1}\text{)} = \text{Compartment biomass (Mg ha}^{-1}\text{)} \times \text{C concentration (\%)} \quad (1)$$

2.3 Soil C Stock

Soil sampling was performed using trenches to quantify soil organic carbon concentration and soil bulk density. At each block and treatment, sampling points were allocated and trenches up to 100 cm depth were dug, exposing the soil profile. The sampling occurred disregarding the edges of the experimental plot, with sampling points in the center of four individuals with mean diameter at breast height (DBH), which better represent the stand.

The trenches were subdivided according to the following depth layers: 0 – 20, 20 – 40, 40 – 60, 60 – 80 and 80 – 100 cm. Samples from each of the spacings and depths were conditioned in plastic containers and sent to the laboratory. The laboratory procedures were as recommended by Embrapa (Teixeira et al., 2017). The soil organic

carbon analysis was made by Walkley-Black organic matter oxidation method. For the soil bulk density (BD) determination, the volumetric ring method was used (Teixeira et al., 2017), with the aid of a metallic rim of known volume and mass. At each depth, undisturbed samples were collected with an undeformed soil sampler and volumetric rings with a volume of 102.14 cm³. In the laboratory, the material was placed in a forced circulation oven at a temperature of 105 ± 3 degrees Celsius for 72 hours. After cooling, they were weighed to obtain the dry mass value, and the BD was calculated.

Soil organic carbon stock was calculated by the association between BD and the organic carbon concentration obtained in the chemical analysis, through Equation 2, adapted from Veldkamp (1994), which also accounts for the thickness of the analyzed soil layer.

$$C \text{ stock} = SOC \times BD \times \frac{e}{10} \quad (2)$$

where: *C stock* = Organic carbon stock for a given depth, in Mg ha⁻¹; *SOC* = Soil organic carbon concentration for a given depth, in g kg⁻¹; *BD* = Soil bulk density for a given depth, in g cm⁻³; *e* = Soil layer thickness, in cm.

2.4 Statistics

The experimental design was in Randomized Block Design (DBC), with three treatments (planting spacings) and three replications. Data were tested for homogeneity of variances and normality of residuals, by the OneilMathews and Shapiro-Wilk tests, respectively. When the requirements were met, analysis of variance (ANOVA) was performed at 5 % probability level. Means were compared using the Tukey test, at 5 % probability. The R software, Expdes.pt package was used.

3. Results

3.1 Biomass C stock

The carbon stocks determined from biomass stock are represented in Figure 3. Only the stembark compartment had statistical significance for the planting spacings. The higher amount of carbon stored in the stembark came from higher stembark biomass stocks for 3 m x 3 m spacing (Gomes, unpublished data). The stemwood compartment accounted for around 7.14 Mg ha⁻¹ C stock. In the leaves, the stands stored a carbon mean of 2.36 Mg ha⁻¹. The branches are responsible for 11.54 Mg ha⁻¹.

