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Above and belowground carbon stock in a tropical forest in Brazil

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ABSTRACT. An increase in atmospheric CO_2 levels and global climate changes have led to an increased focus on CO_2 capture mechanisms. The *in situ* quantification and spatial patterns of forest carbon stocks can provide a better picture of the carbon cycle and a deeper understanding of the functions and services of forest ecosystems. This study aimed to determine the aboveground (tree trunks) and belowground (soil and fine roots, at four depths) carbon stocks in a tropical forest in Brazil and to evaluate the spatial patterns of carbon in the three different compartments and in the total stock. Census data from a semideciduous seasonal forest were used to estimate the aboveground carbon stock. The carbon stocks of soil and fine roots were sampled in 52 plots at depths of 0-20, 20-40, 40-60, and 60-80 cm, combined with the measured bulk density. The total estimated carbon stock was 267.52 Mg ha^{-1}, of which 35.23% was in aboveground biomass, 63.22% in soil, and 1.54% in roots. In the soil, a spatial pattern of the carbon stock was repeated at all depths analyzed, with a reduction in the amount of carbon as the depth increased. The carbon stock of the trees followed the same spatial pattern as the soil, indicating a relationship between these variables. In the fine roots, the carbon stock decreased with increasing depth, but the spatial gradient did not follow the same pattern as the soil and trees, which indicated that the root carbon stock was most likely influenced by other factors.

Keywords: carbon sink; biomass; spatial pattern; secondary forest; soil.

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Introduction

The increase in atmospheric CO_2 levels and global climate changes have led to an increased focus on CO_2 capture mechanisms and increased efforts to reduce CO_2 emissions, such as Reducing Emissions from Deforestation and forest Degradation - REDD+ (Correa, Van der Hoff, & Rajão, 2019). The role of soil in CO_2 capture has gained prominence due to its capacity to store approximately four times more carbon than plant biomass and three times more than the atmosphere (Watson, 2001). Therefore, soil organic carbon is the largest carbon sink in the terrestrial biosphere (Jobbágy & Jackson, 2000) and remains one of the main strategies to mitigate increases in atmospheric CO_2 concentrations (Asner & Mascaro, 2014). In addition, the potential to use soil organic carbon as an indicator of soil quality reinforces the importance of having appropriate techniques to accurately measure soil carbon concentrations and to adequately predict soil carbon storage (Franzluebbers, 2002; Bhattacharya et al., 2016).

The soil carbon balance depends on the relationship between the addition of photosynthesized carbon by plants and carbon losses to the atmosphere resulting from the microbial oxidation of organic carbon into CO2 (King, 2011; Bhattacharya et al., 2016; Crowther et al., 2016). Studies have shown that the storage of organic carbon in soil and its dynamics are determined by factors such as climate, soil type and properties, plant cover, and management practices (Moore et al., 2018; Navarrete-Segueda et al., 2018; Shukla & Chakravarty, 2018).

Forest tree species have a higher capacity for nutrient cycling than annual plants due to the permanent and deep root system that absorbs elements from the subsurface layer, returning them to the surface through litter deposition (Haag, 1985). Tropical ecosystems, such as the Amazon Rainforest and the Atlantic Forest, have high productivity due to the temperature and humidity that favor the decomposition of soil organic matter and to the absence of physical disturbances that allow the formation of large carbon stocks

(Shukla & Chakravarty, 2018). Therefore, forests also play a significant role in the storage of global terrestrial carbon in their different components (Van der Sande et al., 2017).

The horizontal distribution of soil organic carbon and its relationship with climate and vegetation have been extensively studied (Jobbágy & Jackson, 2000; Terra, Mello, & Mello, 2015). Despite many studies on the geostatistical procedures applied to mapping soil attributes, little spatial information is available on the vertical distribution of soil carbon under forests, especially forests with a notable predominance of one tree genus/species. Knowledge of the variation in depth of soil carbon and the solid study of the spatial patterns of this variable, together with information on carbon present in other forest compartments, can provide a better picture of carbon stocks and a deeper understanding of forest ecosystems. Furthermore, these data meet the demand for high-quality in situ data (Duncanson et al., 2019) and can certainly provide a background for more effective conservation and management strategies.

Based on the considerations above, there is a clear demand for carbon estimates in the soil and in other forest compartments in different ecosystems. Therefore, this study aimed to i) determine the soil and root carbon stock at four depths (0-20, 20-40, 40-60, and 60-80 cm) under tropical forest in Brazil, ii) estimate the carbon in tree trunks, and iii) evaluate the spatial patterns of carbon in the three distinct compartments (soil, tree trunks, and fine roots) and in the total stock above and belowground, with the aim of determining the spatial relationships between these variables.

