Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

Evaluation of chemical attributes of soils: definition of management zones in silvipastoral system

ARTICLES doi:10.4136/ambi-agua.2957

Received: 07 Sep. 2023; Accepted: 28 Feb. 2024

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ABSTRACT

Soil chemical analysis is a fundamental to achieve optimal cultivation conditions in a productive silvopastoral system, essential for the planning and management of this activity. The objective of this research is to map the spatial distribution of nutrients in the soil in a 5-year-old silvopastoral system composed of brachiaria-brizantha and jacarandá-da-bahia, and to analyze the effect of tree density and canopy on nutrient levels. The study was conducted at the experimental area of the Capixaba Institute for Research, Technical Assistance, and Rural Extension (INCAPER) in the district of Pacotuba, ES. The delimitation of the work area was done using geographic information systems, to create a regular grid of points to enable systematic soil sampling. A total of 75 disturbed soil samples were collected at depths of 0-0.10 m to obtain quantitative soil nutrient data. High-quality images obtained using a remotely piloted aircraft (RPA) allowed for the overlay of soil nutrient data, pasture data, forest inventory data, and sample plot data to assist in comparative analyses. This enabled identification of the areas with lower canopy development, particularly in the northeast portion. By cross-referencing the spatialized soil nutrient data with the data obtained through RPA, it was possible to correlate them with the lower or higher development of the system. The use of RPA, together with a georeferenced database, proved to be an innovative and powerful tool to support decision-making, allowing for the monitoring of system evolution and serving as a basis for evaluating the relationship between chemical elements and tree canopies.

Keywords: geostatistics, precision agriculture, soil nutrients.

Avaliação de atributos químicos dos solos: definição de zonas de manejo em sistema silvipastoril

RESUMO

A análise química do solo é uma prática fundamental para obter as condições ideais de cultivo em um sistema silvipastoril produtivo, além de ser essencial para o planejamento e manejo dessa atividade. Nesse sentido, esta pesquisa tem como objetivo mapear a distribuição espacial dos nutrientes no solo em um sistema silvipastoril de 5 anos composto por brachiaria-brizantha e jacarandá-da-bahia, analisar o efeito da densidade das árvores e das copas nos teores de nutrientes e espacializar os dados. O estudo foi realizado na área experimental do Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural (INCAPER), localizada no distrito de Pacotuba, ES. A delimitação da área de trabalho foi realizada com o uso de sistemas de informações geográficas, abrangendo a área cultivada, para criar uma malha regular de pontos para permitir a amostragem sistemática do solo. Foram coletadas 75 amostras deformadas de solo nas profundidades de 0-0,10 m para obtenção dos teores de nutrientes do solo. As imagens de alta qualidade obtidas pelo uso de aeronaves remotamente pilotadas (ARP) permitiram sobrepor os dados de nutrientes do solo, de pastagem, do inventário florestal e das parcelas amostrais para auxiliar nas análises comparativas. Isso possibilitou a identificação de áreas com menor desenvolvimento das copas, principalmente na porção nordeste. Por meio do cruzamento dos dados de espacialização dos nutrientes do solo com os dados obtidos com o uso de ARP, foi possível correlacioná-los quanto ao menor ou maior desenvolvimento do sistema. Assim, a utilização de aeronaves remotamente pilotadas, juntamente com banco de dados georreferenciado, mostrou-se uma ferramenta inovadora e poderosa para apoio na tomada de decisões em sistemas silvipastoris, possibilitando o acompanhamento da evolução do sistema, e servir como base para avaliar a relação entre os elementos químicos e as copas das árvores.

Palavras-chave: agricultura de precisão, geoestatística, nutrientes do solo.

1. INTRODUCTION

Silvicultural systems are agroforestry systems that combine tree cultivation with animal or plant production in the same area to increase productivity and sustainability. These systems have great potential for the recovery and conservation of degraded soils, as well as for the reduction of pressure on native forest areas (Skorupa and Manzatto, 2019).