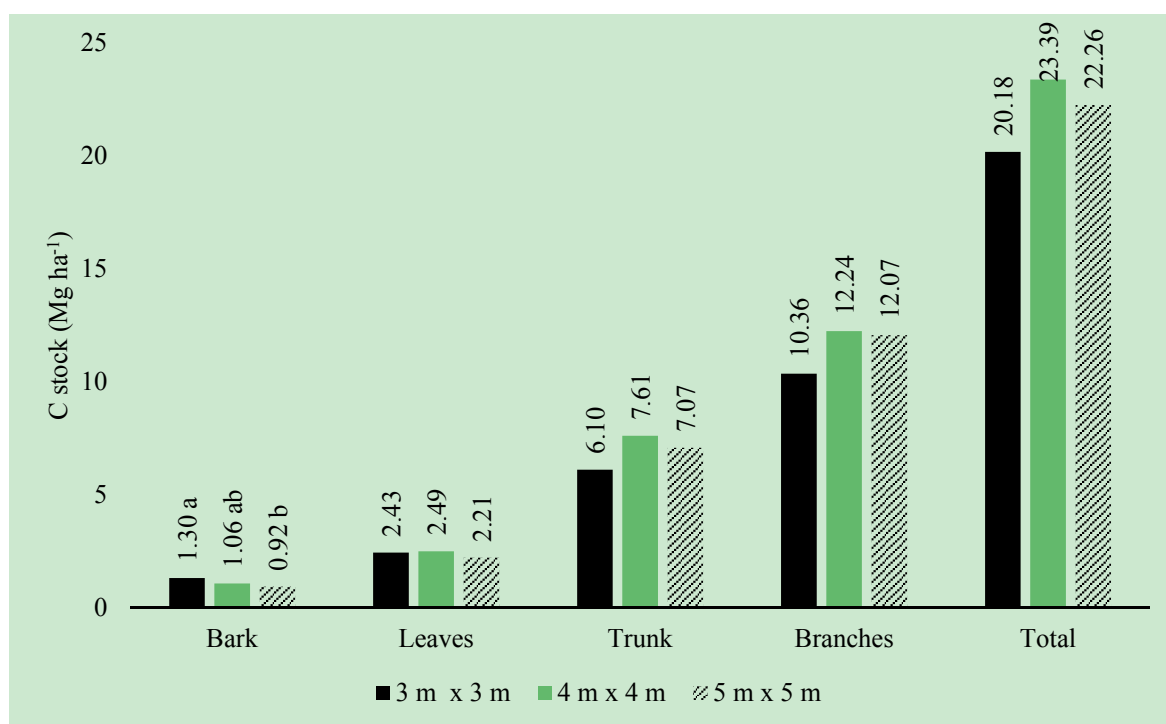


Figure 3. Carbon stock in total and compartmentalized aboveground biomass, for different spacings

As the only compartment with a statistical significance between the spacings was responsible for the smallest part

of the stored carbon (stembark), it did not influence the total carbon stocked in the aboveground biomass. The stands stored a total mean of 22.20 Mg ha⁻¹ in its aboveground biomass. Of this total, about 52.46 % is stored in the branches, 31.54 % in the stemwood, 10.96 % in the leaves and 5.03 % in the stembark.

3.2 Soil C Stock

Data on organic carbon and soil bulk density did not differ in terms of planting spacings ($p > 0.05$) (Table 3). Considering the soil surface layer (0-20 cm), the non-significant variation of BD was 0.12 g cm⁻³ between the 4 m x 4 m and 5 m x 5 m spacings, respectively. There was a non-significant variation of 3.14 g kg⁻¹ in carbon content between 4 m x 4 m and 3 m x 3 m spacing.

Table 3. Mean and standard deviation for soil bulk density and soil organic carbon concentration (SOC) up to 100 cm depth, for different planting spacings, in *A. peregrina* var. *peregrina* stands in Alegre, ES, Brazil

Treatment ^{ns}	Depth	BD ^{ns}	SOC*
	cm	g cm ⁻³	g kg ⁻¹
3 m x 3 m	0 - 20	1.30 (0.09)	16.27 (2.11) a
	20 - 40	1.52 (0.07)	10.67 (1.33) b
	40 - 60	1.47 (0.06)	6.57 (0.86) c
	60 - 80	1.50 (0.07)	5.20 (0.60) c
	80 - 100	1.49 (0.15)	4.63 (0.55) c
4 m x 4 m	0 - 20	1.36 (0.03)	13.13 (2.37) a
	20 - 40	1.48 (0.13)	9.10 (2.33) b
	40 - 60	1.48 (0.10)	5.80 (0.60) bc
	60 - 80	1.46 (0.10)	5.00 (0.35) c
	80 - 100	1.48 (0.01)	4.43 (0.29) c
5 m x 5 m	0 - 20	1.24 (0.19)	14.33 (4.35) a
	20 - 40	1.37 (0.16)	7.33 (0.86) b
	40 - 60	1.40 (0.15)	5.60 (0.35) b
	60 - 80	1.40 (0.16)	4.80 (0.35) b
	80 - 100	1.31 (0.06)	4.60 (0.00) b

Note. ^{ns} – Non-significant; BD – Soil bulk density; SOC – Soil organic carbon; Values followed by the same lowercase letter in the columns do not differ for each treatment, by Tukey's test at 5% probability. Standard deviation in parenthesis.

A significant difference in carbon concentration was observed for the soil depths ($p < 0.05$). In general, the surface layer of the soil up to 20 cm has higher carbon content, with a decrease at greater depths. There was greater variation between the surface layer up to 100 cm in the 3 m x 3 m spacing, with a difference of 11.64 g kg⁻¹.

Soil carbon stocks were calculated for the different planting spacings and sampling depths, represented in Figure 4. The soil carbon stocks also differed statistically in relation to the sampling depth, with higher mean stocks in the 0 – 20 cm depth and lower stocks in the 80 – 100 cm layer, for all evaluated spacings.

