



Spatial mapping of soil penetration resistance in *Khaya* spp. forest stand

Mapeamento espacial da resistência do solo à penetração em povoamento florestal de *Khaya* spp.

Daiane de Cinque Mariano¹, Ricardo Shigueru Okumura², Gislayne Farias Valente³,
 Ângelo Augusto Ebling⁴, Cândido Ferreira de Oliveira Neto², Pedro Henrique Oliveira Simões¹

ABSTRACT

The sustainable management of African mahogany (*Khaya* spp.) cultivation depends on soil penetration resistance (PR) and moisture (M), factors that directly influence plant health, soil physical quality, and management practices. This study investigated the spatial variability of PR and M in an Acrisol (WRB) with a clayey loam texture, cultivated with 20-month-old African mahogany seedlings in Curionópolis, Pará, Brazil. Soil samples were collected in a 10 × 10 m grid, totaling 70 georeferenced points at two depths (0–20 and 20–40 cm). Data were analyzed using semivariograms, and the spatial variability of soil physical properties was represented by maps generated through kriging interpolation. Results indicated that management practices favored the formation of a compacted layer between 20–40 cm, which may compromise root development and the absorption of water and nutrients by plants. Future studies are needed to assess the impact of soil compaction on the growth and productivity of the species, as well as to better understand the relationship between these physical attributes and the agronomic traits of the crop, aiming at the development of more efficient soil management strategies.

Keywords: African mahogany; Geostatistic; Spatial variability

RESUMO

O manejo sustentável do cultivo de mogno africano (*Khaya* spp.) depende da resistência do solo à penetração (PR) e da umidade (M), fatores que influenciam a saúde das plantas, a qualidade física do solo e as práticas de manejo. Este estudo investigou a variabilidade espacial da PR e da M em um Argissolo Vermelho-Amarelo de textura franco-argilosa, cultivado com mudas de mogno africano com 20 meses de idade, em Curionópolis, Pará, Brasil. As amostras foram coletadas em grade de 10 × 10 m, totalizando 70 pontos georreferenciados em duas profundidades (0–20 e 20–40 cm). Os dados foram analisados por semivariogramas, e a variabilidade espacial das propriedades físicas foi representada por mapas obtidos via interpolação por krigagem. Os resultados indicaram que o manejo formou uma camada compactada entre 20–40 cm, que pode comprometer o desenvolvimento radicular e a absorção de água e nutrientes pelas plantas. Estudos futuros são necessários para avaliar o impacto da compactação do solo sobre o crescimento e a produtividade da espécie, bem como para compreender melhor a relação entre esses atributos físicos e os caracteres agrônômicos da cultura, visando ao desenvolvimento de estratégias de manejo mais eficientes.

Palavras-chave: Mogno africano; Geoestatística; Variabilidade espacial.

¹ Universidade Federal de Mato Grosso;

² Universidade Federal Rural da Amazônia;

³ Universidade Federal de Lavras;

⁴ Universidade Federal do Paraná.

Autor correspondente: ricardo_okumura@hotmail.com

Recebido em: 10/06/2025. Aceito em: 14/04/2026.

Este é um artigo publicado em acesso aberto (Open Access) sob a licença Creative Commons Attribution (<https://creativecommons.org/licenses/by/4.0/>), que permite uso, distribuição e reprodução em qualquer meio, sem restrições desde que o trabalho original seja corretamente citado.

1 INTRODUCTION

The species *Khaya* spp. (African mahogany) stands out nationally and internationally due to the high market value of its wood (SOUZA et al., 2002). It also enables agroforestry systems, since the arboreal component protects the soil. Along planting rows, farmers can cultivate additional species, generating variable income, maintaining soil moisture at different depths, and enhancing organic matter cycling (GUILHERME; VIDICA, 2019).

In the Amazon region, Brazilian mahogany (*Swietenia macrophylla* King) and African mahogany (*Khaya ivorensis* A. Chev.) are widely used in forestry systems, agroforestry associations, and monocultures for export (COSTA et al., 2013). The tropical climate, marked by alternating rainy and dry seasons, imposes significant water stress on plants. Droughts lasting up to six months may be followed by intense rainfall (BAKER et al., 2008). Planting mahogany in areas subject to rapid rains helps mitigate erosion in degraded pastures and exposed soils (LU et al., 2013).

Soil hydrological processes, such as water retention capacity and compaction, are directly related to its quality. In this context, the physical structure, assessed through indicators like penetration resistance (PR) and moisture (M), becomes fundamental for understanding plant growth conditions and the proper functioning of this edaphic environment (MENDES et al., 2018). The PR and M, in addition to other physical parameters, are influenced by management practices, which can change its structure, directly affecting porosity, density, water retention and nutrient availability (RIBEIRO et al., 2016). High PR values, above 2 MPa, for example, indicate the presence of compacted layers that restrict root growth in length and diameter, directing them to areas with lower resistance (CARVALHO et al., 2008). In forest planting systems, values below 2 MPa are not restrictive to plant development (NASCIMENTO et al., 2020).

With advances in precision forestry, it is now possible to measure and identify spatial relationships among edaphic factors that limit the growth of forest stands (PELISSARI et al., 2014). Investigating the spatial variability of soil attributes is fundamental in forest science. However, this analysis is complex because attributes such as PR and M can vary in relatively homogeneous areas and within the same soil class (ALMEIDA; GUIMARÃES, 2016). This spatial variability is influenced both by pedogenetic factors, such as the heterogeneous composition of the source material, and by climatic, topographic and management practices (MATIAS et al., 2015). The use of geostatistics, a widely applied tool in the study of spatial variability, allows to identify patterns and spatial dependencies of soil attributes, facilitating the mapping of specific zones with physical, chemical and biological restrictions, which allows the planning interventions for soil recovery and productivity optimization (SILVA et al., 2017).

In the context of forest management of the *Khaya* spp., PR and M analysis integrated with geospatial mapping, can provide key information for sustainable management of African mahogany plantations. This study aims to evaluate the penetration resistance and soil moisture in a stand of *Khaya* spp. through the application of geostatistical techniques, seeking to contribute to sustainable and efficient forest management practices. It is hypothesized that the planting system may promote the

formation of compacted soil layers from a depth of 20 cm, as a consequence of the processes involved in the establishment and management of the crop.

2 MATERIAL AND METHODS

This study was conducted in a *Khaya* spp. seedling plantation, located in Curionópolis city, Brazil, in the Brazilian Amazon, at the geographical coordinates 6°03'38.45"S and 49°45'49.58"W, altitude of 217 m (Figure 1).