Soil nutrient analysis is one of the most important tools for the proper management of silvicultural systems. Soil nutrient analysis allows us to identify possible nutritional deficiencies and adjust fertilization and soil correction according to the needs of plants and animals (Soares *et al.*, 2019).

Geostatistics is a statistical technique applied to the spatial analysis of data, which allows the generation of maps of soil nutrient distribution and the identification of areas with different management characteristics. Geostatistics is an important tool for the management of silvicultural systems, allowing the definition of management zones and the differentiated application of inputs according to the needs of soil and plants (Gómez-Hernández, 2016). Thus, the combination of soil nutrient analysis with the use of geostatistics can be an efficient strategy for the proper management of silvicultural systems, allowing the identification of areas with different needs and the differentiated application of inputs, maximizing productivity and sustainability.

In this sense, the objective of this work was to perform soil nutrient analysis and generate soil management maps, and to maximize the production of wood and forage while minimizing environmental impacts. It also seeks to contribute to the development of more efficient and sustainable management strategies.

2. MATERIAL AND METHODS

2.1. Characterization of the work area

The study area is located in the district of Pacotuba, in Cachoeiro de Itapemirim, Espírito Santo, at the Fazenda Experimental Bananal do Norte, managed by the Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural (Incaper). The agroforestry system of jacarandá-da-bahia with pasture was implemented in August 2017. The area has the following characteristics: minimum temperature ranging from 12 to 18ºC and maximum ranging between 31 and 34ºC, average annual precipitation of 1293 mm, climate classified as Cwa Köppen, wavy topography, elevation of 140 m above sea level and 2 hectares of cultivated area (Pezzopane *et al.*, 2004).

2.2. Evolutionary history of the Silvopastoral System Fazenda Experimental Bananal do Norte (SSP-FEBN)

In 2017, the SSP-FEBN had an area of 2 hectares, predominantly of degraded pasture, and soil samples were collected for the entire experimental area. The soil samples were collected systematically, with the aid of a probe-type auger, to depths of 0-0.20 m and 0.20-0.40 m. The samples were sent to the soil laboratory of the Department of Forest Sciences and Wood of the Federal University of Espirito Santo (DCFM-UFES), for chemical and physical analysis of the soil, to estimate the nutritional deficiencies of the soil and correct the application of mineral fertilizers after planting.

The jacarandá-da-bahia seedlings were acquired in a regional nursery, and the planting was carried out on August 18, 2017. The 1440 seedlings were planted with a spacing of 2 x 6 m, with the lines in the east-west direction. Four rescue irrigations were performed on the seedlings, one irrigation during planting, two at intervals of 7 days, and one at the interval of 15 days after planting.

Ant control was done with the formicide Attames (granulated bait), at the dosage of 10 $g.m^{-2}$ of the anthill and began 60 days before the planting of the seedlings and during the conduction of the experiment through the repass and the round.

The mechanical preparation of the soil was carried out, with plowing and grading in the total area of the experiment to remove the invasive plants and to break the compaction of the pasture. For pH analysis, 30 simple systemic soil samples were collected, forming a composite sample, which indicated a pH between 5.5 and 6.5, considered ideal for native forest species. In the fertilization of the forest seedlings, 50 g of urea, 40 g of P_2O_5, 50 g of KCl, 1 g of B, 1 g of Zn, 0.5 g of Cu, and 0.1 g of Mo per plant were applied. The weed competition control was carried out with manual weeding in the planting lines and mechanical mowing in the interline to allow the regeneration of the brachiaria from the seed bank of the soil, for the formation of silvipastoral systems.

2.3. Creation of the database in a geographic information system (sig) environment

To work with high-precision and accurate georeferenced data, it is necessary to work with equipment that can collect data with little or no error, to process the data in a database in an organized GIS environment with the largest amount of information possible. Thus, the Arcgis 10.5 software was chosen for the spatialization of the data. Through searches in the Integrated System of Geospatial Bases of the State of Espírito Santo (GEOBASES, 2022), the data on Municipal Limit, Drainage, and Level Curves were acquired.