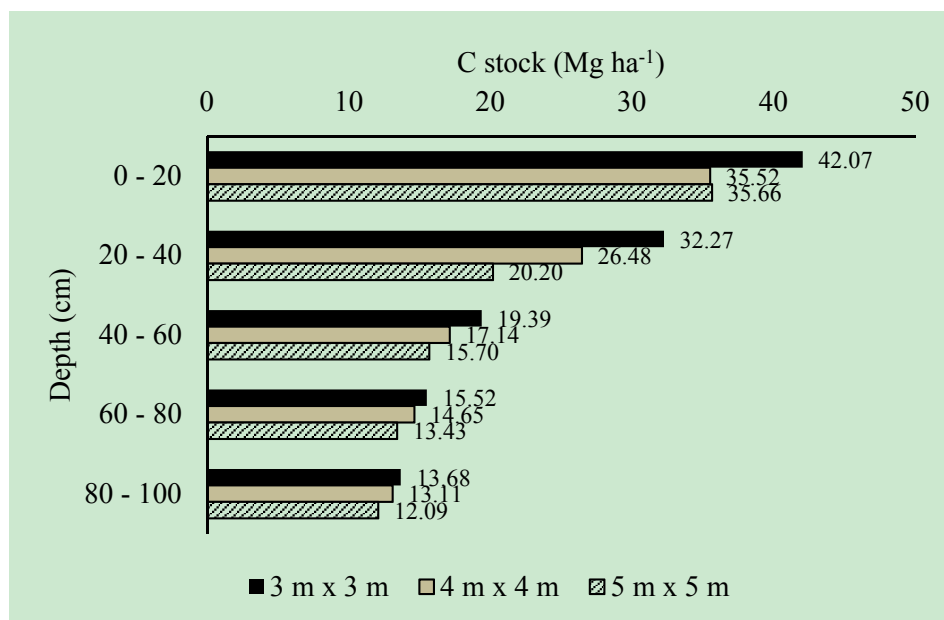


Figure 4. Soil carbon stock at different depths, for three planting spacings, in an *A. peregrina* var. *peregrina* stand in Alegre, ES

Soil carbon stocks were not affected by planting spacing ($p > 0.05$). The carbon stocks in the surface layer range between 35.52 and 42.07 Mg ha⁻¹, for the spacings of 4 m x 4 m and 3 m x 3 m, respectively. There was a non-statistical tendency for larger stocks in the 3 m x 3 m spacing, up to a depth of 40 cm. The sum of the total C stored for each spacing (up to 100 cm depth) was 122.93 Mg ha⁻¹, 106.09 Mg ha⁻¹ and 97.08 Mg ha⁻¹ for 3 m x 3m, 4 m x 4 m and 5 m x 5 m, respectively.

4. Discussion

4.1 Biomass C Stock

The aboveground biomass carbon concentrations (Souza et al., 2023) indicate that the species has similar carbon content as Brazilian native species, such as reported by Dallagnol et al. (2011) for the Fabaceae *Mimosa scabrella*, with the highest concentration among five species evaluated by the authors, indicating great potential for great carbon storage. However, the stand accumulated low carbon stocks at 7.5 years (21,94 Mg ha⁻¹), if compared to other forest species, such as *Eucalyptus* spp. from different locations at 7 years old, reported by Gatto et al. (2010), with stemwood compartment carbon stocks of 64.15 Mg ha⁻¹. It is important to point out that *Eucalyptus* spp. is generally planted in tighter spacings and with higher growth rates. On the other hand, the stocks were higher than some Atlantic Forest mixed species reforestation stands, at 11 years of age, in Sergipe, Brazil (Meira et al., 2020).

The lower stocks for stemwood are linked to the biomass allocation pattern of *A. peregrina* var. *peregrina*, mainly into the branches. The behavior of carbon storage as a function of biomass allocation was also verified by Magnago et al. (2016) in young eucalyptus stands with higher biomass and carbon storage to the stemwood at smaller spacings and higher crown biomass and carbon storage in wider spacings. For the present study, however, there was no influence of planting spacing, except for the stembark compartment, which stores more carbon at the 3 m x 3 m spacing, also as a function of higher biomass amounts at the referred spacing.