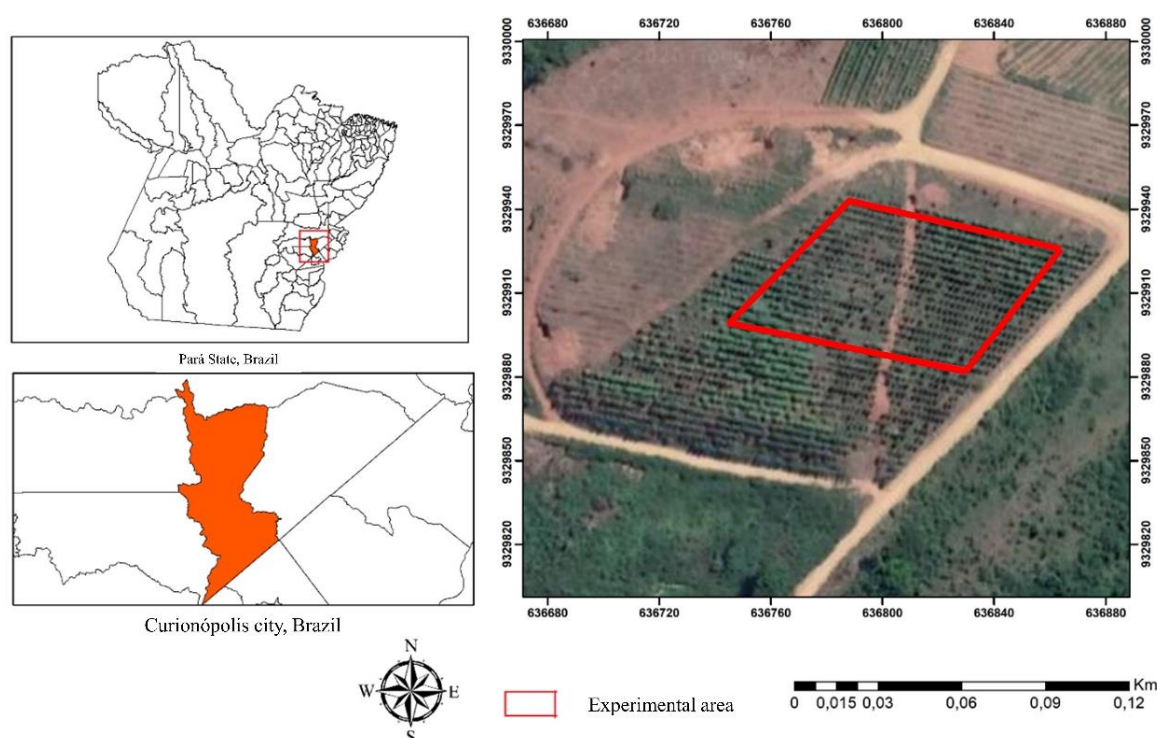


Figure 1. Location map of the experimental area, Curionópolis city, Brazil.

The climate classification of the region where the stand is located, according to Köppen, is "Aw", with rain concentrated in the summer, from december to march, and a dry season in the winter, from june to September (KÖPPEN; GEIGER, 1936). The region does not have a high temperature range during the year, and during the 20 months in the field, the accumulated rainfall was 1,581 mm, average temperature was 24.04 °C, the average maximum temperature was 32.5 °C and the average minimum temperature was 22.3 °C. The previous climatic data were obtained from the Carajás weather station (Latitude: -6.077427', Longitude: -50.142265' and Altitude of 707 m).

The experimental area covers 7.000 m². The soil is classified as an Acrisol according to the World Reference Base for Soil Resources (IUSS WORKING GROUP WRB, 2022), with a clay loam texture. This area hosts a seminal planting of African mahogany *Khaya* spp. at a spacing of 3 m between rows and 2 m between plants. The study region features an average slope ranging from 5.8% to 12.1%, indicating a moderately undulating relief (LEPSCH, 2002). Pre-planting procedures consisted of harrowing to

prepare the soil, without causing significant alterations in the layers between 0–40 cm depth. Whenever necessary, manual weeding and chemical control with glyphosate were carried out in the experimental area. The planting age was determined from the initial planting date to data collection in January 2019, classifying the stand as 20 months old.

2.1 DATA ACQUISITION

The spatial characterization of penetration resistance (PR) and moisture (M) was carried out using georeferenced data collected with a GPS receiver. Sampling was conducted within the study area, excluding a 2.5 m buffer from the fence and a 5 m margin from the side boundary. A regular grid with 10 m spacing was established, resulting in a sampling density of 70 points across the area (Figure 2).

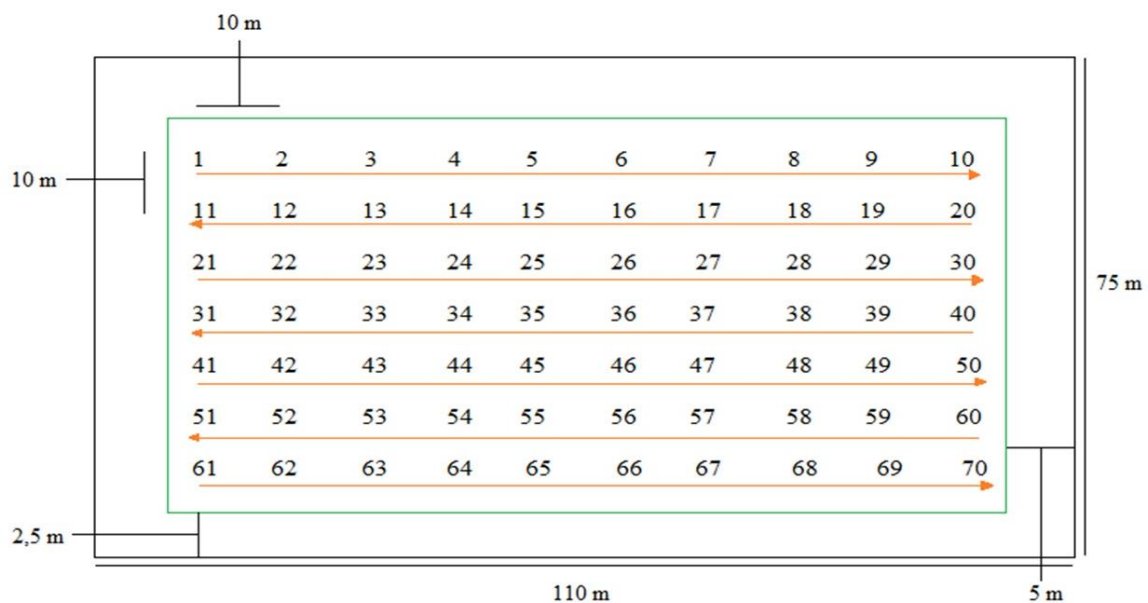


Figure 2. Regular grid model used in the experimental area.