Orthomosaics from 2015 and 2020 were obtained on the website of the State Institute of Environment and Water Resources (IEMA). The Orthomosaics generated by IEMA are at a scale of 1:10,000, have a spatial resolution of 0.25 m, and were developed from the Digital

Aerial Photogrammetry Survey and georeferenced in the UTM Projection System, Datum SIRGAS-2000, Zone 24s. This initial database enabled the spatial visualization of the work area, however, with outdated images. Thus, aiming to improve the quality of the database and image resolution, a flight plan was made in Arcgis, so that it was possible to map the entire area of interest.

2.4. Mapping using remotely piloted aircraft (APR)

The mapping with the use of APR was done through the technique of aerial photogrammetry, with the capture of sequential images of the target area. The flight plan was designed in Arcgis and had 11 acquisition lines with lateral and frontal overlap of approximately 70%. The flight plan was saved in shapefile format and imported into the Google Earth Pro software so that it was possible to convert it to KML format. The KML flight plan was exported to the online platform of the Litchi Software, which was the application chosen to communicate the defined flight plan to the aircraft. Within the Litchi interface, the main flight settings were defined, with a standardized speed of 8.33 m/s, rounded curves, image capture interval every 2 seconds, static Gimbal at 90º, and the online digital elevation model was used to maintain the constant height at 100 meters above sea level.

The APR used was the Mini 2 model, from DJI, embedded with RGB sensor model FC7303, with a maximum take-off weight of less than 250 grams. It has a flight autonomy of 31 minutes, but, for safety reasons, 30% of this time is reserved for emergencies and 10% for take-off and landing, so the flight time was around 18 minutes, enough time to fulfill the planned flight mission. To follow the evolution of the silvipastoral system throughout the research, 4 aerial surveys were carried out, one for each season of the year, starting from autumn. The camera capture settings had the settings adjusted with an exposure time of 1/400 s, ISO speed of 100, focal length of 4 mm, and image resolution of 4000 x 2250 pixels.

The photographs captured were imported into the Agisoft Metashape software for processing and obtaining the Orthophotomosaic and Digital Elevation Model. Within Metashape, the first step was to align the photos to obtain the sparse point cloud, then the densification of this point cloud, mesh generation, and texture. With this database, the next steps were the making of the orthomosaic and Digital Elevation Model.

On April 28, 2022, the first flight was made in the area of SSP-FEBN, the weather conditions were favorable for a safe flight, without gusts of wind and clouds. On July 26, 2022, the second mapping was carried out in the area of SSP-FEBN. The incidence of sunlight was greater and the exposure time for image capture was changed to 1/200 s. The other parameters were maintained. On November 9, 2022, the third aerial photogrammetric mapping was carried out in the area of SSP-FEBN. On February 3, 2023, the fourth aerial photogrammetric mapping was carried out in the area of SSP-FEBN.

2.5. Delimitation of sample plots

The delimitation of the work area was made by creating a limit that encompassed the entire jacarandá-da-bahia cultivated area to serve as a basis for the creation of a regular point grid, which allowed the systematic sampling of the soils. An 18x18 m grid was chosen, to better align with the planting rows, which totaled 75 sample points with known coordinates collected in June 2021 (Figure 1). The points were individually identified and named with letters from "A" to "L" (rows) and from "1" to "12" (columns) so that they can be identified in subsequent analyses. Each plot was renamed with the same identifier as the points and had an area of 324 m^2.

On July 25, 2022, 75 stakes were installed to identify the collection points, which serve as the central point for the development of all other activities. The main tools used were: wooden stakes, identifiers, tape measure, line, hammer, printed maps, and digital maps. Once the location of a collection point was identified, the stake was fixed to the ground with the help of the hammer and identified with its respective identification code. Using the tape measure, 18 meters were measured in the direction of the tree planting rows to identify the other points.

Unlike the methodology used before the implementation of the silvipastoral system in 2017, where samples were collected according to the methodology described by Prezotti *et al.* (2007), this work used point-collection methodologies, as in the experiments of Lopes *et al.* (2020), where the samples were collected based on the specific coordinates.