As expected, the largest biomass compartment stored the largest amount of carbon, with 52,46% of the total carbon stored in branches. With traditional forest harvesting, much of the carbon and nutrients in the biomass is exported by removing stemwood (Caldeira et al., 2014). At the stands, this compartment would export about 31.54 % of the carbon stored in the aboveground biomass. The branches will remain or not on the forest floor, according to the forest harvesting system adopted. In case the producer opts for harvesting the compartment, a total of 84 % of the carbon will be exported (stemwood + branches). If the producer chooses to keep the branches in the area, it is possible that this practice favors the stability of the stocks in the system (Carneiro et al., 2019), since the species has high wood density (Souza et al., 2020).

Considering the data collected by Souza et al. (2023) at 56 months old, the increments to the total biomass carbon stocks of the present study (7.5 years old) were 4.17 Mg ha⁻¹ year⁻¹ for the 3 m x 3 m spacing; 6.54 Mg ha⁻¹ year⁻¹

for the 4 m x 4 m spacing; and 5.68 Mg ha⁻¹ year⁻¹ for the 5 m x 5 m spacing. It is worth stating that important compartments for carbon storage in forests, such as roots, litter and necromass were not sampled.

4.2 Soil C Stock

The planting spacings did not cause noticeable differences in soil bulk density, which for all the tested spacings and depths proved to be adequate to crop development in clayey soils (Brady & Weil, 2013). Possible changes in soil physical characteristics are usually related to the root system of forest species. Root density can be related to physical attributes such as soil porosity, according to the growth characteristics of the species (Yu et al., 2018). Though planting spacing tends to influence root density, it might not reflect in changes for soil bulk density itself. In a study developed by Rosa et al. (2018), for example, the authors did not observe differences in soil bulk density of *Eucalyptus dunnii* stands with different planting spacings one year after planting.

In the study developed by Souza et al. (2023) at 56 months old *A. peregrina* var. *peregrina* stands, the author finds small differences for root biomass related to different spacings, with 3 m x 3 m and 4 m x 4 m spacings showing similar results. At this stage, the implementation of the stands had resulted in significant reduction in soil bulk density. In the literature, most studies report bulk density reduction in the surface layer and an in-depth increase in the establishment of forest stands (Macedo et al., 2008, Korkanç, 2014, Balin et al., 2017).

Soil carbon contents and stocks were not influenced by planting spacing. The main contributions of spacing to soil C are linked to environmental factors and the organic matter C concentration. There may be a strong relationship between planting density and aboveground carbon stocks in some plantations, expressed by the correlation between basal area and carbon stock in biomass in tropical forests (Wassihun et al., 2019). However, the transfer of organic matter to the soil in forest plantations takes place through the deposition of branches and leaves. Even though dense spacings can produce a greater amount of litter, it does not cause greater C input in the soil. The lack of patterns for carbon storage related to tree spacing is also reported by Schwertz et al. (2020), for different species and planting densities.

The soil carbon stocks found in the study are close to the values commonly found in several planted forests, such as in reforestation plantations with leguminous tree species inoculated with *Rhizobia* in ferralsols (Macedo et al., 2008) and in *Eucalyptus* and erva mate stands in cambisols soils (Denardin et al., 2014). In both studies, the C stocks are lower than the native vegetation reference area. In a study developed by Neves et al. (2022) in an area of seasonally dry tropical forest near stands of *A. peregrina* var. *peregrina* here studied, the authors report higher soil carbon stocks than in the present study, with mean values of 57 Mg ha⁻¹, at the depth of 0 - 20 cm. According to Zhou et al. (2019), species compositions that have high nitrogen concentration and low C/N ratio show higher efficiency in organic matter decomposition and C accumulation.

Several factors are responsible for variations in soil carbon contents in forest plantations. The planting arrangement and soil use, the species or mix of species used, climatic variables and clay content in the soil are some of the most relevant (Paula et al., 2021). In a study developed by Gatto et al. (2010), the authors evaluated carbon stocks in *Eucalyptus* spp. stands with different soil and climate characteristics. Although they observed higher stocks in ferralsols, with a predominance of higher clay content, the authors emphasize that part of this result is due to the climatic condition of the studied areas, with higher altitudes, mild climate and little water deficit, making the mineralization of soil organic matter slower.

In a study conducted by Moore et al. (2018) with native species in tropical soils previously occupied by pasture, changes in carbon stocks are observed as a function of time. Based on $\delta^{13}\text{C}$ analyses, the authors show that in processes of land cover change, the conversion of carbon from pastures predating forest planting may take decades. In younger planting stages, Souza (2023) reported changes in the carbon isotopic ratio with the introduction of the stand, with the addition of more negative $\delta^{13}\text{C}$ coming from the forest stand. These contributions were most noticeable in the top-soil layer. The age of the stand, however, makes comparisons of the stocks in relation to the time of establishment inconclusive.