Material and methods

Study area

The study area is a 1.2-ha secondary forest located in the Lavras municipality, state of Minas Gerais, Brazil, at coordinates 21°14' S and 45°00' W and at an average altitude of 900 m. The average annual precipitation and potential evapotranspiration are 1,511 mm and 900 mm, respectively. According to the Köppen classification system, the climate of the region is Cwa (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013). There are two well-defined seasons: the dry season (April to September, winter) and the rainy season (October to March, summer). The average annual temperature is 19.4°C, ranging from 14.4°C (in July) to 22.5°C (in January) (Terra et al., 2018; Marques et al., 2019). According to Carvalho, Mendonça, Lima, and Calegario (2010), the forest is heterogeneous, with multiannual trees and a predominance of the genus *Anadenanthera*, popularly known as angico. The allelopathic potential of these species has been evaluated in the literature (Oliveira et al., 2005). The forest is bordered by a *Eucalyptus urograndis* plantation to the north and west and by an early secondary, semi-deciduous forest stock to the south. There is a road along the eastern side of the forest.

Soil data

One hundred and five permanent 10 x 10-m sampling plots were distributed over the area. The plots for soil sample collection were systematically chosen (Figure 1). The soil sampling points corresponded to the center of each sampling plot, totaling 52 points, 20 m apart from each other.

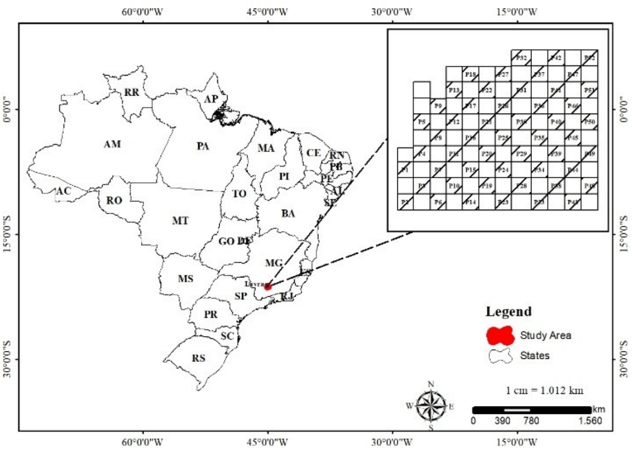

Figure 1. Location and sketch of the study area with the sampled plots.

In all soil sample points, the vegetation cover was removed, and holes 80 cm deep and 20 cm in diameter were made by using a propeller coupled to a chainsaw (Figure 2). Soil samples were collected at depths of 0-20, 20-40, 40-60, and 60-80 cm with a post hole digger. Each soil sample was stored in labeled plastic bags, followed by separation of roots and soil using sieves with mesh sizes of 7.95 and 2.26 mm. The soil samples were dried and classified using sieves with 200 and 270 mesh sizes. The material was dried in an oven at 60 ± 2°C for analysis of elemental carbon.

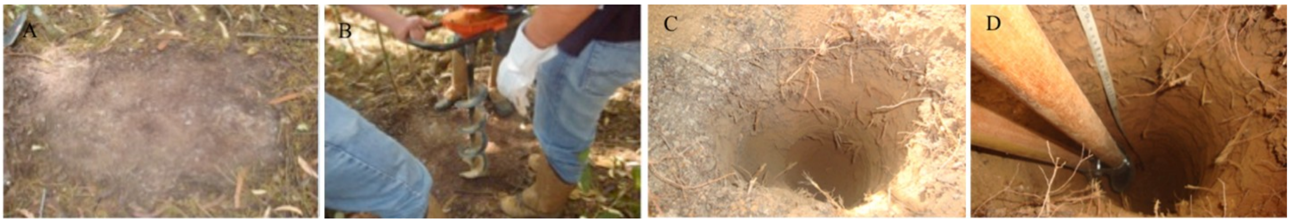

Figure 2. (A) Collection site after cleaning; (B) Instrument used to make the hole; (C) Hole; and (D) Depth of the hole and marking of the post hole digger.

Elemental carbon analysis was performed using the CHN elemental analyzer (Vario MICRO Cube), whose basic principle is the combustion of material to determinate the levels of carbon, hydrogen, nitrogen, and sulfur by the difference in oxygen. Two milligrams of each sample were weighed, packed in tin capsules, and then transferred to the apparatus. The soil density was determination by collecting samples at five points representative of the area and at the four depths studied, using a volumetric ring with a 98.174 cm^3 volume. The samples were oven dried at 105 ± 2°C to determine the dry weight. With the volume and dry weight data, it was possible to determine the mean soil density at each depth.

The expression of Veldkamp (1994) (Equation 1) was used to determine the total carbon stock of the soil at each sampling point and depth:

$$SOCS = OC * BD * e \quad (1)$$

where: *SOCS* is the soil organic carbon stock at each point and depth (Mg ha^{-1}); *OC* is the total organic carbon content at the points and depths sampled (%); *BD* is the bulk density at each depth (g cm^{-3}); and *e* is the thickness of the considered layer (cm).