Soil penetration resistance (PR) was measured using a digital penetrometer (Penetro LOG PLG 1020) at depths of 0–20 cm and 20–40 cm. The moisture (M) was determined at the same depths from disturbed soil samples collected in sealed aluminum cans. The samples were subsequently sent to a soil analysis laboratory to obtain moisture values, following the methodology described by Teixeira (2017).

2.2 STATISTICAL ANALYSES

Prior to the geostatistical analysis, descriptive statistics were applied to characterize the variability of penetration resistance (PR) and moisture (M). The analysis included mean, median, minimum and maximum values, coefficient of variation (CV), skewness, and kurtosis. Variability was classified according to Warrick and Nielsen (1980), with CV values considered low (<12%), moderate (12–60%), and high (>60%). This classification enables a precise assessment of soil heterogeneity in the study area.

Normality was tested using the Shapiro–Wilk test, appropriate for sample size $n=50$. Data processing was facilitated with spreadsheets, and all statistical analyses were conducted in R (R DEVELOPMENT CORE TEAM, 2023) using the stats package.

2.3 GEOSTATISTICAL ANALYSIS

The field data were subjected to geostatistical analysis to characterize the spatial variability of the PR and M variables, using GS+ software (version 7) (ROBERTSON, 2000). A semivariance analysis was performed to assess the presence of spatial dependence (VIEIRA, 2000), with semivariance calculated according to Equation, as proposed by Matheron (1963).

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

In which:

- $\hat{\gamma}(h)$ is the semivariance value for a distance h ;
- $N(h)$ is the number of experimental pairs of observations;
- $Z(x_i)$ is the value of attribute Z at position x_i ;
- $Z(x_i + h)$ is the value of attribute Z at position x_i , separated by a distance h .

The parameters nugget effect (C_0), sill variance ($C_0 + C_1$), and range (a) were obtained from the semivariogram equation, fitted based on the graphical behavior of spherical, exponential, and Gaussian models. In this study, the selection of the best-fitting model was guided by the highest coefficient of determination (R^2) and the highest Degree of Spatial Dependence (DSD). Furthermore, the reliability of data estimation was assessed using the Degree of Spatial Dependence, which is determined by the contribution of spatial variance to the total sample variance (VIEIRA, 2000). To evaluate the DSD, Cambardella et al. (1994) proposed a classification based on the ratio between the nugget effect (C_0) and the sill variance ($C_0 + C_1$). The confidence can be considered weak with a DSD greater than 75%, moderate between 25% and 75%, and strong for DSD less than 25%.

2.4. KRIGING MAPS

Semivariogram adjustment was used to identify the spatial variability of PR and M. These adjustments enabled the interpolation of data through ordinary Kriging and map construction. In this step, PR and M maps were generated at depths of 0–20 and 20–40 cm. The maps were constructed using the QGIS software (QGIS DEVELOPMENT TEAM, 2018). The sampled points were interpolated to obtain an estimate (z^*) consisting of a linear combination of neighboring measurement values (X_0), represented by Equation:

$$z^*(x_0) = \sum_{i=1}^N \lambda_i z(x_i)$$

In which:

z^* is the estimate;

x_0 is a linear combination of neighboring measurement values;

N is the number of measured values involved in the z estimate (x_i);

i is the weight associated with each measured value.

2.5. ANALYSIS OF KRIGING MAPS

For the interpretation of the kriging maps of PR, colors were patterned according to the values obtained, in which: light yellow surface when the values found were between 0.3 and 0.5 MPa; yellow (0.5 to 0.7 MPa); orange (0.7 to 0.9 MPa); red (0.9 to 1.2 MPa); and dark red (> 1.2 MPa). The maps of M received yellow color surface when they presented values < 20 g g⁻¹; green (20 to 30 g g⁻¹); light blue (30 to 40 g g⁻¹); blue (40 to 50 g g⁻¹); and dark blue (> 50 g g⁻¹). The results of PR obtained in the area were classified according to an adaptation based on Soil (1993) and presented in Table 1.

Table 1. System of categories used to determine the soil resistance to penetration (PR).

Category	PR (MPa)
Low	$< 0,1$
Moderate	0.1 – 2.0
High	> 2.0
Very High	4.0 – 8.0

Table 2. Category system used for the soil moisture (M).

Category	M (g g ⁻¹)
Dry	< 20
Medium dry	20-30
Medium wet	30-40
Wet	>40

The results of M obtained in the area were classified according to Lopes et al. (2011).

3 RESULTS AND DISCUSSION

The results of the descriptive analysis of the parameters: mean, median, maximum, minimum, coefficient of variation (CV), kurtosis coefficient (Ck), asymmetry coefficient (Cs) and the W value of the test Shapiro-Wilk (W) for the determination of soil resistance to penetration (PR) and moisture (M), are shown in Table 3.

PR in the depth of 20-40 cm (mean 1.77 MPa) is significantly higher than at the depth of 0-20 cm (mean 0.83 MPa), indicating greater PR in depth. Both depths have positive asymmetry ($C_s > 0$), with platykurtic kurtoses ($C_k < 3$), suggesting not perfectly normal distributions. The M is greater at a depth of 0-20 cm (average 32.75 g g⁻¹) than at a depth of 20-40 cm (average 27.10 g g⁻¹). The M presents positive asymmetry in 0-20 cm and negative in 20-40 cm, with platykurtic asymmetry in both depths.

Table 3. Descriptive statistics of soil resistance to penetration (PR) and soil moisture (M) at the depths 0-20 cm and 20-40 cm in soil African mahogany stand.

	Values					Coefficients		
	Mean	Median	Maximum	Minimum	CV%	Cs	Ck	W
Depth 0-20 (cm)								
PR (MPa)	0.83	0.81	1.85	0.29	33.00	0.93	2.17	0.96
M (g g ⁻¹)	32.75	33.60	70.11	9.75	35.00	0.26	1.23	0.95
Depth 20-40 (cm)								
PR (MPa)	1.77	1.77	3.35	0.90	28.50	0.86	0.77	0.89
M (g g ⁻¹)	27.10	29.03	48.93	2.61	33.00	-0.33	0.37	0.87

PR = soil resistance to penetration; M = moisture; CV% = coefficient of variation; Cs = asymmetry coefficient; Ck = kurtosis coefficient; W = Shapiro-Wilk normality test.