Within all the complexity of carbon conversion processes, the soil is considered one of the largest compartments of C storage in forest ecosystems, even though it is susceptible to variations caused by changes in soil management systems, which affect carbon contents (López-Díaz et al., 2017). Studies indicate that reforestations or forest planting established in areas with different previous uses cause an initial decrease in soil carbon, until the planting begins to increase significant amounts of carbon in the system, usually after 30 years (Paul et al., 2001). Thereafter, tree planting may or may not result in increased carbon stocks, with the risk of losses and impact on global climate change (Friggens et al., 2020).

Considering the high temperatures, good precipitation volume (despite the dry winter) and low altitude, in addition

to the relatively short evaluation period, the *A. peregrina* var. *peregrina* stand carbon stocks were satisfactory, compatible with the pattern of other forest crops. The results reported by Souza et al. (2023) characterize a decrease in stocks compared to the initial soil carbon stock, mainly because of the decrease in BD at 58 months. The decrease is not noticeable for the evaluation period of the present study, in which the stand presents greater canopy closure, a characteristic with potential for increasing soil C contents (Maraseni & Pandey, 2014).

5. Conclusions

Under the conditions of the experiment, the planting spacing did not influence the soil and aboveground biomass carbon stock. Carbon storage was not intensified, though the species stored significant amounts of carbon. The study reveals inedited information about carbon storage in *A. peregrina* var. *peregrina* stands and demands new investigations regarding different soil types and sampling methods. The species do have potential for carbon storage regardless of tree spacing and should be considered for pure or mixed stands, associating high value timber production and environmental services.

References

- Alvares, C. A., Stape, J. L., Sentelhas, P. C., Moraes, G., Leonardo, J., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, 22(6), 711-728. <https://doi.org/10.1127/0941-2948/2013/0507>
- Athayde, E. A., & Morellato, L. P. C. (2014). Anthropogenic edges, isolation and the flowering time and fruit set of *Anadenanthera peregrina*, a cerrado savanna tree. *International Journal of Biometeorology*, 58(4), 443-454. <https://doi.org/10.1007/s00484-013-0727-y>
- Balin, N. M., Ziech, A. R. D., Oliveira, J. P. M., Girardello, V. C., Stumpf, L., & Conceição, P. C. (2017). Frações da matéria orgânica, índice de manejo do carbono e atributos físicos de um Latossolo Vermelho sob diferentes sistemas de uso. *Scientia Agraria*, 18(3), 85-94. <https://doi.org/10.5380/rsa.v18i3.53114>
- Brady, N. C., & Weil, R. R. (2009). *Elementos da natureza e propriedades dos solos*. Porto Alegre: Bookman Editora.
- Caldeira, M. V. W., Godinho, T. O., Saidelles, F. L. F., Viera, M., Schumacher, M. V., & Castro, K. C. (2014). Exportação de carbono e nutrientes pela colheita de *Acacia mearnsii* De Wild. aos quatro anos de idade na Depressão Central, RS. *Comunicata Scientiae*, 5(1), 68-74.
- Carneiro, K. M. S., Reis, S. M., Morandi, P. S., Elias, F., Oliveira, E. A., Marimon-Junior, B. H., & Marimon, B. S. (2019). Estoque e perda de necromassa da vegetação lenhosa em um gradiente fitofisionômico na transição Amazônia-Cerrado. *Rodriguésia*, 70, e02892017. <https://doi.org/10.1590/2175-7860201970060>
- Chen, L., Smith, P., & Yang, Y. (2015). How has soil carbon stock changed over recent decades? *Global Change Biology*, 21(9), 3197-3199. <https://doi.org/10.1111/gcb.12992>
- Cunha, A. D. M., Feitoza, H. N., Feitoza, L. R., Oliveira, F. S., Lani, J. L., Cardoso, J. K. F., & Trindade, F. S. (2016). Atualização da legenda do mapa de reconhecimento de solos do estado do Espírito Santo e implementação de interface no Geobases para uso dos dados em SIG. *Geografares*, 2(22), 32-65. <https://doi.org/10.47456/geo.v2i22.30205>
- Dallagnol, F. S., Mognon, F., Sanquetta, C. R., & Corte, A. P. D. (2011). Teores de carbono de cinco espécies florestais e seus compartimentos. *Floresta e Ambiente*, 18(4), 410-416. <https://doi.org/10.4322/floram.2011.060>
- De Souza, P. B., Costa, W. S., Pinheiro, A. L., & Coelho, D. J. C. (2017). *Ecologia, manejo, silvicultura e tecnologia de espécies nativas da Floresta Atlântica: Angico-vermelho (Anadenanthera peregrina (L.) Speg.)*. Viçosa: Gráfica Seculus.
- Denardin, R. B. N., Matias, J. L., Wildner, L. P., Nesi, C. N., Sordi, A., Kolling, D. F., Busnello, F. J., & Cerutti, T. (2014). Estoque de carbono no solo sob diferentes formações florestais, Chapecó-SC. *Ciência Florestal*, 24(1), 59-69. <https://doi.org/10.5902/1980509813323>
- Dos Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., Almeida, J. A., Araujo Filho, J. C., Oliveira, J. B., & Cunha, T. J. F. (2018). *Sistema Brasileiro de Classificação de Solos* (5th ed.). Brasília: Embrapa.
- Fawzy, S., Ahmed, I. O., Doran, J., & Rooney, D. W. (2020). Strategies for mitigation of climate change: a review. *Environmental Chemistry Letters*, 18, 1-26. <https://doi.org/10.1007/s10311-020-01059-w>

