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Mapping of Carbon Stock in Litter and Soil Using Krigage and Inverse Distance Weighted

Mapeamento do Estoque de Carbono na Serapilheira e no Solo Utilizando Krigagem e Inverso do Quadrado da Distância

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Abstract

The significant climate changes occurring on the planet are mainly due to the increase in concentrations of carbon dioxide in the atmosphere. In this context, the objective of this field study was to quantify, evaluate and map the carbon stored in litter and soil in the Mário Xavier National Forest, in Seropédica, Rio de Janeiro, Brazil. For this, 20 sampling units (1 m²) were installed using the simple casual sampling process, where samples of litter present on the soil surface were collected and after that a trench was opened to collect the soil. For the soil, undisturbed and deformed samples were collected in the following five depths. After sorting, the litter samples were taken to the muffle furnace to determine the organic matter content, and then the carbon stock was calculated. For the soil samples, after determining the density, the total soil organic content was obtained using the methods proposed by Yeomans and Bremner and then the carbon stock was determined. Next, an analysis of the experimental semivariogram and adjustment of the geostatistical models was carried out to obtain the parameters and apply ordinary kriging. The carbon stock in litter has a spatially dependent structure, with an average value of 3.38 Mg ha^{-1}. The soil didn´t show spatial dependence, having to be mapped using the inverse weighted method, but the highest average carbon stock is in the 20 – 30 cm layer with 42.57 Mg ha-^{1}.

Keywords: Geostatistics. Spatial dependence. Atlantic forest. Conservation Unit.

Resumo
As expressivas mudanças climáticas que ocorrem no planeta são, principalmente, devido ao aumento das concentrações de dióxido de carbono na atmosfera. Nesse contexto o objetivo deste estudo de campo foi quantificar, avaliar e mapear o carbono estocado na serapilheira e no solo na Floresta Nacional Mário Xavier, em Seropédica, Rio de Janeiro, Brasil. Para isso, foram instaladas 20 unidades amostrais (1 m^2) pelo processo de amostragem casual simples, onde foram realizadas coletas de amostras de serapilheira presente na superfície do solo e após isso foi aberta uma trincheira para a coleta do solo. Para o solo foram coletadas amostras indeformadas e deformadas nas seguintes em cinco profundidades. Após a triagem as amostras de serapilheira foram levadas as mufla para determinação do teor de matéria orgânica, para em seguida ser calculado o estoque de carbono. Para as amostras de solo, após a determinação da densidade, foi obtido o orgânico total solo utilizando os métodos propostos por Yeomans e Bremner e em seguida determinado o estoque de carbono. Em seguida foi realizado análise do semivariograma experimental e ajuste dos modelos geoestatísticos para obtenção dos parâmetros e aplicação da krigagem ordinária. O estoque de carbono na serapilheira apresenta estrutura de dependência espacial, sendo o seu valor médio de 3,38 Mg ha^{-1}. O solo não apresentou dependência espacial, tendo que ser mapeado pelo método do Inverso do Quadrado da Distância, mas a maior média de estoque de carbono está na camada de 20 – 30 cm com 42,57 Mg ha^{-1}.

Palavras-chave: Geoestatística. Dependência Espacial. Mata Atlântica. Unidade de Conservação.

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1 Introduction

The significant climate changes occurring on the planet are mainly due to the increase in carbon dioxide (CO_2) concentrations in the atmosphere. Deforestation, land-use changes, and forest fires are activities that significantly contribute to annual atmospheric CO_2 emissions (Junges *et al.*, 2018). Along with arboreal individuals, the soil and litter compartments are responsible for a large share of the carbon stored on the planet.

The soil is the most complex carbon sink, as it is a layer of transformed material resulting from the mixture of minerals, organic matter, air, living organisms, and water (Guilherme; Lima, 2003). The presence of forest vegetation and, consequently, biomass on its surface promotes the accumulation of organic matter, which contributes to soil carbon storage (Novais *et al.*, 2016; Pulrolnik *et al.*, 2021). Litterfall also acts as a carbon sink in forest ecosystems.

In general, studies focusing on carbon stock typically consider the arboreal individual as a whole (Neves *et al*., 2022), only the trunk (Ribeiro *et al*., 2009), or even the soil (Braga; De Assis Braga; Venturin, 2022), but not litterfall, which connects these environments. Some studies, however, have addressed this aspect, such as those conducted by Torres *et al*. (2013) and Rocha *et al.* (2014).

Most of these studies use classical statistics to represent the variable and determine the local stock average, disregarding its potential spatial dependence, as seen in the study conducted by Morais *et al.* (2017). The application of the geostatistical method enables the estimation and mapping of regionalized variables in unsampled locations by leveraging contributions from samples with known values (Yamamoto; Landim, 2013).

Currently, geostatistics is applied across various fields of study, including geological sciences (Oliveira; Antônio, 2017), agronomy and soil sciences (Alves *et al.*, 2022), meteorology (Mello; Oliveira, 2016), and environmental and forest sciences (Morais *et al*., 2017; Ataíde *et al*., 2022).

There are studies demonstrating the potential of using geostatistics and ordinary kriging for the spatialization and estimation of biomass and carbon, showing that classical statistics alone is insufficient to explain the behavior of such forest variables when they exhibit spatial dependence (Amaral *et al*., 2010). The technique has proven effective in estimating the spatial distribution of arboreal carbon stock using regression kriging in the Atlantic Forest, Caatinga, and Cerrado biomes (Scolforo *et al*., 2015).