The W values for all variables and depths are high, suggesting that distributions do not deviate drastically from normality. The coefficient of variation (CV) indicates moderate variability for PR and M at both depths, with showed at depths 0-20 for PR (33%) and M (35%) and 20-40 for PR (28.5%) and M (33%), medium variation. Although the mean and median are close for PR and M, suggesting symmetry, the asymmetry (Cs) and kurtosis (Ck) coefficients indicate that the distributions are not perfectly normal. Although the data did not follow a perfectly normal distribution, the absence of very elongated tails is a positive factor for geostatistical analysis, since it reduces the impact of outliers. According to Cressie (2015), normality is not a strict requirement for this type of analysis, and the absence of very elongated tails in the data lessens the impact of outliers that could compromise the results.

For the PR represented by the semivariograms (Figure 3 a, c), the best adjusted model was the exponential model and linear model, however, both presented low R^2 values, that is, close to 0.03 for the studied depths. This limitation can be attributed to the high natural spatial variability of the soil, especially in tropical environments with moderately undulating relief, such as the experimental area. These conditions tend to generate considerable heterogeneity in soil physical attributes, which hinders the achievement of more robust model fits, even though the selection criteria also considered the mean prediction error and the degree of spatial dependence. The geostatistical parameters of the soil PR semivariograms (0-20 cm) (Figure 3 a) indicate weak spatial dependence, possibly due to sampling distance or low variation of data. However, the 20-40 cm layer (Figure 3 c) presented strong spatial dependence. Therefore, the spatial distribution was not random (OLIVEIRA et al., 2015).

For M (Figure 3 b, d) the best adjusted model was the gaussian, with R^2 of 0.7 and 0.9 at depths of 0-20 and 20-40 cm. These results suggest that the spatial distribution of PR (0-20 cm) and M (0-20 and 20-40 cm) is influenced by factors such as anthropic action (soil management, irrigation) or intrinsic characteristics of the soil (texture, structure).

The semivariogram of the variable for PR at 0-20 cm (Figure 3 a) was best fitted by an exponential model. The semivariogram of the analyzed variable PR at 20-40 cm (Figure 3 c), was best fitted by a linear model, as evidenced by the increasing semivariance with distance (h) and the absence of a defined sill. This indicates a spatial dependence that increases proportionally with distance within the studied range. The gradual upward trend suggests that the spatial structure of the data does not reach a limit of spatial autocorrelation, which is typical of a linear spatial dependence pattern. The best adjusted

models (gaussian and exponential) showed strong spatial dependence, verified by the DSD value obtained, which remained between 0 and 10%. The adjusted models produced ranges varying between 7 and greater than 78 meters for PR, and a range of 15 meters for M.

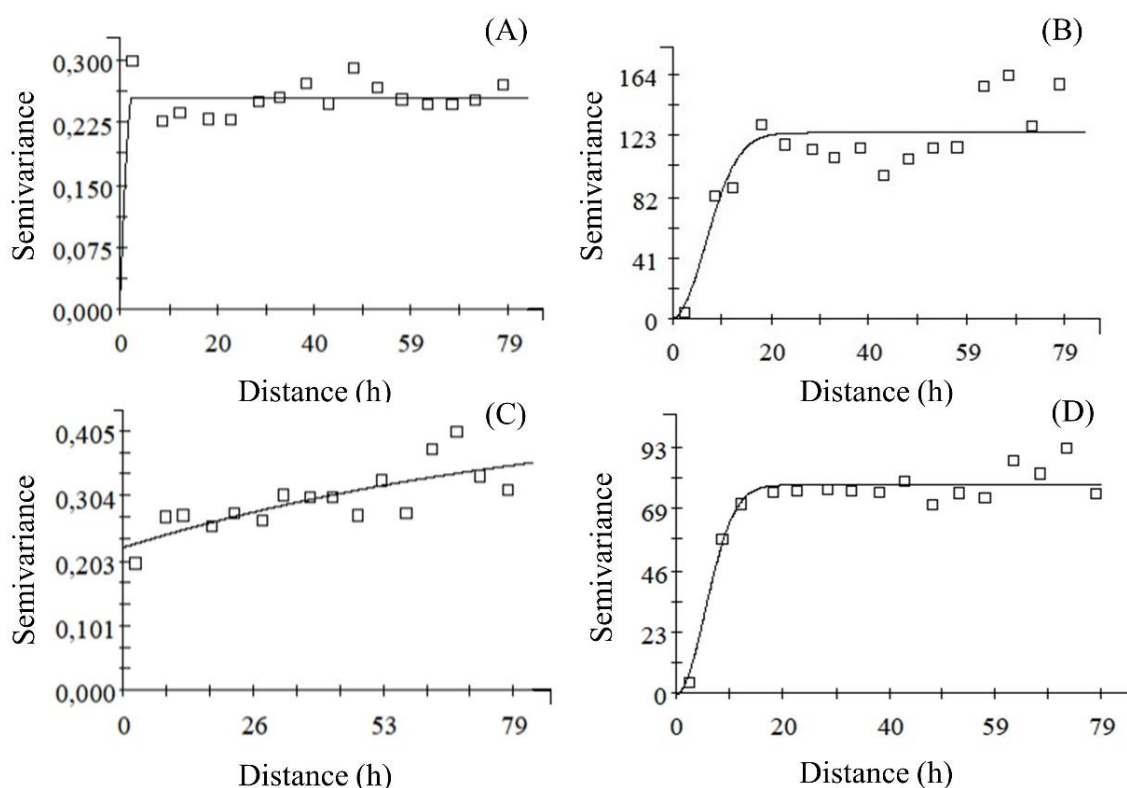


Figure 3. Semivariograms of soil resistance to penetration and moisture. (a) exponential model adjusted for PR at 0-20 cm; (b) gaussian model adjusted for M at 0-20 cm; (c) linear model adjusted for PR at 20-40 cm; (d) gaussian model adjusted for M at 20-40 cm.

The interpretation of the spatial structure of PR and M at depths of 0–20 cm and 20–40 cm is facilitated by the analysis of the semivariogram parameters and the degree of spatial dependence presented in Table 4, which were estimated based on the semivariogram modeling (Figure 3 a, b, c and d). The RP presented a level of 0.27 and a relatively low pepita effect of 0.02, with a range of 7 meters.

Table 4. Semivariogram parameters sill, nugget, range and degree of spatial dependence (DSD) for penetration resistance (PR) and moisture (M) in the depths of 0-20 cm and 20-40 cm.