Roots tree data

The roots originating from the soil samples, were separated using 7.95 and 2.26 mm mesh sieves. After sorting, the samples were washed in running water for complete soil removal. They were then oven dried at 60 ± 2°C until reaching a constant weight (Figure 3).

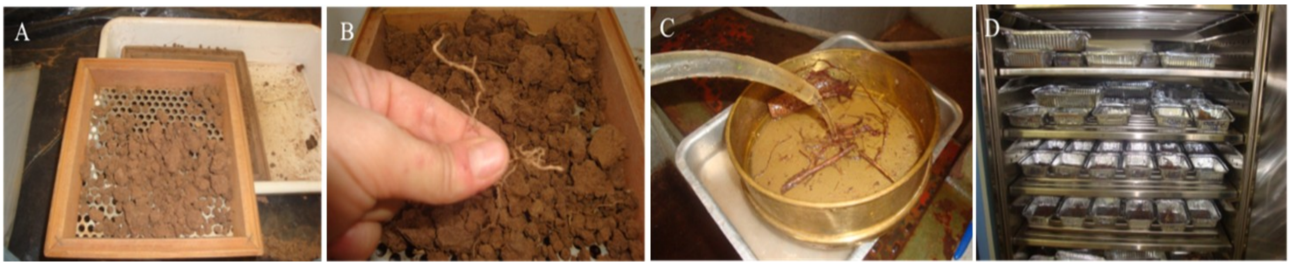

Figure 3. (A) Root separation; (B) Root of *Anadenanthera* sp.; (C) Root wash; and (D) Samples packed in the oven.

After drying, the samples were weighed to determine the dry weight. Next, they were ground in a Willey mill and classified using 200 and 270 mesh sieves, where the aliquot retained in the 270-mesh sieve was used (Figure 4). Subsequently, the material was oven dried at 65°C for 24 hours for elemental CHN analysis.

The elemental CHN analyzer was used to determination the carbon content in each sample. For that purpose, 2 mg of each sample was weighed on an analytical scale, with 0.01 mg precision, placed in the tin capsules, and taken to the elemental analyzer (Figure 5). The carbon values were expressed as percentage. After these steps, it was possible to obtain the amount of carbon by multiplying the carbon content by the rot dry biomass.

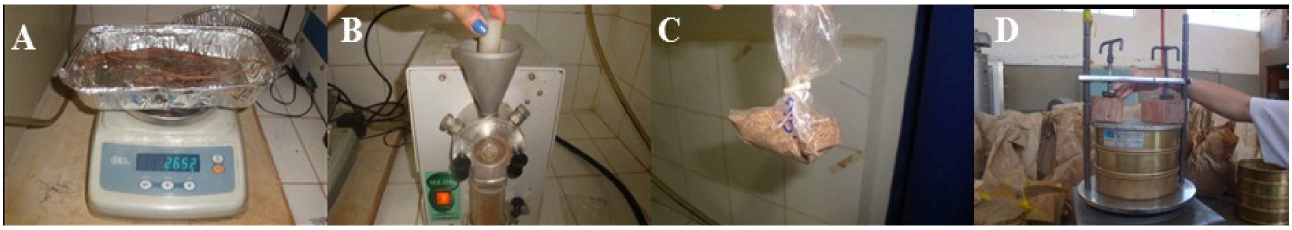

Figure 4. (A) Weighing the samples in a scale; (B) Grinding the samples in Wiley mill; (C) Sampling after grinding; and (D) Classification of samples in 200 and 270 mesh sieves.

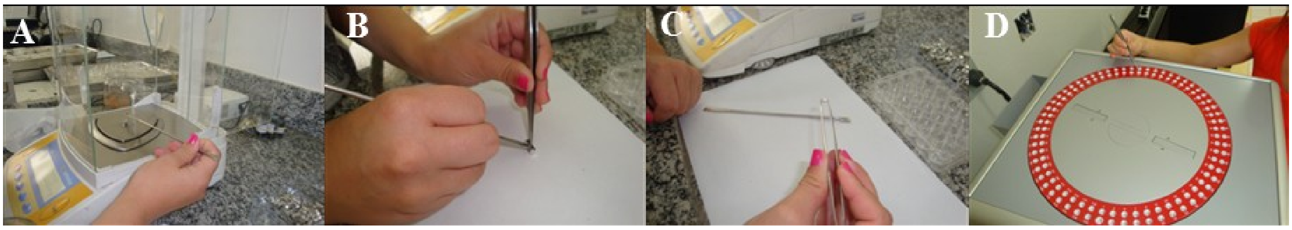

Figure 5. (A) Weighing 2 mg of sample into the tin sample holder; (B) Closing the sample holder; (C) Sample ready for analysis; and (D) Placing the samples on the CHN carousel for elemental analysis.