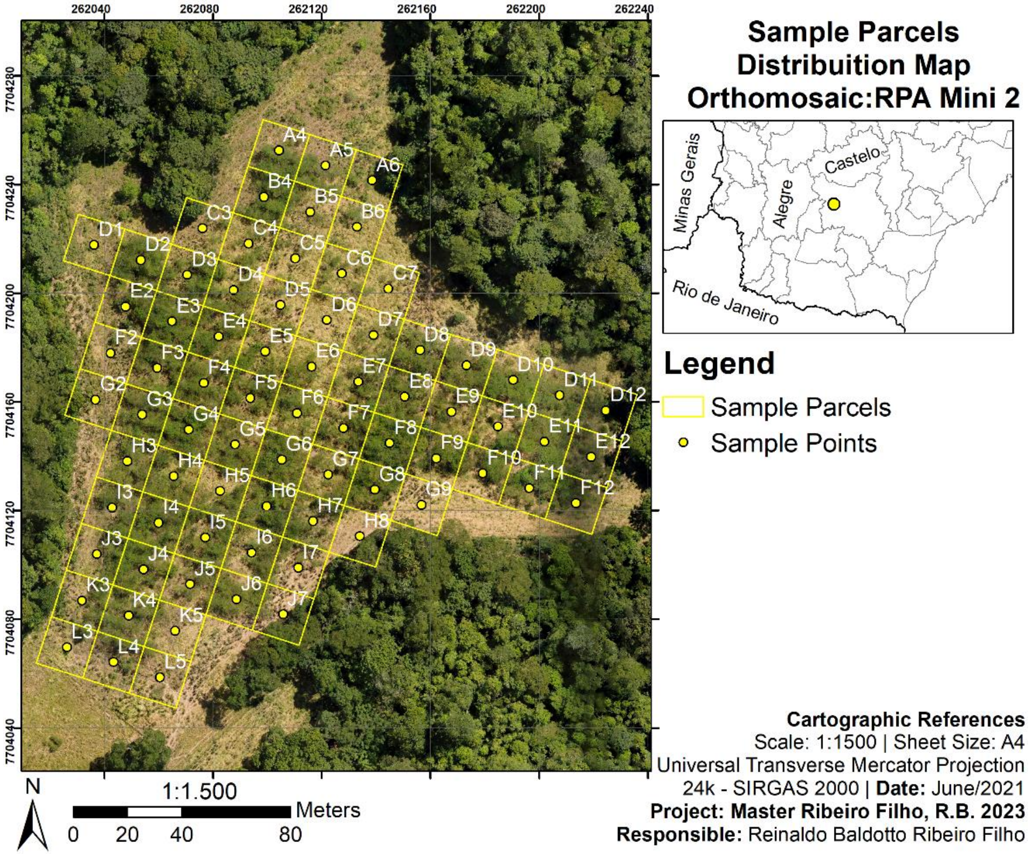

Figure 1. Map of the distribution of the sample plots at the Fazenda Experimental Bananal do Norte, Pacotuba, in Cachoeiro de Itapemirim, ES, superimposed on the orthophoto mosaic obtained through the mapping with the use of a remotely piloted aircraft.

2.6. Soil sampling

The soil sampling activity was systematic, following the spacing of 18m, between the crop rows, and started after the marking of the stakes. On July 25, 2022, the first soil sampling campaign was carried out to obtain data for the dry period. The main tools used were: a manual auger, identifier, and sampling bag. Near the sampling point, 3 soil samples were collected at a depth of 0-0.10 m, to collect at least 400 g of soil sample. At the end of the collection, the bags were tied and identified on the inside and outside.

The samples were cataloged in a spreadsheet and sent to the LABOMINAS Agronomic Laboratory, in Manhuaçu (MG), to obtain the values related to the chemical elements of the soils, pH in H_2O, Ca+Mg, Ca, Mg, Al, H+Al, K, S, P-Mehlich, Mat Org, Zn, B, Cu, Fe, Mn, Base Sum, CTC, Base Sat, Al Sat, Ca/Mg, Ca/K, Mg/K, %Ca/CTC, %Mg/CTC, %K/CTC and %H+Al/CTC. These data were organized and superimposed on the existing point data in the project database and in this way, it was possible to integrate this information in the geographic information software and to spatialize the levels of each element.