Regression kriging yielded even better results for mapping and estimating carbon stock distribution across the entire state of Minas Gerais (Scolforo *et al*., 2016). With the aid of kriging, Oliveira *et al*. (2021) developed a methodology that enabled the periodic updating of carbon stocks in Cerrado fragments, generating productivity maps for this variable.

In this context, the objective of this field study was to quantify, assess, and map the carbon stored in the litterfall and soil in the Mário Xavier National Forest (FLONA MX), located in Seropédica, Rio de Janeiro, Brazil.

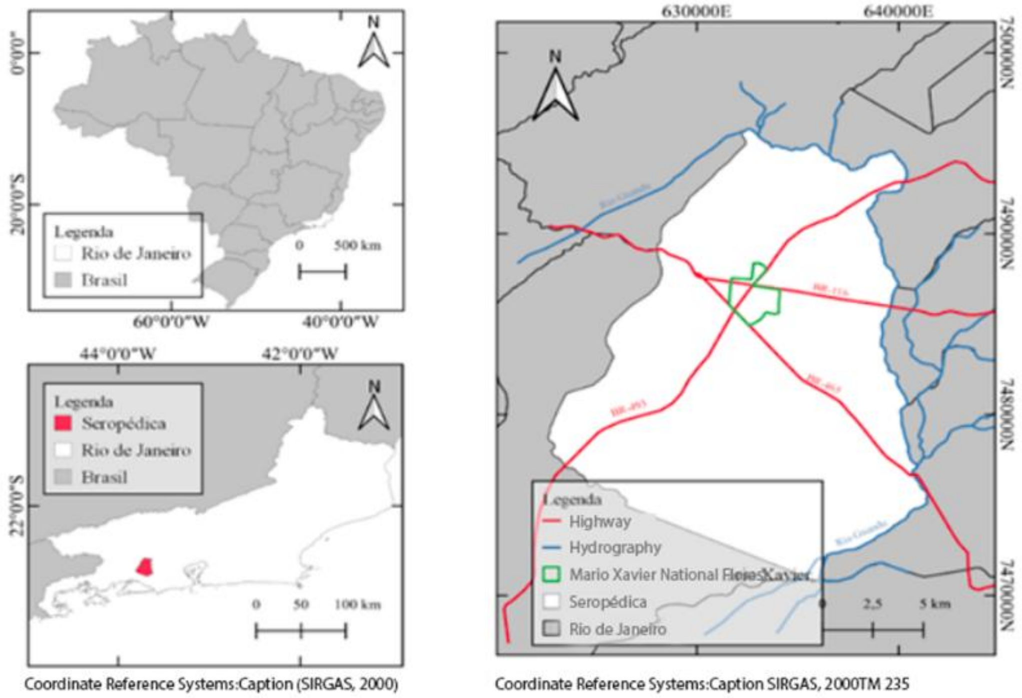
2 Material and Methods

2.1 Location and characterization of the study

The study was conducted in the Mário Xavier National Forest (FLONA), located in the municipality of Seropédica (22°44’0.62” S, 43°42’33.25” W), in the state of Rio de Janeiro, covering an area of 496 hectares. FLONA was established by Decree No. 93.369 on October 8th, 1986 (Brasil,

1986) and belongs to the Sustainable Use category of Conservation Units (Brasil, 2000) (Figure 1).

Figure 1 - Location of Mário Xavier National Forest, Seropédica, Rio de Janeiro, Brazil



Source: research data.

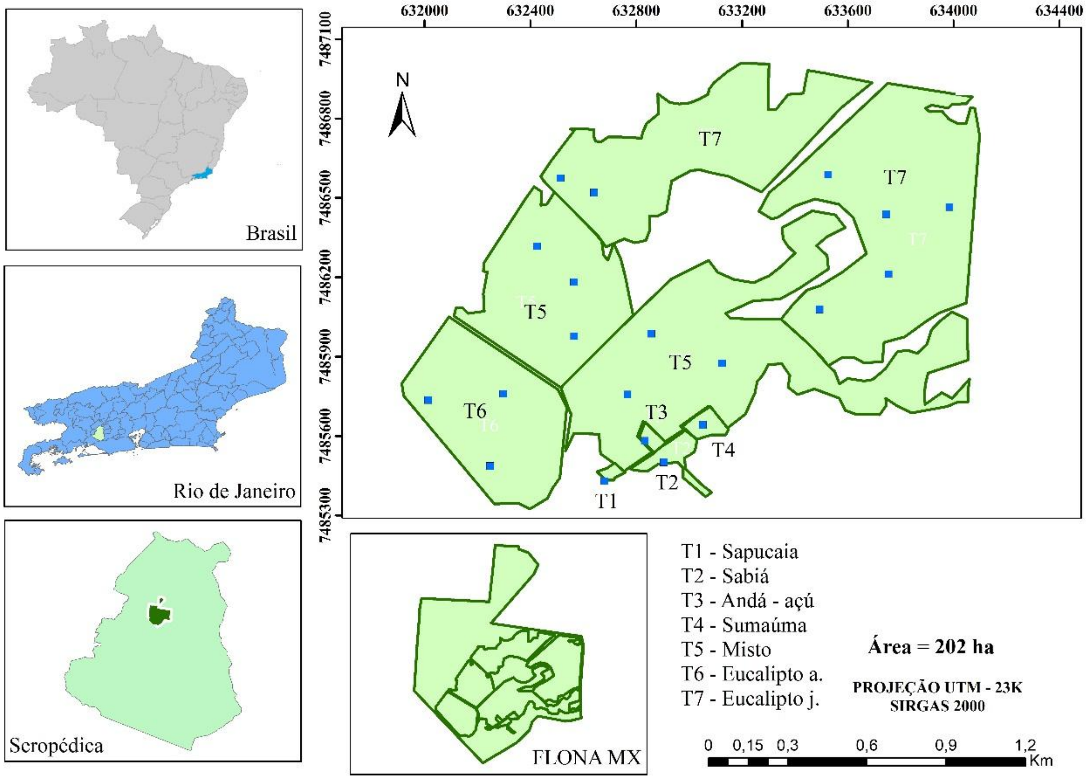
According to the Köppen classification, the region's climate is classified as Aw, tropical with rainy summers and dry winters (Alvares *et al*., 2014). The altitude ranges from 0 to 25 meters, and the terrain is generally flat (Gasparini *et al.*, 2013).