Tree data

The tree biomass was obtained from inventory data (diameter at 1.30 m aboveground, known as diameter at breast height or DBH, and total height) combined with wood density estimates. According to Chave et al. (2014), the AboveGround Biomass – AGB was obtained in Mg using the *computeAGB* function of the *Biomass* package (Réjou-Méchain, Tanguy, Piponiot, Chave, & Hérault, 2017) in software R (R Development Core Team, 2018), adopting an average wood density of 0.620 g cm^{-3} obtained by means of the function *getWoodDensity*, from the same package. The biomass values were transformed into carbon by applying the constant 0.471, proposed by Thomas and Martin (2012) as the concentration of carbon in the tissues of tropical angiosperms. The estimate carbon stock for each sampling plot was calculated as the sum of the carbon in each tree trunk in the plot.

Statistical Analysis

The carbon estimation was statistically analyzed for each forest compartment (soil, fine roots, and tree stems) and the different depths (0-20, 20-40, 40-60, and 60-80cm), including the average, variance, standard deviation, and coefficient of variation. The statistical significance of the differences in the average carbon stock between the depths (for soil and roots data) was tested by using Tukey's HSD test. Differences with $p < 0.05$ were considered statistically significant.

Semivariograms for each variable (soil carbon stock at four depths, tree root carbon at four depths, and tree carbon stock) were used to test the spatial dependence (SD) of the variable according to the estimator Cressie and Hawkins (1993). The spherical, exponential, and Gaussian models were fitted to the experimental semivariograms by the ordinary least square method. The goodness of fit of each model was evaluated in terms of AIC and degree spatial dependence (Cambardella et al., 1994; Mello et al., 2009). Next, based on the best models for each variable, a carbon stock prediction map was constructed using ordinary kriging (Webster & Oliver, 2007). In the absence of spatial dependence, variables were interpolated using inverse distance weighting (power of 2). According to Cambardella et al. (1994), an SD < 25% indicates weak spatial dependence, SD between 25 and 75% indicates moderate SD and, finally, SD > 75% indicates strong spatial dependence.

Descriptive statistics and geostatistical analyses were performed using the *geoR* package (Ribeiro Júnior & Diggle, 2001) in R (R Development Core Team, 2018). The spatial variability of the data was considered stationary and isotropic.

Results and discussion

Soil carbon stock

Table 1 shows the descriptive statistics for soil carbon stock in the study area.

Table 1. Soil density and descriptive statistics of soil carbon stock at each depth in the study area.

Statistic	Depth			
	1	2	3	4
Soil density (g cm^{-3})	0.89[a]	1.07[b]	1.09[b]	1.11[b]
Carbon content (%)	3.09[a]	2.01[b]	1.69[c]	1.53[c]
Soil carbon stock (Mg ha^{-1})*	55.0465[a]	44.6903[b]	36.7707[c]	32.6309[c]
Variance (Mg ha^{-1})^2	264.7700	103.7429	89.9311	67.6550
Standard deviation (Mg ha^{-1})	16.2718	10.1854	9.3237	8.2253
CV (%)	29.56	22.79	25.36	25.21

*Different letters indicate significant differences between the values according to Tukey's HSD test at 0.05.

A low variation in soil density can be observed at depths between 20 and 80 cm, with values varying ranging from 1.07 to 1.11 g cm^{-3}. In the topsoil, from 0 to 20 cm, there is a lower density, 0.89 g cm^{-3}, which can be explained by the presence of more organic matter in this layer (Parras-Alcántara, Lozano-García, & Galán-Espejo, 2015). Generally, there is a negative relationship between soil density and depth as a result of the high organic matter content at the surface because organic matter is less dense than mineral grains (Hossain, Chen, & Zhang, 2015).

The carbon content, values decrease as the depth increased, from 3.09 to 1.53%. This result corroborates other studies that found carbon content in the upper 20 cm of soil ranging from 2.9 to 4.1% (Powers, Corre, Twine, & Veldkamp, 2011; Ngo et al., 2013). Higher levels of organic carbon in the surface soil in forest environments are due to the presence of the organic mat formed by fallen leaves, tree branches, and bark, and by the higher density of fine roots (Santos, Mello, Mello, & Ávila, 2013, Navarrete-Segueda et al., 2018). Thus, the addition of organic litter material is responsible for the accumulation of carbon in the topsoil layer because it is humified (Mafra et al., 2008), which increases the nutrient cycling in the upper layers of the soil profile (Mora et al., 2018).