2.7. Processing of geographic data from soil samples

To spatialize the values of soil attributes, the non-statistical IDW (inverse distance weight) interpolator was initially used to generate the spatial distribution of soil element values. The symbology of the maps and the distribution of the contour lines were done through the classification of the histogram into geometric intervals. The second form of soil attribute analysis was through descriptive statistics, according to Nourzadeh *et al.* (2012), where the maximum, minimum, mean, median, and variation coefficients, asymmetry, and kurtosis were obtained. In addition, the Ryan-Joiner test was used, because it is the simplest and most agile, to verify the normality of the data.

For each element, a preliminary statistical evaluation was performed within ArcMap, to identify the sample distribution curve in the histogram, so that a later correction could be made for the application of kriging. Afterward, the data was adjusted with linear, linear with step, spherical, Gaussian, and exponential models. The model adjustments were made to obtain the lowest R^2 value. According to the statistical parameters generated, the soil attributes that presented R^2 greater than 0.75 were submitted to the cross-validation test, to validate the method used. The elements that had R^2 greater than 0.25 in the cross-validation were interpolated to generate the maps of the spatial distribution of soil attributes. Only the Cu, Fe, Mn, and Ca+Mg analyses passed this test.

2.8. Definition of management zones

The results generated by interpolation through geostatistics and IDW had their data classified according to what was proposed by Prezotti and Garçoni (2013) to define the management zones. The maps were separated into areas with a nutrient deficiency in the yellow color (Low), with the ideal average amount of nutrients, which does not need management, in the green color (Medium), and with an excess of nutrients about the values considered ideal, in the orange color (High).

3. RESULTS AND DISCUSSION

3.1. Orthophotomosaics and digital models

After processing the images obtained through the first aerial mapping, it was possible to obtain orthomosaics with a spatial resolution of 3 cm/pixel. Figure 1 shows the plots found in the edge areas with little or no development of jacarandá-da-bahia (C7, D1, F2, G2, K5, L3, and L5), in the central part of the work area, the northeastern portion presented the plots with the lowest development (C5, C7, D5, and D6). The sampling points: D2, D8, D9, D10, E3, E8, E11, F4, F8, G3, G4, G6, G8, H6, I4, J4, J6, and K4 showed good development of the crowns according to the visual aspect.

The plots C3, C4, C5, C6, C7, D1, D5, D6, D7, E6, E9, E10, F2, F6, G2, H5, I7, J5, K3, K5, L3, L4 and L5 showed low development in the size of the jacarandá-da-bahia. The plots D2, D8, D9, D10, E3, E11, F8, G4, G6, G8, and I4 showed denser and higher tree crowns. The orthomosaic made in July corresponded to winter and was captured near the peak of the drought of 2022. The reduction in the contrast of green tones can be attributed mainly to the greater incidence of sunlight at the time of mapping, as well as the jacarandá-da-bahia leaves in their deciduous period (Figure 2).