The Mário Xavier National Forest (FLONA MX) consists of different areas where native and exotic species have been planted. Currently, FLONA has seven distinct plots, each with specific species: sapucaia (plot 1), sabiá (plot 2), Andá-açu (plot 3), sumaúma (plot 4), a mix of 50 species (plot 5), old eucalyptus trees planted in the 1940s (plot 6), and young eucalyptus trees planted in 1997 (plot 7) (Souza, 2017). The total area covered by tree vegetation is 202 hectares.

2.2 Sampling and data collection

A total of 20 sampling units (SU) were allocated, georeferenced, and set at an area of 1 m² (1 × 1 m). These units were randomly distributed (simple random sampling) within each plot. Due to variations in plot size, some plots received only one sampling unit (Figure 2).

Figure 2 - Distribution of plots and sampling units (blue squares) in the Mário Xavier National Forest, Seropédica, Rio de Janeiro, Brazil



Source: research data.

In May 2022, all litterfall present above the soil surface was collected from each sampling unit. The samples were stored in paper bags and labeled for further analysis.

In the laboratory, the samples were sieved and dried in an oven with forced air circulation at a temperature of 65–70 °C until they reached a constant weight. The dry biomass (g) of each sample was then weighed using a precision balance and separated into compartments: leaves, woody material, reproductive material, and miscellaneous.

The samples from each sampling unit and their respective compartments were ground using a Willey mill, and 1 g subsamples were taken, totaling 80 samples. Each 1 g sample was placed in an open porcelain crucible and subjected to muffle furnace incineration at 550 °C for 3 hours, ensuring complete combustion. After removal from the muffle furnace, the samples were cooled in a desiccator before being weighed on a precision balance (0.0001 g accuracy). The organic matter content (OM%) was determined based on the mass loss of the incinerated residue, considering the material lost during combustion (Equation 1). The OM% value was then divided by the factor 1.8 (Jiménez; Garcia, 1989) and multiplied by the biomass of each sample to calculate the carbon stock.

$$MO(\%) = \frac{(P-(T-C)*100)}{P}$$

Where: P = sample weight (g) after drying at 105°C; C = crucible tare weight (g); and T = weight of ash plus the crucible (g).

Soil samples were collected from the same sampling units. A 40-cm deep mini trench was excavated, and undisturbed samples were taken using a Kopeck ring to determine soil bulk density (Ds). Additionally, disturbed samples were collected for further analyses. Each sampling unit (SU) yielded a total of ten samples: five disturbed and five undisturbed, with two samples collected at each depth level (0–5 cm, 5–10 cm, 10-20 cm, 20-30 cm, and 30-40 cm).

For the determination of soil bulk density (Ds), the undisturbed samples were oven-dried at 110°C until they reached a constant weight. The soil density was then calculated using the volumetric ring method, based on the mass/volume ratio.

The disturbed samples were air-dried, crushed, and sieved through a 2.00 mm mesh to obtain air-dried fine soil (TFSA). These samples were used to determine total soil organic carbon (SOC) following the methods proposed by Yeomans and Bremner (1988).

The soil carbon stocks (C) were then calculated using Equation 2.

$$C = \frac{(COT * DS * P)}{10}$$

Where:

- C = total organic carbon content in the layer (g kg^{-1})
- Ds = soil bulk density (Mg m^3)
- p = depth of the analyzed layer (cm)

2.3 Spatial distribution of carbon stock in litter and soil

After obtaining the carbon stock in litter, its compartments, and soil, an exploratory data analysis was conducted to identify outliers, calculate descriptive statistics, and perform the Shapiro-Wilk normality test (α=0.05) to ensure proper data geostatistical modeling.

The variographic study (Equation 3) of carbon stock was carried out in the 0º, 45º, 90º, and 135º directions to verify the isotropy and spatial continuity of the variable of interest. The spherical (Equation 4), exponential (Equation 5), and Gaussian (Equation 6) models were fitted to obtain the nugget effect (C_0), contribution (C), and range (a). The fitting process was performed using the maximum likelihood method, with the GeoR package (Ribeiro Júnior; Diggle, 2001) in R software (R CORE TEAM, 2015).