Similar to the carbon content, the carbon stock shows a decreasing trend along the soil profile, from 55.05 to 32.63 Mg ha^{-1}, also as a function of the incorporation dynamics of organic matter in the soil profile. The amounts of carbon found in the subsurface layers highlight the importance of subsoils in the terrestrial carbon balances. A similar pattern was observed by Balbinot, Shumacher, Watzlawick, and Sanquetta (2003) when estimating the soil carbon stock under a 5-year *Pinus taeda* plantation in Rio Grande do Sul State, Brazil. The authors found carbon stock values of 83.9, 63.9, 47.6, and 19.6 Mg ha^{-1} at depths 0-20, 20-40, 40-60, and 60-80 cm, respectively. Morais et al. (2017) found an estimated soil carbon stock of 208 Mg·ha^{-1} in vegetation of the Cerrado (woodland savana) biome, in Brazil. Therefore, it can be inferred that the differences in soil carbon stock observed between these studies are related to the type of forest cover as well as the climatic and soil conditions of each area.

Although both the carbon content and stocking exhibit the same behavior in this area, other studies have found different behaviors for these variables when analyzing them independent. For example, Novaes Filho et al. (2007) observed in a primary forest in Southern Amazonia that, although the carbon content of the soil decreases with depth, the carbon stock did not follow this trend with the same intensity, which was explained by the increase of the bulk density of the soil with depth that compensated for the decrease content. The total soil carbon stock under this forest fragment is 169.11 Mg ha^{-1}.

Roots carbon stock

Table 2 shows the descriptive statistics for the root carbon stock in the study area.

Table 2. Average root carbon stock at each depth in the study area.

Statistic	Depth			
	1	2	3	4
Average (Mg·ha^{-1}) *	1.6776[a]	1.3055[b]	0.7931[c]	0.3537[d]
Variance (Mg·ha^{-1})^2	0.0169	0.0154	0.0039	0.0016
Standard deviation (Mg·ha^{-1})	0.1300	0.1242	0.0627	0.0394
CV (%)	7.75	9.51	7.90	11.14

*Different letters indicate significant differences between the values according to Tukey's HSD test at 0.05.

The value found in the top 20 cm of the soil is higher than at the other depths, and there is a significant difference in the root carbon stock between the depths analyzed, which results in a descending gradient of carbon stock in the roots. There is little high variation between the root carbon stock values throughout the area at each depth, as indicated by the low CV values (⩽ 11.14%).

Paiva and Faria (2007), studying root biomass in a cerrado *sensu stricto* area, observed that the more superficial soil layers concentrated most of the root biomass. According to Laclau et al. (2004), the agglomeration of fine roots in the organic horizon represents a strategy to acquire nutrients in infertile soils with nutrient deficiency. Fine roots (roots up to 2 mm in diameter) mainly fulfil nutritional, metabolic, and symbiotic functions in the upper soil layers and horizons (Hendrick & Pretziger, 1996; Jaloviar, Bakošová, Kucbel, & Vencurik, 2009), where there is greater porosity (Baker, Conner, Lockaby, Stanturf, & Burke, 2001). The root system is a vital part of understanding carbon accumulation, nutrient and water absorption by plants, and groundwater infiltration. The total root carbon stock under this forest fragment is 4.1299 Mg ha^{-1}.

Tree carbon stock

Table 3 shows the descriptive statistics of tree carbon stock in the study area.

Table 3. Average tree carbon stock in the study area.

Descriptive statistics	
Average (Mg ha^{-1})	94.25
Variance (Mg ha^{-1})	4,495.71
Standard deviation (Mg ha^{-1})	67.05
CV (%)	71.14

The forest with a predominance of *Anadenanthera* sp. has an average carbon stock of 94.25 Mg ha^{-1}. Aboveground carbon stocks vary widely according to the degree of tree cover, but comparatively, some authors found values similar to those found in this studying other Semideciduous Seasonal Forests. For example, Ribeiro et al. (2009), who quantified the biomass and carbon stock of tree in a mature forest in the Viçosa municipality, Brazil, using the average wood density of the species and found 166.67 Mg ha^{-1} of biomass and 83.34 Mg ha^{-1} of carbon. Additionally, Figueiredo, Soares, Sousa, Leite, and Da Silva (2015), who evaluated the dynamics of tree carbon stock in Minas Gerais State, Brazil, found an average tree carbon stock of 71.81 Mg ha^{-1}.

Aboveground and belowground carbon stocks

Of the three compartments measured (trees, soil, and roots), most of the carbon stock is belowground. The total estimated carbon stock is 267.5183 Mg ha^{-1}, of which 35.23% is in aboveground biomass, 63.22% in soil, 1.54% in roots. According to Dixon et al. (1994), in tropical forests, approximately 50% of the total carbon is stored in aboveground biomass, and 50% is in the layer extending from the soil surface down to 1 m. However, there is a difference between different regions reported in the literature. For example, Djomo, Knohl, and Gravenhorst (2011), when analyzing an African moist tropical forest, found over three times more carbon in the aboveground biomass than in the soil, whereas Gibbon et al. (2010) found twice as much carbon in soil than in aboveground biomass in a Peruvian montane forest.