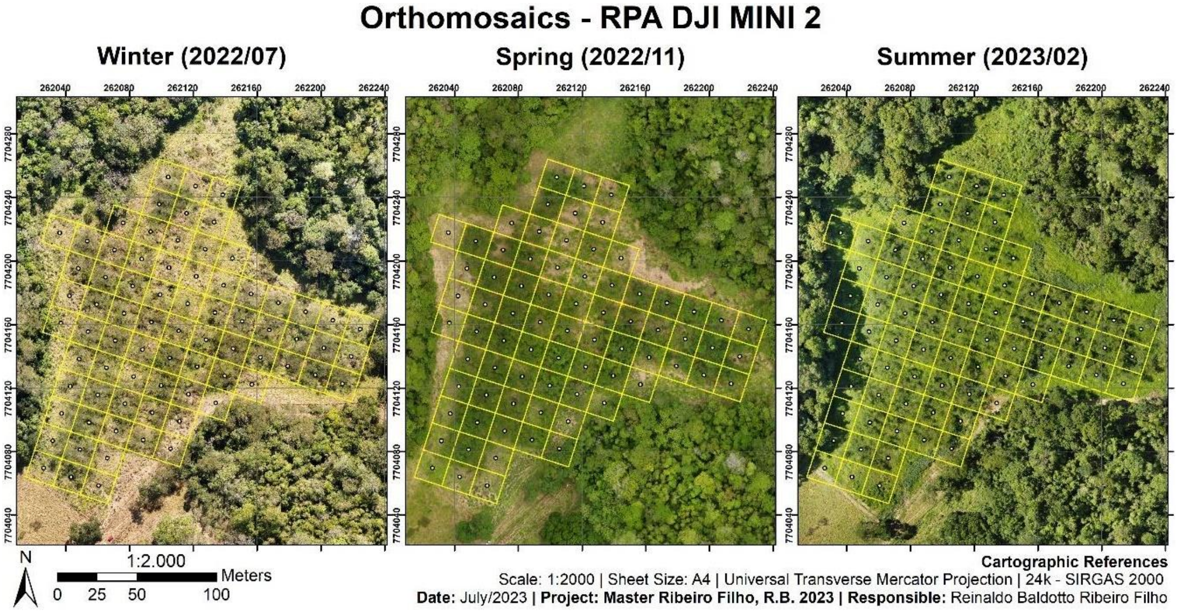

Figure 2. Orthophomosaic obtained through mapping using a remotely piloted aircraft during the Winter season (left), Spring (center) and Summer (right) at the Fazenda Experimental Bananal do Norte, Pacotuba, in Cachoeiro de Itapemirim, ES.

3.2. Descriptive and geostatistical analysis of soil nutrients

Table 1 presents descriptive statistics of soil nutrients obtained after laboratory analysis and ranges for soil chemical attributes. Oliveira Junior *et al.* (2020) analyzed the frequency distribution center, through the proximity between the mean and the median, to estimate the normality of data distribution and identify the frequency distribution.

Table 1 shows that it is possible to identify that only the elements Fe, K, Mn, and Aluminum Saturation were low, according to Prezotti and Garçoni (2013). Using the coefficients of asymmetry (Cs) and kurtosis (Ck), the symmetry and normality of the data was verified. The more the skewness coefficient approaches zero, the more symmetrical the distribution is, while the kurtosis coefficient close to zero characterizes the normality of the distribution. In element K, the lowest data symmetry was found, since it presented the highest Cs (10.72), while Ca/Mg presented the Cs closest to 0 (-0.03).

For Ck, only element Al presented values close to 0, characterizing normality in its distribution. Montezano *et al.* (2006), and Montanari *et al.* (2005), studying the spatial variability of chemical attributes in soils, did not find normal distribution for most of the studied elements, corroborating the data obtained in this work. For Bamboriya *et al.* (2022), when the Coefficient of Variation (CV) has a value greater than 65%, there is an indication that the series is very heterogeneous and the average has no meaning.

According to Prezotti and Garçoni (2013), higher acid pH values in soils increase the solubility of Al^{3+}, which is one of the toxic forms of aluminum, as well as decrease the availability of macronutrients and micronutrients Cl, Mo and B. Soils with pH above 6.5 present a reduction in the availability of micronutrients Zn, Cu, Fe and Mn. Thus, the pH of the soil considered suitable for the development and high productivity of plants is between 6.0 and 6.5. In this range of pH values, there is no presence of Al^{3+} (toxic form) and there is good availability of nutrients. In the SSP-FEBN, average values of 5.63 were found for the pH, which, according to Table 1, can be considered as average.

However, Barbieri (2020) and Bamboriya *et al.* (2022) indicated that pH in soils with a range between 6.0 and 6.8 showed cultures with higher productivity. Thus, with pH values found in Table 1, it is possible to identify, in general, that the soil in the work area has a more acidic pH than ideal.

Table 1. Analysis of descriptive statistics of soil nutrient values for a depth of 0-0.10 m at the Fazenda Experimental Bananal do Norte, Pacotuba, in Cachoeiro de Itapemirim, ES.