	Sill	Nugget	Range (m)	DSD (%)
Depth 0-20 (cm)				
PR (MPa)	0.27	0.02	7	92
M (g g ⁻¹)	125	10	15	92
Depth 20-40 (cm)				
PR (MPa)	0.35	0.22	>79	37
M (g g ⁻¹)	78	5	15	94

In the 0-20 cm depth (Figure 4 b) it was possible to observe that M varied from 24.2 g g⁻¹ (medium dry) to 71.8 g g⁻¹ (wet), in most of the area, while in in the 20-40 cm

layer (Figure 4 d), the soil presented small areas with moisture (M) of 12 g g^{-1} (dry) in the upper left part of the map, plus regions with 24.9 g g^{-1} (medium dry). However, most of the map displays values of 50.8 g g^{-1} (wet).

Still, this layer has a smaller extension compared to the 0-20 cm layer, which has a larger area with M in wet condition ($M > 40$). In the maps (Figure 4 b and d), soil moisture varied slightly in the two layers, but at 0-20cm (Figure 4 b), moisture was higher due to the incorporation of organic waste, which favors the maintenance of moisture on the surface and subsurface. On the soil surface, the senescence of tree leaves adds a greater amount of organic material. This process forms a layer composed of litter, roots, and forage biomass from the involved species. Such coverage alters the physical conditions of the soil and reduces soil penetration resistance in the more superficial layer (SARTOR et al., 2020).

Furthermore, moisture (M) can be explained by the textural class (clay loam) of the soil, as it has granulometric proportions with a large number of fine particles, which tend to organize themselves into small porous structural units (micropores), characterized by a slow movement of water in the soil section (CENTENO et al., 2017). It is emphasized that the organic matter deposited by crops, consists of another factor that contributes to the preservation of surface humidity (KLEIN; KLEIN, 2015), resulting in the largest values of M (24.2 g g^{-1} to 71.8 g g^{-1}) found on the surface. Melo Neto et al. (2017), studying temporal stability of soil moisture in a clay-sandy soil (45% of clay, 10% of silt and 45% of sand), well-drained, verified an increase in M as the soil depth increased. Evidencing that intrinsic soil characteristics acted as one of the main factors that regulate the dynamics of water in the soil.

The results show that PR in the 0–20 cm layer ranged from 0.30 to 0.96 MPa (Figure 4 a). In the subsurface layer (20–40 cm), PR values increased significantly, ranging from 0.88 (low) to 1.53 MPa (moderate) (Figure 4c).

Moreover, the influence of soil moisture, another determining factor for plant root growth is PR, which can be affected by variations in moisture and organic matter deposition. PR maps in the 0-20 cm layer (Figure 4 a) indicate that the soil does not present significant mechanical impediments ($PR < 1 \text{ MPa}$) and has less spatial variation. These findings indicate favourable conditions for root growth in this layer, due to the low resistance offered by the soil.

In studies conducted in a seven-year-old guaraná cultivation system, more pronounced spatial microvariations in soil penetration resistance (PR) were identified, with a recorded value of 1.01 MPa (SOUZA et al., 2024). In ten-year-old Paricá plantations, the mean values obtained for the surface layer from 0 to 20 cm indicated a resistance of 0.94 MPa, whereas in the subsequent layer, from 20 to 40 cm, the average observed was 1.4 MPa (ATAIDES et al., 2022). These values, remain within the critical limits established for the development of mahogany cultivation, demonstrating that despite spatial variations and differences between soil depths, the physical conditions of the soil are still compatible with the species growth. Values greater than 2 MPa may restrict root growth (GREACEN & SANDS, 1980; TORMENA et al., 1998), while values exceeding 3 MPa are considered limiting for forest species (ZOU, 2000).

These results likely reflect residue deposition from African mahogany and effective cover crop management. Studies indicate that African mahogany improves the physical

attributes of the soil, especially in the surface layers, since part of its roots is distributed close to the surface, contributing to the reduction of soil density, increased porosity and organic carbon content. Consequently, there is less resistance to soil penetration on the surface, although this improvement decreases with depth (SILVA et al., 2016).