Semivariogram: $\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2$

Spherical Model: $\gamma(h) = C_0 + C\left[1{,}5\frac{h}{a} - 0{,}5\left(\frac{h}{a}\right)^3\right]$ para $h < a$

$\gamma(h) = C_0 + C$ para $h \geq a$

Exponential Model: $\gamma(h) = C_0 + C\left[1 - e^{\left(-\frac{h}{a}\right)}\right]$

Gaussian Model: $\gamma(h) = C_0 + C\left[1 - e^{\left(-\frac{h}{a}\right)^2}\right]$

Where : γ(h) = estimated semivariance between pairs of points; N(h) = number of pairs of measured values z(x_i), z(x_i + h), separated by distance h; C0 = nugget effect; C = contribution; a = range.

The quality of model fitting was assessed through cross-validation, Akaike Information Criterion (AIC) (Equation 7), mean reduced error ((ER)̅) (Equation 8), and standard deviation of reduced errors (Ser) (Equation 9).

$$AIC = -2 \log \log L + 2K$$

$$\overline{ER} = \frac{1}{n}\sum_{i=1}^{n}\frac{z(x_{i0}) - \hat{z}(x_{i0})}{\sigma(x_{i0})}$$

$$S_{er} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left\{\frac{z(x_{i0}) - \hat{z}(x_{i0})}{\sigma(x_{i0})}\right\}^2}$$

In which: L = likelihood of the candidate model; K = number of parameters of the candidate model; n = number of observations; z(x_i0) = observed value at point i0; ẑ(x_i0) = estimated value at point i0; σ(x_i0) = kriging standard deviation at point i0.

With the adjusted parameters, the spatial dependence index (Equation 10) was obtained, classifying it as low (IDE ≤ 25%), moderate (25% ≤ IDE ≤ 75%), and strong (IDE > 75%), as described by Zimback (2003).

$$IDE = \frac{C}{(C_0 + C)}$$

Where : C0 = nugget effect; C = contribution; IDE = spatial dependence index.

After selecting the model that best fits the experimental semivariogram, ordinary kriging (Equation 11) was performed to obtain spatial estimates of carbon stock in the litter and soil at unsampled locations.

$$Z(x_0) = \sum_{i=1}^{n}\lambda_i Z(x_i)$$

Where: Z(x_0) = estimate at the unsampled point; Z(x_i) = observed value at the i-th sampled point; n = number of sampled points; λ_i = weight associated with the i-th sampled points (i = 1,2,3,...,n).

3 Results and Discussion

3.1 Descriptive statistics

For the litter data, the Shapiro-Wilk normality test (α=0.05) rejected the normality hypothesis for the reproductive and miscellaneous compartments, which also showed a high coefficient of variation. Considering the 20 sampling units (UAs), the highest stored carbon value was detected in the miscellaneous compartment, while the lowest value was found in the reproductive compartment. Regarding the average stock, the highest mean corresponds to the woody compartment (Table 1).

Table 1 - Table - Descriptive statistics and Shapiro-Wilk normality test for stored carbon (Mg ha⁻¹) in litter and its compartments

Compartments	Min	Max	$\bar{x}$	s	CV%	p-value
Leaves	0.04	1.76	0.76	0.38	50.36	0.4329
Woody material	0.18	2.44	1.36	0.72	52.83	0.2533
Reproductive material	0.01	0.87	0.12	0.20	201.50	0.0005*
Miscellaneous	0.18	2.87	1.18	0.81	68.02	0.0348*
Total	1.17	5.77	3.38	1.22	36.33	0.2553

In which: Min = minimum value; Max = maximum value; s = standard deviation; CV% = coefficient of variation in percentage; p-value = p-value from the Shapiro-Wilk normality test (α = 5%); C = stored carbon (Mg ha⁻¹); * = rejection of the normality hypothesis according to the Shapiro-Wilk test (α = 5%).
Source: research data.

For the soil samples, the main descriptive statistics on the total organic carbon (TOC) content and carbon stock (C) show a higher coefficient of variation for TOC than for C in the first three analyzed layers. However, in the last two layers, this result is reversed (Table 2).

Table 2 - Descriptive statistics for total organic carbon (TOC) content and stored carbon (C) at five soil depths in the Mário Xavier National Forest, in the municipality of Seropédica, Rio de Janeiro, Brazil

Soil Depth (cm)	Variables	Mean	Maximum Value	Minimum Value	Standard Deviation	Coefficient of Variation (%)
0 – 5 cm	TOC (g kg⁻¹)	27.08	42.23	11.46	10.52	38.85
	C (Mg ha⁻¹)	12.62	18.81	6.02	4.42	34.99
5 – 10 cm	TOC (g kg⁻¹)	20.70	36.59	8.89	7.16	34.58
	C (Mg ha⁻¹)	21.49	37.61	10.04	6.68	31.09
10 – 20 cm	TOC (g kg⁻¹)	16.13	27.75	5.89	5.97	37.04
	C (Mg ha⁻¹)	36.75	63.18	14.29	13.39	36.43
20 – 30 cm	TOC (g kg⁻¹)	11.92	27.04	4.06	5.70	47.82
	C (Mg ha⁻¹)	42.57	95.11	15.60	20.61	48.42
30 – 40 cm	TOC (g kg⁻¹)	8.17	13.17	1.51	3.08	37.70
	C (Mg ha⁻¹)	39.14	66.83	7.69	15.07	38.50

Source: research data.

Considering the sum of the average values across the five layers and sampling units, the total stored carbon (C) was 152.57 Mg ha⁻¹. The coefficients of variation for carbon stock were below 40% for all layers, except for the 20–30 cm layer, which showed values above 45% (Table 2). The highest carbon stock in the soil was found in the 20–30 cm layer (95.11 Mg ha⁻¹), while the lowest value was observed in the 0–5 cm layer (6.02 Mg ha⁻¹).