- Ferez, A. P. C., Campoe, O. C., Mendes, J. C. T., & Stape, J. L. (2015). Silvicultural opportunities for increasing carbon stock in restoration of Atlantic forests in Brazil. *Forest Ecology and Management*, 350, 40-45. <https://doi.org/10.1016/j.foreco.2015.04.015>
- Friggens, N. L., Hester, A. J., Mitchell, R. J., Parker, T. C., Subke, J., & Wookey, P. A. (2020). Tree planting in organic soils does not result in net carbon sequestration on decadal timescales. *Global Change Biology*, 26(9), 5178-5188. <https://doi.org/10.1111/gcb.15229>
- Gatto, A., Barros, N. F., Novais, R. F., Silva, I. R., Leite, H. G., Leite, F. P., & Villani, E. M. A. (2010). Estoques de carbono no solo e na biomassa em plantações de eucalipto. *Revista Brasileira de Ciência do Solo*, 34, 1069-1079. <https://doi.org/10.1590/S0100-06832010000400007>
- Indústria Brasileira de Árvores – Ibá. (2023). *Relatório Anual Ibá 2023*. Retrieved from <https://iba.org/datafiles/publicacoes/relatorios/relatorio-anual-iba2023-r.pdf> [Accessed on September 10, 2024]
- Instituto Brasileiro de Geografia e Estatística – IBGE. (2012). *Manual técnico da vegetação brasileira*. Rio de Janeiro: IBGE.
- Korkanç, S. Y. (2014). Effects of afforestation on soil organic carbon and other soil properties. *Catena*, 123, 62-69. <https://doi.org/10.1016/j.catena.2014.07.009>
- Lázaro-Lobo, A., Ruiz-Benito, P., Cruz-Alonso, V., & Castro-Díez, P. (2023). Quantifying carbon storage and sequestration by native and non-native forests under contrasting climate types. *Global Change Biology*, 29(16), 4530-4542. <https://doi.org/10.1111/gcb.16810>
- López-Díaz, M. L., Benítez, R., & Moreno, G. (2017). How do management techniques affect carbon stock in intensive hardwood plantations? *Forest Ecology and Management*, 389, 228-239. <https://doi.org/10.1016/j.foreco.2016.11.048>
- Macedo, M. O., Resende, A. S., Garcia, P. C., Boddey, R. M., Jantalia, C. P., Urquiaga, S., Campello, E. F. C., & Franco, A. A. (2008). Changes in soil C and N stocks and nutrient dynamics 13 years after recovery of degraded land using leguminous nitrogen-fixing trees. *Forest Ecology and Management*, 255(5-6), 1516-1524. <https://doi.org/10.1016/j.foreco.2007.11.007>
- Magnago, L. F., Arantes, M. D. C., Vidaurre, G. B., Moulin, J. C., & Trugilho, P. F. (2016). Energy estimate and carbon stock in short-rotation Eucalyptus stands. *Cerne*, 22, 527-534. <https://doi.org/10.1590/01047760201622042209>
- Maraseni, T. N., & Pandey, S. S. (2014). Can vegetation types work as an indicator of soil organic carbon? An insight from native vegetations in Nepal. *Ecological Indicators*, 46, 315-322. <https://doi.org/10.1016/j.ecolind.2014.06.038>
- Martins, J. F. C., Silva, A. S., Coutinho, V. M., Orso, G. A., Behling, A., & Corte, A. P. D. (2020). Carbono nos componentes da biomassa de *Acacia mearnsii* De Wild. *Biofix*, 5(1), 32-38. <https://doi.org/10.5380/biofix.v5i1.67131>
- Meira, A. C. S., Melo, A. A. M., Sanquetta, C. R., & Ferreira, F. A. (2020). Estimativas de biomassa e carbono em área de mata atlântica, implantada por meio de reflorestamento misto. *Biofix*, 5(1), 130-134. <https://doi.org/10.5380/biofix.v5i1.67298>
- Mendonça, G. C., Chichorro, J. F., Mendonça, A. R., & Guimarães, L. A. O. P. (2017). Avaliação silvicultural de dez espécies nativas da Mata Atlântica. *Ciência Florestal*, 27, 277-290. <https://doi.org/10.5902/1980509826466>
- Moore, T. R., Abraham, M., Kalácska, M., Murphy, M. T., & Potvin, C. (2018). Changes from pasture to a native tree plantation affect soil organic matter in a tropical soil, Panamá. *Plant and Soil*, 425, 133-143. <https://doi.org/10.1007/s11104-018-3574-0>
- Neves, N. M., Paula, R. R., Araujo, E. A., Rodrigo, G. G., Abreu, K. M. P., & Kunz, S. H. (2022). Contribution of legume and non-legume trees to litter dynamics and CNP inputs in a secondary seasonally dry tropical forest. *iForest Biogeosciences and Forestry*, 15(1), 8-15. <https://doi.org/10.3832/ifor3442-014>
- Noulèkoun, F., Mensah, S., Kim, H., Jo, H., Gouwakinnou, G. N., Houéhanou, T. D., & Khamzina, A. (2023). Tree size diversity is the major driver of aboveground carbon storage in dryland agroforestry parklands. *Scientific Reports*, 13(1), 22210. <https://doi.org/10.1038/s41598-023-49119-9>