Ngo et al. (2013) indicated that the contribution of the different compartments to total carbon stock varies markedly between primary and secondary forests. Specifically, in primary forest, the dominant compartment is the aboveground biomass, and the soil contributes less due to a greater number of trees with larger diameters, while the opposite is true in secondary forest. In a secondary tropical forest in Singapore, these authors found a total carbon stock of 274 Mg ha^{-1}, with 38% in aboveground biomass, 52% in soil, 6.9% in coarse roots, 1.5% in coarse woody debris, and 1.3% in fine roots.

Spatial analysis

The results of the geostatistical modeling for the variables with spatial dependence are shown in Table 4. In all cases, the exponential model has performance the best.

Overall, spatial dependence has increased at deeper soil layers. In the deeper soil layers, the soil texture is highly heterogeneous, and the soil is younger and have less carbon (Terra et al., 2015). Therefore, there is a tendency for a more aggregate carbon distribution, increasing the spatial dependence of the process. Furthermore, the surface layers are highly exposed to weathering and fluctuations in the canopy (Parras-Alcántara et al., 2015), which could explain the pure nugget effect found in the layer 1 (0-20 cm) (i.e., spatial dependence is detected) and the moderate/strong spatial dependence in the other layers.

Table 2. Parameters of the Semivariogram for the aboveground and belowground carbon stock under a forest fragment with predominance of *Anadenanthera* sp. at different depths.

Carbon stock	Model	Nugget	Partial sill	Range	SD	
Soil (Depth 2)	Exponential	50.84	81.72	142.13	61.65	Moderate
Soil (Depth 3)	Exponential	19.54	64.22	40.48	76.67	Strong
Soil (Depth 4)	Exponential	33.44	53.00	142.13	61.31	Moderate
Roots (Depth 2)	Exponential	0.01	0.01	142.13	51.84	Moderate
Roots (Depth 4)	Exponential	6.10E-04	8.69E-04	26.22	58.75	Moderate
Trees	Exponential	2515.41	3101.73	142.13	55.22	Moderate

Cambardella et al. (1994) argue that strong spatial dependence can be explained by soil properties, while weak spatial dependence is influenced by external factors. In contrast to our results, Chaves and Farias (2010) observed (in a soil cultivated with sugarcane) that the carbon stock in surface soil layer showed a moderate degree of spatial dependence, while in the subsurface layers, there was a strong degree of dependence. In addition, Novaes Filho et al. (2007) found spatial dependence of soil carbon in the surface and subsurface horizon. These authors concluded that the carbon concentration varies according to the vegetation type, topographical position of the landscape, and intrinsic soil characteristics, such as texture.

Cerri et al. (2004) observed high heterogeneity among soil attributes in the state of Rondônia, Brazil, despite the apparent similarity between the studied sites. The authors used samples at a distance of 25 m from each other and observed a pure nugget effect in most of the soil attributes, indicating high variability within a small space, even at distance shorter than that of the plots.

For the root carbon stock, spatial dependence has not been observed in layers 1 and 3 (0-20 and 40-60 cm, respectively), indicating the occurrence of random root development in these layers. In layers 2 and 4 (20-40 and 60-80 cm, respectively), there is moderate spatial dependence with a range of 142.13 and 26.22 m, respectively. This finding may be associated with the horizontal and vertical variation of the soil texture. In superficial, layers there is a greater porosity (Baker et al., 2001) and homogeneity soil texture, whereas in deeper layers, there is a greater soil texture heterogeneity (Terra et al., 2015), resulting in a more aggregate distribution of roots.

The tree carbon stock exhibits moderate spatial dependence, with a range of 142.13 m. Spatial dependence of the tree carbon stock was also observed by other authors (Amaral, Ferreira, Watzlawick, & Genú, 2010; Terra et al., 2015).

For the variables that exhibited spatial dependence, an interpolation was performed by ordinary kriging, and for those without spatial dependence, an IDW interpolation was performed.

The spatial distribution maps of soil carbon stock at each depth clearly show the presence of a north-south gradient of the soil carbon stock throughout the area at all depths analyzed (Figure 6). The values are higher in the northern part than in the southern part, and a decrease in the amount of soil carbon stock can be observed with increasing depth.