These results may be related to the different conditions of the studied plots. The sampling units located in plots 2 and 7 are more degraded areas, with constant anthropogenic influence, including fire (plot 7) for pasture renewal. This scenario prevents the accumulation of organic matter on the soil surface, directly impacting carbon stock.

3.2 Spatialization of stored carbon

The average total litter biomass stock in the area was 6.08 Mg ha^{-1}, while the average carbon stock was 3.38 Mg ha^{-1}. The carbon stored in the litter exhibited a spatial dependence structure in the spherical, exponential, and Gaussian theoretical semivariogram models, with strengths ranging from moderate (woody material, miscellaneous, and total) to strong (leaf and reproductive) (Table 3). In the Cerrado biome, Morais *et al.* (2017) also found a strong spatial dependence structure of carbon stored in litter, with spatial pattern variations ranging from 3.95 Mg ha^{-1} to 9.75 Mg ha^{-1}.

Table 3 - Model fitting statistics for semivariance and spatial dependence index for the carbon variable (Mg ha^{-1}) in the Mário Xavier National Forest, municipality of Seropédica, Rio de Janeiro, Brazil

Stored Carbon (Mg ha^{-1})								
Comp.	**Mod.**	**C_0**	**C**	**A**	**IDE%**	**AIC**	**$\overline{ER}$**	**S_{er}**
Leaf	Exp	0.000	0.133	159.315	100.00	23.024	0.046	1.139
	Sph	0.001	0.126	478.029	98.67	22.328	0.074	1.193
	Gau	0.022	0.112	222.030	83.53	22.392	0.085	1.307
Woody Material	Exp	0.221	0.278	234.887	55.70	49.786	-	-
	Sph	0.294	0.231	468.398	44.02	48.964	-0.052	1.264
	Gau	0.242	0.266	821.199	52.36	49.059	-0.064	1.278
Reproductive Material	Exp	0.000	0.045	214.213	100.00	1.861	0.409	2.166
	Sph	0.000	0.045	572.560	100.00	0.752	0.412	2.609
	Gau	0.000	0.047	268.522	100.00	-0.045	0.385	2.618
Miscellaneous	Exp	0.335	0.319	646.233	48.73	52.997	-0.096	1.417
	Sph	0.343	0.278	1272.042	44.78	52.354	-0.090	1.455
	Gau	0.274	0.324	885.357	54.12	51.992	0.073	1.424
Total	Exp	0.487	0.976	190.591	66.71	71.392	1.220	-0.047
	Sph	0.946	0.561	449.910	37.23	70.784	-	-
	Gau	0.735	0.767	813.251	51.06	71.015	-	-

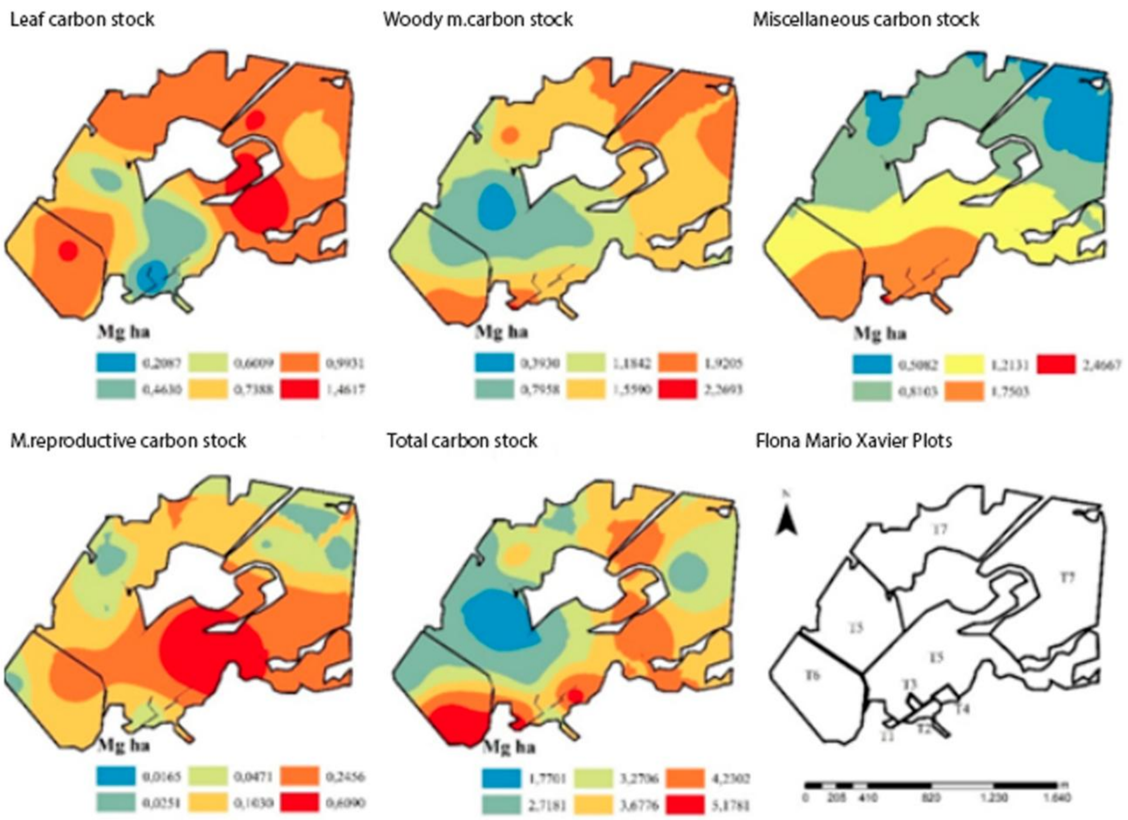
Where:Comp. = Compartment;Mod. = Model;C_0 = Nugget effect;C = Contribution;A = Range;AIC = Akaike Information Criterion;$\overline{(ER)}$ = Mean reduced error;Ser = Standard deviation of reduced errors;IDE (%) = Spatial dependence index.
Source: research data.