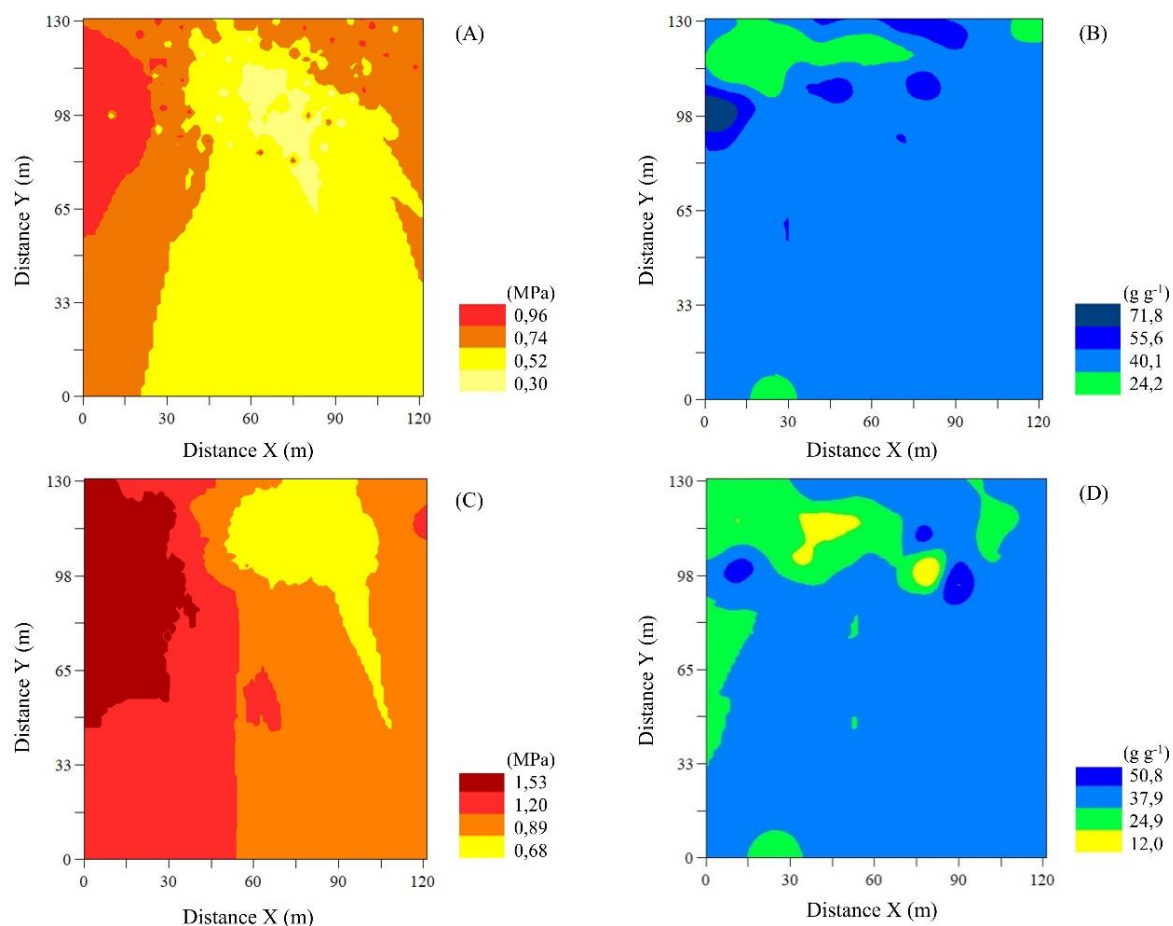


Figure 4. Kriging maps of soil resistance to penetration and moisture. (a) Spatial distribution of PR in MPa at 0-20 cm depth; (b) Spatial distribution of M in g g^{-1} at 0-20 cm depth; (c) Spatial distribution of PR in MPa at 20-40 cm depth; (d) Spatial distribution of M in g g^{-1} at 20-40 cm depth.

Although favourable results were observed in the 0–20 cm layer, resistance increased in the 20–40 cm layer, PR values indicate a potentially limiting soil for root penetration and water movement. These higher values in the subsurface may represent a mechanical barrier limiting root development at depth. Water content strongly influences soil compaction, alongside root distribution and organic matter deposition. Soil water content is highly correlated with PR, helping to explain soil compaction dynamics (ALMEIDA et al., 2008). Martins and Santos (2017) described that with the decrease in water content, there is an increase in soil resistance to penetration.

Evaluating the aggregation of a humic clayey Cambisol in stands of *Pinus taeda* L. (pine), Abrão et al. (2017), obtained lower soil density values in the 0-5 cm layer (0.89 mg m^{-3} and 0.88 mg m^{-3}) and higher values in the 20-40 cm layer (1.08 mg m^{-3} and 1.07 mg m^{-3}), for RT1 and CN1, respectively, being (RT1 = natural field area (control), adjacent to *P. taeda* L. in first rotation) and (CN1 = natural field area (control), adjacent to stands of *P.*

taeda L. in second rotation). The low soil density values occurred due to the high content of organic matter present in the soil and the texture being clayey, which gives greater aggregation and total porosity to the soil.

The 20-40 cm layer, which has lower soil moisture percentage, corresponds to the higher values of penetration resistance (PR). This evidence points to that the lower availability of moisture in depth may be contributing to an increase in soil compaction and mechanical strength. In drier soils, the PR tends to increase, hindering nutrients and water uptake. Studies conducted by Souza et al. (2024) and Lopes et al. (2023), showed similar results, demonstrating that PR increases as moisture decreases. In addition, the PR is directly correlated with several soil attributes such as texture, density, organic matter and, especially, moisture content at the time of evaluation (BERGAMIN et al., 2010; BUSSCHER et al., 1997). To address subsurface compaction, it is recommended to implement localized subsoiling in areas identified with higher soil resistance to penetration, as indicated by the spatial variability maps. Additionally, adopting controlled traffic practices, such as restricting the movement of heavy machinery, especially during periods of high moisture, can prevent further compaction. Similar strategies have been effective in other tropical forest systems, such as eucalyptus plantations, where spatially-guided mechanical interventions improved root development and overall productivity (MARTINS et al., 2018; SANTOS; REICHERT, 2022). Comparing the findings of this study with such systems reinforces the relevance of spatial diagnostics as a tool for sustainable forest soil management.

Both M and PR are essential physical attributes that directly influence the root growth and, consequently, the development of the aerial part of plants. When the PR is high, the root system develops in a limited way, which can compromise the productivity of the crop. Therefore, it is essential to carry out more studies to monitor the development of the crop and soil characteristics until the establishment of planting.

4 CONCLUSIONS

The mapping of soil resistance to penetration and moisture in the African mahogany stand provided critical information on soil conditions at different depths. Therefore, the results show a targeted soil management, especially in the subsurface layer (20-40 cm), where the increase of PR values can hinder the penetration of roots and water movement.

The study confirmed that soil texture and organic matter content significantly influence M and PR distribution. While the 0-20 cm layer exhibits favourable conditions for root growth, the 20-40 cm layer presents potential constraints. Consequently, these findings emphasize the importance of implementing proper soil management practices to mitigate compaction and enhance water retention, ensuring sustainable African Mahogany cultivation.

5 ACKNOWLEDGEMENTS

The authors would like to thank the Amazônia Foundation for Supporting the Studies and Research in the State of Pará (FAPESPA), the National Council for Scientific

and Technological Development (CNPq), and the Federal Rural University of the Amazon (UFRA) for the financial and structural support for the execution of this experiment.

REFERENCES

- ABRÃO, S.F.; ROSA, S.F.; REINERT, D.J.; REICHERT, J.M.; EBLING, A.A. Aggregation of a haplumbrept in *Pinus taeda* L. stands with different rotations. **Ciência Florestal**, v.27, p.445–455, 2017. DOI: <https://doi.org/10.5902/1980509827727>
- ATAIDES, G.C.; MELO, R.R.; SOUZA, F.R.; SCCOTI, M.S.V.; PEREIRA, V.L.; TEIXEIRA, R.G.; TRONCO, K.M.Q.; CARVALHO, A.O.; SANTOS, C.M.M.; NEVES, A.H.B.; MASCARENHAS, A.R.P. Variação espacial dos atributos físicos e estoques de carbono do solo em plantio de *Schizolobium amazonicum* na Amazônia. **Nativa**, v.10, n.4, p.566–576, 2022. DOI: <https://doi.org/10.1590/S0100-06832008000600003>
- ALMEIDA, L.S.; GUIMARÃES, E.C. Geostatistics and exploratory factor analysis for special representation of soil chemical attributes in coffee growing. **Coffee Science**, v.11, p.195–203, 2016.
- ATAIDES, G. C., MELO, R. R., SOUZA, F. R., SCCOTI, M. S. V., PEREIRA, V. L., TEIXEIRA, R. G., TRONCO, K. M. Q., CARVALHO, A. O., SANTOS, C. M. M., NEVES, A. H. B., & MASCARENHAS, A. R. P. (2022). **Variação espacial dos atributos físicos e estoques de carbono do solo em plantio de *Schizolobium amazonicum* na Amazônia**. *Nativa*, 10(4), 566–576. <https://doi.org/10.31413/nativa.v10i4.14540>
- BAKER, I.T.; PRIHODKO, L.; DENNING, A.S.; GOULDEN, M.; MILLER, S.; ROCHA, H.R. Seasonal drought stress in the Amazon: Reconciling models and observations. **Journal of Geophysical Research: Biogeosciences**, v.113, p.G00B01, 2008. DOI: <https://doi.org/10.1029/2007JG000644>
- BERGAMIN, A.C.; VITORINO, A.C.T.; FRANCHINI, J.C.; SOUZA, C.M.A.; SOUZA, F.R. Induced compaction of a rhodic Acrustox as related to maize root growth. **Revista Brasileira de Ciência do Solo**, v.34, p.681–691, 2010. DOI: <https://doi.org/10.1590/S0100-06832010000300009>
- BUSSCHER, W.J.; BAUER, P.J.; CAMP, C.R.; SOJKA, R.E. Correction of cone index for soil water content differences in a coastal plain soil. **Soil and Tillage Research**, v.43, p.205–217, 1997. DOI: [https://doi.org/10.1016/S0167-1987\(97\)00015-9](https://doi.org/10.1016/S0167-1987(97)00015-9)
- CAMBARDELLA, C.A.; MOORMAN, T.B.; NOVARK, J.L.; PARKIN, T.B.; KARLEN, D.L.; TURCO, R.F.; KONOPKA, A.E. Field-scale variability of soil properties in Central Iowa soils. **Soil Science Society of America Journal**, v.58, p.1501–1511, 1994. DOI: <http://dx.doi.org/10.2136/sssaj1994.03615995005800050033x>