Attributes	Min.	Max.	Average	Md.	s	Q1	Q3	CV (%)	Ck	Cs
pH pH in H_2O	4.80	6.30	5.63	5.70	0.30	5.43	5.80	5.26	3.07	-0.37
Ca+Mg (cmol$_c$ dm^{-3})	1.50	4.00	2.67	2.60	0.56	2.30	3.00	20.96	2.78	0.39
Ca (cmol$_c$ dm^{-3})	0.90	3.00	1.84	1.80	0.43	1.60	2.10	23.34	3.17	0.37
Mg (cmol$_c$ dm^{-3})	0.50	1.60	0.83	0.80	0.25	0.70	0.90	29.76	4.95	1.45
Al (cmol$_c$ dm^{-3})	0.00	0.10	0.05	0.00	0.05	0.00	0.10	107.2	0.13	1.01
H+Al (cmol$_c$ dm^{-3})	2.00	4.10	2.72	2.70	0.45	2.30	3.10	16.65	2.97	0.66
K (mg dm^{-3})	18.00	331.0	67.32	46.00	61.45	35.00	73.50	91.28	2.74	10.72
S (mg dm^{-3})	13.00	42.00	21.68	21.00	6.18	17.00	24.50	28.51	3.98	1.07
P Mehlich (mg dm^{-3})	1.00	4.60	1.91	1.80	0.66	1.50	2.20	34.46	6.21	1.44
OM (dag/kg)	1.30	2.60	1.85	1.80	0.29	1.60	2.07	15.57	2.64	0.45
Zn (cmol$_c$ dm^{-3})	1.20	9.50	4.14	3.80	1.77	2.92	5.17	42.66	3.59	0.79
B (cmol$_c$ dm^{-3})	0.30	0.50	0.35	0.40	0.06	0.30	0.40	16.29	2.20	0.35
Cu (cmol$_c$ dm^{-3})	1.50	6.10	3.31	3.20	1.03	2.60	3.97	31.12	2.71	0.52
Fe (cmol$_c$ dm^{-3})	34.00	334.0	97.65	80.00	60.02	56.25	123.3	61.47	6.10	1.69
Mn (cmol$_c$ dm^{-3})	32.70	147.9	90.53	94.60	27.04	70.32	109.3	29.87	2.67	-0.27
Sum of Bases (cmol$_c$ dm^{-3})	1.56	4.50	2.84	2.78	0.61	2.45	3.12	21.48	3.18	0.59
CTC (cmol$_c$ dm^{-3})	4.23	7.40	5.56	5.48	0.65	5.02	6.02	11.69	2.68	0.41
Sat Bases %	33.50	65.80	50.85	51.80	7.41	46.45	56.15	14.57	2.69	-0.21
Ca/Mg	1.17	3.57	2.33	2.40	0.62	1.80	2.76	26.61	2.19	-0.03
Ca/K	1.88	48.33	16.12	15.00	9.34	9.55	20.86	57.94	4.17	0.96
Mg/K	1.16	16.67	6.87	6.15	3.69	4.38	8.33	53.71	3.22	0.90

Min.: minimum value; Max.: maximum value; Md: median; s: standard deviation; Q1: first quartile; Q3: third quartile; CV: coefficient of variation; Ck: kurtosis coefficient; a Cs: coefficient of asymmetry.

In tropical environments, organic matter is one of the main factors responsible for the generation of negative charges and the organic matter content of the soil is an excellent indicator of its production potential since soils with a greater amount of OM have a greater capacity to supply nutrients to plants. Considering the data presented in Table 1, values of 1.85 dag kg^{-1} on average for organic matter in the soil were identified in the SSP-FEBN. Barbieri (2020), got organic matter values similar to this work (1.83 dag kg^{-1}), which may be related, as both locations are located in an environment classified as tropical forest. Macronutrient P has its classes categorized as low (< 8 mg dm^{-3}), medium (8 to 12 mg dm^{-3}), and high (> 12 mg dm^{-3}) according to Skorupa and Manzatto (2019). The mean P in the work area was 1.91 $mg.dm^{-3}$, showing that this element is deficient. Prezotti and Garçoni (2013) suggests that for areas with P deficiency there should be application of mineral fertilizers, to correct the levels to provide adequate plant growth and the desired productivity.