- Páscoa, K. J. V., Scolforo, J. R. S., Ferraz Filho, A. C., Altoé, T. F., & Gomide, L. R. (2019). Growth of *Eremanthus erythropappus* (DC.) MacLeish in different planting spacings. *Floresta e Ambiente*, 26(2), e20170834. <https://doi.org/10.1590/2179-8087.083417>
- Paul, K., Polglase, P. J., Nyakuengama, J. G., & Khanna, P. K. (2002). Change in soil carbon following afforestation. *Forest Ecology and Management*, 168(1-3), 241-257. [https://doi.org/10.1016/S0378-1127\(01\)00740-X](https://doi.org/10.1016/S0378-1127(01)00740-X)
- Paula, R. R., Calmon, M., Lopes-Assad, M. L., & Medonça, E. S. (2021). Soil organic carbon storage in forest restoration models and environmental conditions. *Journal of Forestry Research*, 33, 1123-1134. <https://doi.org/10.1007/s11676-021-01426-5>
- Pukkala, T. (2018). Carbon forestry is surprising. *Forest Ecosystems*, 5, 1-11. <https://doi.org/10.1186/s40663-018-0131-5>
- Rolim et al. (2019). The exact title is missing for this reference; please provide it for accurate formatting.
- Rosa, S. F., Reinert, D. J., Reichert, J. M., Fleig, F. D., Rodrigues, M. F., & Gelain, N. S. (2018). Propriedades físicas e químicas de um Argissolo sob cultivo de *Eucalyptus dunnii* Maiden no Pampa Gaúcho. *Ciência Florestal*, 28(2), 580-590. <https://doi.org/10.5902/1980509832040>
- Sanquetta, C. R., Behling, A., Corte, A. P. D., Simon, A., Pscheidt, H., Ruza, M. S., & Mochiutti, S. (2014). Estoques de biomassa e carbono em povoamentos de acácia negra em diferentes idades no Rio Grande do Sul. *Scientia Forestalis*, 42(103), 361-370.
- Schwerz, F., Neto, D. D., Caron, B. O., Tibolla, L. B., Sgarbossa, J., Eloy, E., Elli, E. F., & Carvalho, L. G. (2020). Carbon stocks, partitioning, and wood composition in short-rotation forestry system under reduced planting spacing. *Annals of Forest Science*, 77(3), 1-18. <https://doi.org/10.1007/s13595-020-00974-w>
- Souza, C. O., Silva, J. G. M., Arantes, M. D. C., Vidaurre, G. B., Dias Júnior, A. F., & Oliveira, M. P. (2020). Pyrolysis of *Anadenanthera peregrina* wood grown in different spacings from a forest plantation in Brazil aiming at the energy production. *Environment, Development and Sustainability*, 22(6), 5153-5168. <https://doi.org/10.1007/s10668-019-00418-0>
- Souza, P. H., Caldeira, M. V. W., Delarmelina, W. M., Trazzi, P. A., Paula, R. R., Momolli, D. R., Moreau, J. S., Gomes, G. S. L., Gomes, R., & Sanquetta, C. R. (2023). Comparing spacings of *Anadenanthera peregrina* (L.) Speg stand: response in biomass and carbon stock above and below ground. *Revista Ambiente & Água*, 18, e2919. <https://doi.org/10.4136/ambi-agua.2919>
- Teixeira, P. C., Donagemma, G. K., Fontana, A., & Teixeira, W. G. (2017). Manual de métodos de análise de solo. Embrapa.