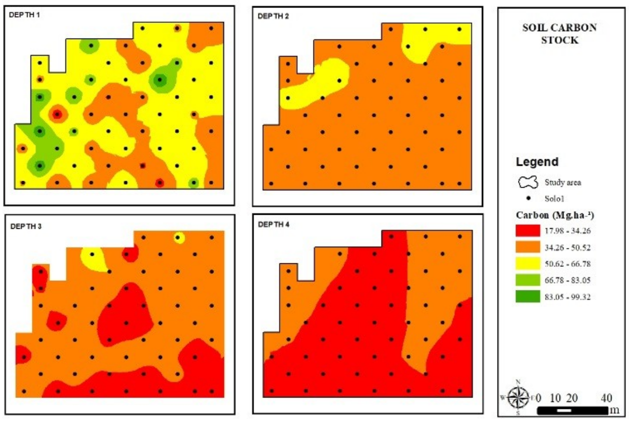

Figure 6. Spatial distribution maps of soil carbon stocks under a forest fragment with a predominance of *Anadenanthera* sp. at depths 1 (0-20 cm), 2 (20-40 cm), 3 (40-60 cm), and 4 (60-80 cm).

The comparison between the spatial distribution map of the total soil carbon stock and map of tree carbon stock show that these variables have an approximately similar spatial pattern throughout the study area (Figures 7 and 8), indicating a relation between them. Some authors have already shown the existence of a close relationship between the tree carbon stock and soil carbon stock in tropical forests (Mafra et al., 2008; Don, Schumacher, & Freibauer, 2010; Fan et al., 2015). Morais et al. (2017) studied the spatialization of carbon stock in the cerrado biome and concluded that its spatial distribution follows a reasonable trend among the studied compartments, where the highest soil carbon stock is observed under the plots with higher tree carbon stocks.

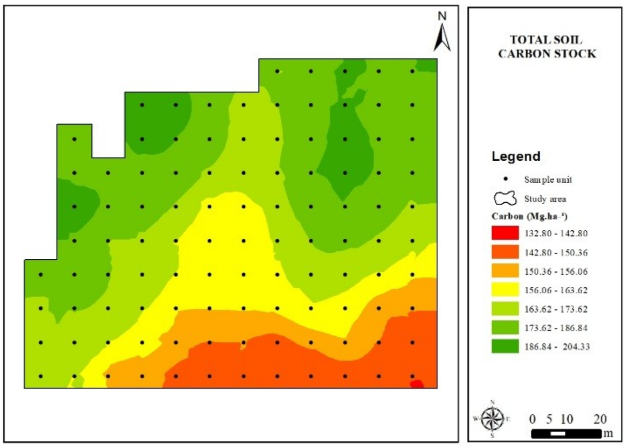

Figure 7. Spatial distribution map of the total soil carbon stock under a forest fragment with a predominance of *Anadenanthera* sp.

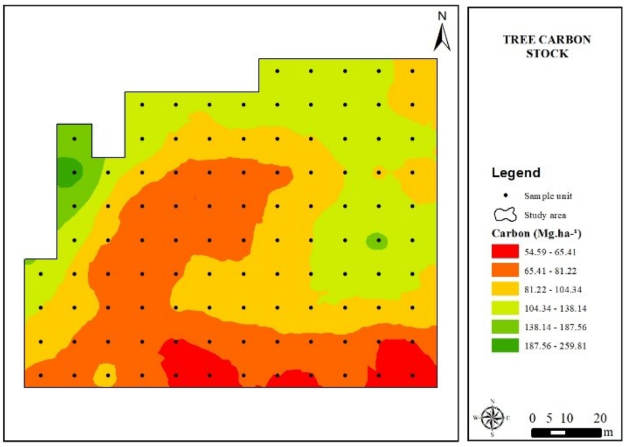

Figure 8. Spatial distribution map of the tree carbon stock in a forest fragment with predominance of *Anadenanthera* sp.

When evaluating the north-south gradient observed in the soil carbon stock, it is important to consider the vegetation around the studied area. On the northern side, there is a mature eucalyptus stand (15 years old) consisting of trees with an average diameter of 23 cm and an average height of 25 m. This eucalyptus stand may explain the greater amount of carbon in the soil on the northern side due to biomass recycling and litter deposition, influencing not only the increase of in the amount of carbon but also nutrients cycling (Wink et al., 2018), which is essential for the growth and increment of vegetation. Dantas et al. (2018), when analyzing the influence of soil on the distribution of tree species in the Cerrado, observed that soil organic matter influences the distribution of species and the number of trees. This finding explains the gradient also observed in the tree carbon stock.

The roots carbon stock maps (Figure 9) indicate that there is no horizontal variation at each depth, but there is decreasing trend in root carbon stock depths. The depth increases and the carbon stock decreases. However, when analyzing the total carbon map of the root, there is a spatial structure in the distribution of this variable, which does not follow the gradient observed in the soil carbon stock map nor the tree carbon stock map. Mou, Jones, Mitchell, and Zutter (1995) studied the relationship between aboveground and belowground biomass and found that fine roots had weak and often nonsignificant correlations with local aboveground biomass. The authors suggested that the heterogeneity in soil resources at small scales may be a key mechanism that controls the spatial distribution of fine roots and that is crucial for understanding belowground interactions in plant communities.