The exponential model was the best fit for the experimental semivariogram across the evaluated compartments, presenting the best adjustment statistics. This result was also found by Scolforo *et al.* (2016) and Morais *et al*. (2017) when assessing carbon stocks in forests.

The range value of spatial dependence varied according to the analyzed compartment, demonstrating the average radius within which two points are spatially related.

Ordinary kriging enabled the spatialization of carbon stock in the litter and its compartments, represented by a color gradient from cooler to warmer tones (Figure 3). There is a similarity between the spatial distribution of the leaf and reproductive material compartments, both showing the highest stock between plots 5 and 7. The same relationship is also observed in plot 6 when comparing the leaf compartment and total litter, as the leaf compartment represents the largest contribution to litter.

Figure 3 - Spatialization of carbon stock in litter and its compartments (Mg ha^{-1}) using ordinary kriging across all studied plots in the Mário Xavier National Forest, municipality of Seropédica, Rio de Janeiro, Brazil.Where:T1 = Sapucaia;T2 = Sabiá;T3 = Andá-açú;T4 = Sumaúma;T5 = Mixed;T6 = Eucalyptus a.;T7 = Eucalyptus j



Source: research data.

The carbon stored in the woody compartment shows high values in areas where eucalyptus species are present, due to the greater accumulation of bark and branches on the soil surface. The highest stock in the reproductive material occurs in part of plot 4, where sumaúma trees are found, and in plot 5, where most individuals of the arco-de-pipa species are concentrated. For both species, a high fruit production was observed at certain times of the year, explaining this accumulation on the soil surface.

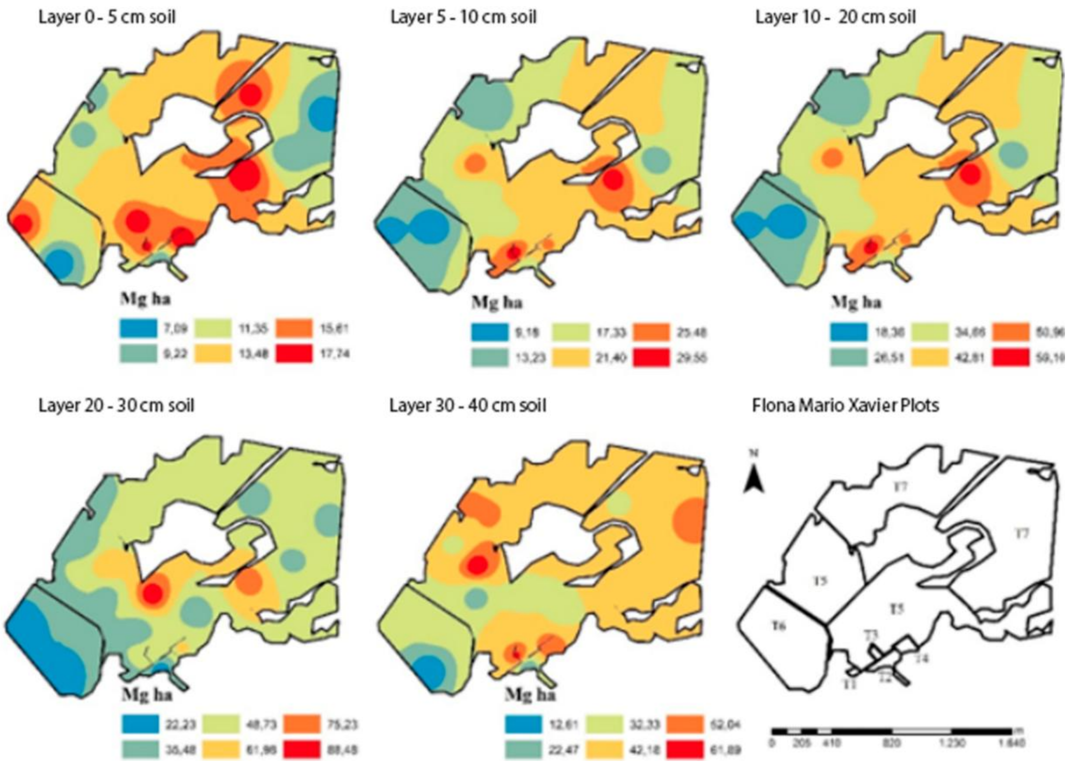
The variation in carbon stock among the studied plots allows for a correlation with the characteristics of the vegetation in each area. The largest carbon stock was detected in plot 6. In 1945, ten eucalyptus species were planted in this area. Over the years, this region has undergone a process of natural regeneration, aided by seed dispersal and influenced by the planting of native species in surrounding areas. It is also a more isolated plot, where anthropogenic access is limited due to the river that encircles the area.