- Thomas, S. C., Malczewski, G., & Sapruff, M. (2007). Assessing the potential of native tree species for carbon sequestration forestry in Northeast China. *Journal of Environmental Management*, 85(3), 663-671. <https://doi.org/10.1016/j.jenvman.2006.04.027>
- Veldkamp, E. (1994). Organic carbon turnover in three tropical soils under pasture after deforestation. *Soil Science Society of America Journal*, 58(1), 175-180. <https://doi.org/10.2136/sssaj1994.03615995005800010025x>
- Wassihun, A. N., Hussin, Y. A., Leeuwen, L. M. V., & Latif, Z. (2019). Effect of forest stand density on the estimation of above ground biomass/carbon stock using airborne and terrestrial LIDAR derived tree parameters in tropical rain forest, Malaysia. *Environmental Systems Research*, 8(1), 1-15. <https://doi.org/10.1186/s40068-019-0155-z>
- Yu, B., Xie, C., Cai, S., Chen, Y., Lv, Y., Mo, Z., Liu, T., & Yang, Z. (2018). Effects of tree root density on soil total porosity and non-capillary porosity using a ground-penetrating tree radar Unit in Shanghai, China. *Sustainability*, 10(12), 4640. <https://doi.org/10.3390/su10124640>
- Zhou, G., Xu, S., Ciais, P., Manzoni, S., Fang, J., Yu, G., Tang, X., Zhou, P., Wang, W., Yan, J., Wang, G., Ma, K., Li, S., Du, S., Han, S., Ma, Y., Zhang, D., Liu, J., Chu, G., Zhang, Q., Li, Y., Huang, W., Ren, H., Lu, X., & Chen, X. (2019). Climate and litter C/N ratio constrain soil organic carbon accumulation. *National Science Review*, 6(4), 746-757. <https://doi.org/10.1093/nsr/nwz045>

Acknowledgments

We would like to acknowledge the Instituto Federal do Espírito Santo for the experimental site and support. We

also acknowledge the ongoing financial support from Fundação de Amparo à Pesquisa e Inovação do Espírito Santo (FAPES), call N° 19/2018; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), call N° 09/2018 and 132001/2020-9; and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), call N° 10/2018.

Authors contributions

M.Sc. R. Gomes was responsible for data curation, writing and editing the original draft. Dr. M.V.W. Caldeira, Dr. A.R. Mendonça and Dr. O.J.P. Rangel were responsible for the experimental design and implementation. Dr. M.V.W. Caldeira and Dr. P.A. Trazzi were responsible for supervision, data collection and fund acquisition. M.Sc. F.S. de Oliveira, Dr. V.B.R. Duarte, Dr. G.S.L. Gomes and Dr. M.A. Aragão were responsible for software, validation, review and editing. All authors read and approved the final manuscript.

Funding

Not applicable.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Canadian Center of Science and Education.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

Not commissioned; externally double-blind peer reviewed.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

Open access

This is an open-access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/4.0/>).

Copyrights

Copyright for this article is retained by the author(s), with first publication rights granted to the journal.