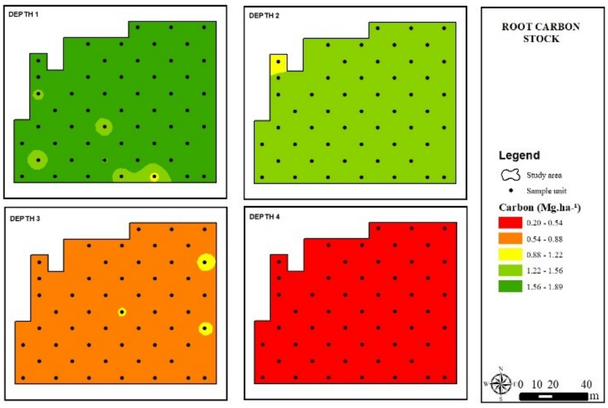

Figure 9. Spatial distribution maps of root carbon stocks under a forest fragment with a predominance of *Anadenanthera* sp. at the depths 1 (0-20 cm), 2 (20-40 cm), 3 (40-60 cm), and 4 (60-80 cm).

There is an east-west horizontal gradient of the total root carbon stock (Figure 10), albeit with a low variation from 4.28 to 3.63 Mg ha^{-1}. The higher root carbon stock observed on the eastside side may be associated with the edge effect in this region, where lower competition may favor greater root development.

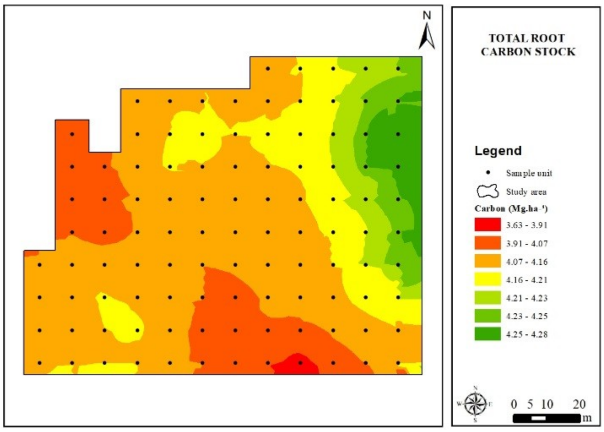

Figure 10. Spatial distribution map of the total root carbon stock under forest fragment with predominance of *Anadenanthera* sp.

The map of total aboveground and belowground carbon stock (Figure 11) shows the spatial distribution of the carbon stock in the three compartments analyzed (soil, roots, and trees). The presence of a north-south gradient is evidence, influenced by the higher soil and tree carbon stocks when compared to the root carbon stock. There is high variability in the values found I the entire area, ranging from 201.79 to 423.27 Mg ha^{-1}. The lowest carbon stock values occur along the southern border, where there is a low-carbon, secondary sucessional semi-deciduous forest.

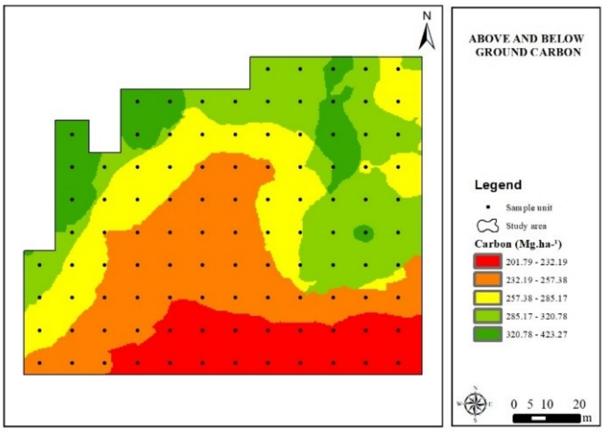

Figure 11. Spatial distribution map of the total aboveground and belowground carbon stock in a forest fragment with predominance of *Anadenanthera* sp.

This study provides high-quality *in situ* data on carbon stock and compartments, which is important for understand carbon stocks and cycling controls, to calibrating global models of the carbon cycle, and supporting regulatory frameworks such as the United Nations REDD+ program.

Conclusion

Soil and tree carbon stock have a moderate degree of spatial dependence, while the root carbon stock exhibits a weak degree of dependence.

In the soil, a spatial pattern of the carbon stock is repeated at all depths analyzed, but there is a reduction in the amount of carbon as the depth increases. Tree carbon stock follows the same pattern as the soil, indicating that there is a relationship between these variables. In the fine roots, the carbon stock decreases with increasing depth, but the spatial gradient does not follow the same pattern as the soil and tree carbon stock.

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