The carbon stock can vary according to the characteristics of specific areas, potentially increasing over the years with vegetation growth (Cordeiro *et al*., 2018). Studies conducted in legal reserves and permanent preservation areas, where anthropogenic influence is minimal, also highlight the increase in stored carbon (Bello *et al*., 2015).

It is important to note that the carbon stock in the sample units located in plot 7 does not reflect values accumulated since the plantation was established. This plot is frequently affected by wildfires and livestock intrusion for grazing, which hinders the accumulation of litter on the soil and, consequently, the carbon stock in the region.

The analysis of the experimental semivariogram did not reveal spatial dependence of the carbon variable in the soil, as the parameter results indicated only nugget effect values, with zero contribution and range at all analyzed depths. Therefore, the inverse distance squared method was used for mapping, considering 15 neighboring points (Figure 4).

Figure 4 - Spatialization of soil carbon stock considering its depths (Mg ha^{-1}) using the inverse distance squared method across all studied plots in the Mário Xavier National Forest, municipality of Seropédica, Rio de Janeiro, Brazil.Where:T1 = Sapucaia;T2 = Sabiá;T3 = Andá-açú;T4 = Sumaúma;T5 = Mixed;T6 = Eucalyptus a.;T7 = Eucalyptus j



Source: research data.

In the presented maps, a similarity can be observed in the spatial distribution between the 5–10 cm and 10–20 cm depths; however, the 10–20 cm layer shows significantly higher values. The 20–30 cm layer has the highest carbon stock, which is particularly evident in the center of plot 5, where mixed species are present, especially in sample units 4 and 6, as well as in part of plot 7, near sample unit 8.

Plot 2 consistently shows the lowest carbon stock values across all soil layers. In the 0–5 cm and 5–10 cm layers of plot 7, there is a greater variation in carbon levels, likely due to the annual wildfires affecting the area. However, in deeper layers, plot 7 generally exhibits a more stable carbon stock, ranging between 34 and 42 Mg ha^{-1}. Given that carbon stocks are directly impacted by vegetation cover loss (Sanquetta *et al.*, 2018), it is crucial to maintain forested areas protected so they continue to act as carbon sinks rather than contributing to CO_2 emissions.

Projects aimed at forest conservation, reducing wildfires and deforestation, minimizing greenhouse gas emissions, and highlighting the importance of a conservation unit in an urban environment should be considered. Tropical forests serve as important carbon sinks, likely as a response to increasing atmospheric carbon concentrations, which enhance forest productivity (Clark, 2004).

Studies estimating carbon stock are essential, as the conservation of these areas ensures long-term carbon credit estimation.

4 Conclusion

The carbon stock in the litter exhibits a spatial dependence structure, with an average stock value of 3.38 Mg ha^{-1} in the FLONA. It was possible to spatialize the total litter carbon stock and its compartments across the seven plots of the FLONA using the exponential model through ordinary kriging. The highest concentrations were mainly identified in plots 6 and 7—areas where eucalyptus was planted in 1945 and is now undergoing natural regeneration, as well as where eucalyptus was planted in 1997.

The soil carbon stock does not exhibit spatial dependence, so mapping was conducted using the Inverse Distance Squared method. The highest carbon stock is found at a depth of 20–30 cm in plots 5 and 7.

References

ALVARES, C.A. et al. Koppen’s climate classification map for Brazil. Meteorologische Zeitschrift, v.22, n.6, p.711-728, 2014. doi: 10.1127/0941-2948/2013/0507.

ALVES, M.A.B. et al. Geoestatística, krigagem e multivariada de atributos físicos de um Latossolo sob pastagem. Rev Ibero-Am. Ciênc. Amb., v.13, n.6, p.1-11, 2022. doi: 10.6008/CBPC2179-6858.2022.006.0001

AMARAL, L.P. et al. Análise da distribuição espacial de biomassa e carbono arbóreo acima do solo em floresta ombrófila mista. Ambiência, v.6, n.4, p.103-114, 2010.

ATAÍDE, D.H.S. et al. Dependência espacial de variáveis dendrométricas em diferentes idades e intensidades amostrais em povoamento de eucalipto. Ciênc. Florestal, v.31, p.1591-1611, 2022. doi: 10.5902/1980509837867.

BELLO, C. et al. Defaunation affects carbon storage in tropical forests. Sci. Adv., v.1, n.11, p.1-10, 2015. doi: 10.1126/sciadv.1501105

BRAGA, R.M.; DE ASSIS BRAGA, F.; VENTURIN, N. Carbono orgânico no solo sob mata nativa e florestas plantadas em longo prazo. Pesq. Florestal Bras., v.42, 2022. doi: 10.4336/2022.pfb.42e202002121.

BRASIL. Lei nº 9.985, de 18 de julho de 2000. Regulamenta o art. 225, § 1o, incisos I, II, III e VII da Constituição Federal, institui o Sistema Nacional de Unidades de Conservação da Natureza e dá outras providências. Diário Oficial da União, Brasília, DF, 2000.

BRASIL. Decreto nº 93.369 de 08 de outubro de 1986. Cria a FLORESTA NACIONAL MÁRIO XAVIER, no Estado do Rio de Janeiro, e dá outras providências. Diário Oficial da União, Brasília, DF, 1986.

CLARK, D.A. Sources or sinks? The responses of tropical forests to current and future climate and atmospheric composition. Philos. Trans. Royal Soc. London B, 359, p.477-491, 2004.