- CARVALHO, L.A.; NETO, V.J.; SILVA, L.F.; PEREIRA, J.G.; CHAVES, C.H.C. Resistance mechanics of the soil to penetration (RMP) under cane-of-sugar culture, in the city of Rio Brilhante-MS. **Agrarian**, v.1, p.7–22, 2008.
- CENTENO, L.N.; GUEVARA, M.D.F.; CECCONELLO, S.T.; SOUSA, R.O.; TIMM, L.C. Soil texture: Concepts and applications in sandy soils. **Revista Brasileira de Engenharia e Sustentabilidade**, v.4, p.31–37, 2017. DOI: <https://doi.org/10.15210/rbes.v4i1.11576>
- COSTA, J.R.; MORAIS, R.R.; CAMPOS, L.S. **Cultivo e manejo do mogno (Swietenia macrophylla King)**. Embrapa Amazônia Ocidental, 2013. Available at: <https://www.infoteca.cnptia.embrapa.br/bitstream/doc/1007849/1/Doc114A5.pdf> (Accessed: February 26, 2025)
- CRESSIE, N. **Statistics for Spatial Data**. Revised edition. Hoboken: John Wiley & Sons, 2015. 928 p.
- EMBRAPA. **Manual de Métodos de Análise de Solo**. 3th edn. Embrapa, Rio de Janeiro, Brazil, 2017.
- GREACEN, E.L.; SANDS, R. Compaction of forest soils: A review. **Australian Journal of Soil Research**, v.18, p.163–189, 1980. DOI: <https://doi.org/10.1071/SR9800163>
- GUILHERME, H.D.; VIDICA, B. Integration of tree crops and pastures. **African Journal of Agricultural Research**, v.14, p.1091–1096, 2019. DOI: <https://doi.org/10.5897/AJAR2018.13545>
- IUSS WORKING GROUP WRB. World Reference Base for Soil Resources: International soil classification system for naming soils and creating legends for soil maps. 4th ed. **Vienna: International Union of Soil Sciences (IUSS)**, 2022.
- KLEIN, C.; KLEIN, V.A. Strategies to improve the retention and availability of soil water. **Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental**, v.19, p.21–29, 2015. DOI: <https://doi.org/10.5902/2236117014990>
- KÖPPEN, W.; GEIGER, R. *Klimate der Erde*. Gotha: Verlag Justus Perthes, 1936.
- LEPSCH, I.F. **Formação e Conservação dos Solos**. 2th edn. Oficina de Textos, São Paulo, Brazil, 2002.
- LOPES, C.C.; VALENTE, G.F.; MARIANO, D.C.; OKUMURA, R.S.; VIÉGAS, I.J.M.; FERRAZ, G.A.S.; FERRAZ, P.F.P.; SANTOS, S.A. Spatial variability of soil resistance to penetration in fruit cultivation in Eastern Amazonia. **AgriEngineering**, v.5, p.1302–1313, 2023. DOI: <https://doi.org/10.3390/agriengineering5030082>

LOPES, E.S.; SAMPIETRO, J.A.; LOMBARDI, K.C.; DIAS, A.N. Evaluation of moisture content on compaction of soil submitted to forest harvesting machine traffic. **Revista Árvore**, v.35, p.659–667, 2011. DOI: <https://doi.org/10.1590/S0100-67622011000400010>

LU, C.X.; YU, G.; XIAO, Y.; XIE, G.D. Wind tunnel simulation and evaluation of soil conservation function of alpine grassland in Qinghai–Tibet Plateau. **Ecological Economics**, v.86, p.16–20, 2013. DOI: <https://doi.org/10.1016/j.ecolecon.2012.10.015>

MARTINS, F.P.; SANTOS, E.L. Water infiltration speed and penetration resistance as land use. **Acta Iguazu**, v.6, p.28–40, 2017.

MARTINS, P.C.C.; DIAS JUNIOR, M.S.; AJAYI, A.E.; TAKAHASHI, E.N.; TASSINARI, D. Soil compaction during harvest operations in five tropical soils with different textures under eucalyptus forests. **Ciência e Agrotecnologia**, v.42, p.103–113, 2018. DOI: <https://doi.org/10.1590/1413-70542018421005217>

MATHERON, G. Principles of geostatistics. **Economic Geology**, v.58, p.1246–1266, 1963. DOI: <https://doi.org/10.2113/gsecongeo.58.8.1246>

MATIAS, S.S.R.; NÓBREGA, J.C.A.; NÓBREGA, R.S.A.; ANDRADE, F.R.; BAPTISTEL, A.C. Spatial variability of soil chemical properties of Latosol (Oxisol) cultivated conventionally with Glycine max in the cerrado of the Piauí State. **Revista Agro@mbiente On-line**, v.9, p.17–26, 2015. DOI: <https://doi.org/10.5327/Z1982-8470201500012036>

MELO NETO, J.O.; MELLO, C.R.; SILVA, A.M.; MELLO, J.M.; VIOLA, M.R.; YANAGI, S.N.M. Temporal stability of soil moisture under effect of three spacings in a eucalyptus stand. **Acta Scientiarum. Agronomy**, v.39, p.393–399, 2017. DOI: <https://doi.org/10.4025/actasciagron.v39i3.32656>