CORDEIRO, N.G. et al. Variação temporal do estoque de carbono e volume de madeira em um fragmento de cerrado sensu stricto. Enciclop. Biosf., v.13, n.24, p.152-166, 2018. doi: 10.18677/EnciBio_2018B76

GASPARINI, K.A. et al. Técnicas de geoprocessamento e sensoriamento remoto aplicadas na identificação de conflitos do uso da terra em Seropédica-RJ. Floresta e Ambiente, v.20, n.3, p.296-306, 2013. doi: 10.4322/floram.2013.030

GUILHERME, L.R.G.; LIMA, J.M. Recursos naturais renováveis e impacto ambiental. Lavras: UFLA/FAEPE, 2003.

JIMÉNEZ, E.I.; GARCIA, V.P. Evaluation of city refuse compost maturity: a review. Biol. Wastes, v.27, n.2, p.115-142, 1989. doi: 10.1016/0269-7483(89)90039-6

JUNGES, A.L. et al. Efeito estufa e aquecimento global: uma abordagem conceitual a partir da física para educação básica. Exp. Ens. Ciênc., v.13, n.5, p.126-151, 2018.

MELLO, Y.R.; OLIVEIRA, T.M.N. Análise estatística e geoestatística da precipitação média para o município de Joinville (SC). Rev. Bras. Meteorol., v.31, p.229-239, 2016. doi: 10.1590/0102-778631220150040

MORAIS, V.A. et al. Spatial and vertical distribution of litter and belowground carbon in a Brazilian Cerrado vegetation. Cerne, v.23, p.43-52, 2017. doi: 10.1590/01047760201723012247.

NEVES, A.H.B. et al. Biomassa e carbono em plantio comercial de paricá na Amazônia. Nativa, v.10, n.2, p.154-162, 2022. doi: 10.31413/nativa.v10i2.13330.

NOVAIS, J.W.Z. et al. Condições térmicas e dependência espacial da temperatura de diferentes superfícies pelo Método da Krigagem em Cuiabá-MT, Brasil. Ens. Ciênc. v.20, n.3, p.133-138, 2016. doi: 10.17921/1415-6938.2016v20n3p133-138

OLIVEIRA, B.R.; ANTÔNIO, G.B. Modelagem geoestatística aplicada a geologia de engenharia. Bol. Paran. Geociênc., v.73, n. 1, 2017.

OLIVEIRA, I.M.S. et al. Estoque do potencial produtivo do Cerrado utilizando geotecnologias. Ciênc. Florestal, v.31, n.2, p.766-785, 2021. doi: 10.5902/1980509838596

PULROLNIK, K. et al. Estoques de carbono e nitrogênio no solo e biomassa florestal em sistema de integração lavoura-pecuária-floresta no cerrado. Embrapa Cerrados. Planaltina, DF: 2021.

R CORE TEAM. R: A language and environment for statistical computing. Vienna, Austria. R Foundation for Statistical Computing, 2015.

RIBEIRO JÚNIOR, P.J.; DIGGLE, P.J. GeoR: a package for geostatistical analysis. RNEWS, v.1, n.2, p.15–18, 2001.

RIBEIRO, S.C. et al. Quantificação de biomassa e estimativa de estoque de carbono em uma floresta madura no município de Viçosa, Minas Gerais. Rev. Árvore, v.33, p.917-926, 2009. doi: 10.1590/S0100-67622009000500014

ROCHA, G.P. et al. Caracterização e estoques de carbono de sistemas agroflorestaisno Cerrado de Minas Gerais. Ciênc. Rural, v.44, p.1197-1203, 2014. doi: 10.1590/0103-8478cr20130804

SANQUETTA, C.R. et al. Dinâmica em superfície, volume, biomassa e carbono nas florestas plantadas brasileiras: 1990-2016. BIOFIX Sci. J., v.3, n.1, p.152-160, 2018

SCOLFORO, H.F. et al. Spatial distribution of aboveground carbon stock of the arboreal vegetation in brazilian biomes of Savanna, Atlantic Forest and Semi-arid woodland. PLoS ONE, v.10, n.6, p.1-20, 2015.

SCOLFORO, H.F. et al. Spatial interpolators for improving the mapping of carbon stock of the arboreal vegetation in brazilian biomes of Atlantic forest and Savanna. Forest Ecol. Manag., v.376, p.24-35, 2016. doi: 10.1016/j.foreco.2016.05.047

SOUZA, R.L.N. Restauração da mata atlântica: potencialidades, fragilidades e os conflitos ambientais na Floresta Nacional Mário Xavier, Seropédica/RJ. Rio de Janeiro: Universidade Federal Rural do Rio de Janeiro, 2017.

TORRES, C.M.M.E. et al. Quantificação de biomassa e estocagem de carbono em uma floresta estacional semidecidual, no Parque Tecnológico de Viçosa, MG. Rev. Árvore, v.37, n.4, p.647-655, 2013. doi: 10.1590/S0100-67622013000400008

YAMAMOTO, J.K.; LANDIM, P.M.B. Geoestatística: conceitos e aplicações. São Paulo: Oficina de Textos, 2013.

YEOMANS, J.C.; BREMNER, J.M. A rapid and precise method for routine determination of organic carbon in soil. Comm. Soil Scie. Plant Anal., v.19, n.13, p.1467-1476, 1988.

ZIMBACK, C.R.L. Geoestatística. Botucatu: UNESP, 2003.