MENDES, M.S.; LATAWIEC, A.E.; SANSEVERO, J.B.B.; CROUZEILLES, R.; MORAES, L.F.D.; CASTRO, A.; PINTO, H.N.A.; BRANCALION, P.H.S.; RODRIGUES, R.R.; CHAZDON, R.L.; BARROS, F.S.M.; SANTOS, M.; IRIBARREM, A.; MATA, S.; LEMGRUBER, L.; RODRIGUES, A.; KORYS, K.; STRASSBURG, B.B.N. Look down there is a gap the need to include soil data in Atlantic Forest restoration. **Restoration Ecology**, v.27, p.361–370, 2018. DOI: <https://doi.org/10.1111/rec.12875>

NASCIMENTO, L.S do; ARAÚJO, A. R de; FERREIRA, A.D; CORRÊA, B.O.; MACEDO, M.C.M; BONO, J.A.M; ZIMMER, A.H. **Soil resistance to penetration under different use and management systems in the Cerrado region**. Campo Grande, MS: Embrapa Beef Cattle, 2020. 32p. (Documents/Embrapa Beef Cattle, no. 285). Available at: <https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1127937> (Accessed: March 30, 2026).

OLIVEIRA, L.B.T.; SANTOS, A.C.; LIMA, J.S.; NETO, D.N.N. Spatial variability of yield response and morphological Marandu grass depending on the chemical and topographical. **Revista Brasileira de Saúde e Produção Animal**, v.16, p.772–783, 2015. DOI: <https://doi.org/10.1590/S1519-99402015000400002>

QGIS DEVELOPMENT TEAM. QGIS **Geographic Information System**. Open Source Geospatial Foundation Project: Beaverton, OR, USA, 2018.

R CORE TEAM. **R: A Language and Environment for Statistical Computing**. R Foundation for Statistical Computing: Vienna, Austria, 2023. Available at: <https://www.R-project.org/> (Accessed: April 14, 2024)

RIBEIRO, L.D.S.; OLIVEIRA, I.R.D.; DANTAS, J.S.; SILVA, C.V.D.; SILVA, G.B.D.; AZEVEDO, J.R.D. Spatial variability of physical attributes of a cohesive soil under conventional and no-tillage management systems. **Pesquisa Agropecuária Brasileira**, v.51, p.1699–1702, 2016. DOI: <https://doi.org/10.1590/S0100-204X2016000900071>

ROBERTSON, G.P. **GS+ Geostatistics for the Environmental Sciences: GS+ User's Guide Version 5**. Gamma Design Software: Plainwell, MI, USA, 2000.

SANTOS, K.F.; REICHERT, J.M. Best tillage practices for eucalyptus growth and productivity: A review on the Brazilian experience. **Revista Brasileira de Ciência do Solo**, v.46, p.e0210091, 2022. DOI: <https://doi.org/10.36783/18069657rbcs20210091>

SARTORI, L.R.; RAMÃO, J.; SILVA, V.P.; CASSOL, L.C.; BRUN, E.J. Mechanical resistance to soil penetration in a silvipastoral system after eleven years of implantation. **Ciência Florestal**, v.30, n.1, p.306–314, 2020. DOI: <https://doi.org/10.5902/1980509831205>.

SILVA, A.R.; SALES, A.; VELOSO, C.A.C. Influence of African mahogany rows on the physical attributes and organic carbon content of a Yellow Oxisoil. **Scientia Agraria Paranaensis**, v.15, p.291–297, 2016. DOI: <http://dx.doi.org/10.18188/1983-1471/sap.v15n3p291-297>

SILVA, F.J.; OLIVEIRA, C.A.A.; SILVA, A.L.; LIMA, L.P.; GUIMARÃES, E.C. Spatial variability of soil resistance to penetration and productivity of maize. **Revista de Agricultura Neotropical**, v.4, p.77–84, 2017.

SOIL, S.S. **Soil Survey Manual**. 18th edn. USDA, Washington, DC, USA, 1993.

SOUZA, A.G.; SMIDERLE, O.J.; CHAGAS, E.A.; ALVES, M.S.; FAGUNDES, P.R.O. Growth, nutrition and efficiency in the transport, uptake and use of nutrients in African mahogany. **Revista Ciência Agronômica**, v.51, p.1–11, 2020. DOI: <https://doi.org/10.5935/1806-6690.20200024>

SOUZA, F.G.; CAMPOS, M.C.C.; MANTOVANELLI, B.C.; SANTOS, R.V.; CUNHA, J.M.; OLIVEIRA, F.P.; LIMA, A.F.L.; BRITO, W.B.M.; FREITAS, L.; BRITO FILHO, E.G.; SILVA, J.B. Spatial variability of soil resistance penetration in forest areas converted for agricultural uses in the Amazon, Brazil. **Revista Brasileira de Geografia Física**, v.17, p.332–348, 2024. DOI: <https://doi.org/10.26848/rbgf.v17.1.p.332-348>

TEIXEIRA, P. C.; DONAGEMMA, G. K.; FONTANA, A.; TEIXEIRA, W. G. (org.). **Soil Analysis Methods Manual**. 3. ed. rev. e ampl. Brasília, DF: Embrapa, 2017. 573 p. Available at: <https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1085209/manual-de-metodos-de-analise-de-solo> (Accessed: March 30, 2026).

TORMENA, C.A.; SILVA, A.P.; LIBARDI, P.L. Characterization of the least limiting water range of an oxisol under no-tillage. **Revista Brasileira de Ciência do Solo**, v.22, p.573–581, 1998. DOI: <https://doi.org/10.1590/S0100-06831998000400002>

PELISSARI, Allan Libanio; CALDEIRA, Sidney Fernando; SANTOS, Vanderley Severino dos. Variabilidade espacial dos atributos químicos do solo em povoamento de *Tectona grandis*. **CERNE**, Lavras, v. 20, n. 3, p. 377-384, 2014. DOI: <https://doi.org/10.1590/01047760201420031437>

VIEIRA, S.R. **Geoestatística em Estudos de Variabilidade Espacial do Solo**. 1th edn. Sociedade Brasileira de Ciência do Solo, Viçosa, Brazil, 2000.

WARRICK, A.W.; NIELSEN, D.R. **Spatial variability of soil physical properties in the field. In Applications of Soil Physics**. Hillel, D., edn. Academic Press, New York, NY, USA, 1980.

ZOU, C.B. Impact of soil compaction on root growth and hydraulic properties of *Xanthium strumarium*. **Plant and Soil**, v.226, p.249–258, 2000. DOI: <https://doi.org/10.1023/A:1026575825440>