Potassium is one of the essential macronutrients for plants and is required in amounts equal to or greater than those of N and P. Brazil tends to have soils that are depleted in K, but average values of 67.32 mg dm^{-3} were found in the SSP-FEBN. The high values of K are related mainly due the presence of felsic igneous rocks in the area, where K becomes available during the rock weathering and consequently to the soil formation process. Calcium and magnesium are important for plant development, and tend to have lower values in more acidic soils and higher values in soils with good fertility. In the SSP-FEBN, the values found for Ca and Mg are, respectively, 1.84 and 0.83 $cmol_c dm^{-3}$, which are considered medium and low. Prezotti and Garçoni (2013) suggests the application of limestone for corrections of acidity and increase of these elements.

Sulfur, a component that easily rests in soil, can be balanced through soil management or via rainfall since it is easily leached in the form of sulfate. In the SSP-FEBN, mean values of 21.68 mg dm^{-3} were found, which is considered a high value. High values of S were also found in Bamboriya *et al.* (2022). In addition, Prezotti and Garçoni (2013) indicated a high amount of S in his work area and concluded that it was beneficial to vegetable and legume production due to their demand for high values of S.

3.3. Interpolation of soil nutrients by geostatistics

The adjustments of the semivariograms can be seen in Table 2, which shows the geostatistical data. Oliveira Junior *et al.* (2020), studying the spatial distribution and chemical attributes in soils in areas under different agricultural uses, found the best fit using spherical and exponential models.

Another important piece of data to be analyzed in Table 2 is the nugget effect (C0), which represents unexplained or chance variance, often caused by measurement errors or attribute variations that cannot be detected in the sampling scale (Nourzadeh *et al.*, 2012). In the SSP-FEBN, the elements Ca+Mg, Mat Org, and B showed a nugget effect, or error, with almost the totality of the variation. Oliveira Junior *et al.* (2020) found a pure nugget effect for P and Barros *et al.* (2021) found a pure nugget effect for K, Al, and Mat Org elements. The ratio between the nugget effect and the threshold (k) allows the classification of attributes according to the degree of spatial dependence (GDE), where if $k \leq 25\%$ is considered strong spatial dependence, for the range of o $25\% \leq k \leq 75\%$ means that there is moderate dependence and above 75% there is weak spatial dependence (Barros *et al.*, 2021). In the spatial dependence analysis of the SSP-FEBN attributes, no GDE was found in the strong class, only in the moderate and weak classes. Oliveira Junior *et al.* (2020) found classes with low GDE for P and moderate for K and Mat Org. Correia *et al.* (2021) studying the analysis of spatial and temporal variability in a soybean and wheat seed production field also found low GDE for pH and Mat Org attributes. According to Yan *et al.* (2020), several factors, such as the nature of the data, sampling errors, measurement errors, or even micro regionalizations of the variable under analysis, can be the causes of a low GDE. Barros *et al.* (2021) used R^2 and SQR as metrics to evaluate the performance of the methods so that R^2 with values close to 1 indicate better performance.

Table 2. Models and parameters estimated from experimental semivariograms for soil chemical characteristics at depths of 0-0.10 m, at Fazenda Experimental Bananal do Norte, Pacotuba, in Cachoeiro de Itapemirim, ES.

	Geostatistics						Spatial Dependency		Cross-validation	
Element	Model	Co	Co+C	Ao	SQR	R²	k	GDE	SQR	R²
pH pH in water	LP	0.075	0.081	59.399	0	0.084	0.93	Weak	0	0.084
Ca+Mg (cmol$_c$ dm^{-3})	LIN	0.33	0.31	64.15	0	0.29	1.06	Weak	0.59	0.04
Ca (cmol$_c$ dm^{-3})	LP	0.1	0.17	42.53	0	0.72	0.59	Moderate	0.38	0.13
Mg (cmol$_c$ dm^{-3})	LP	0.03	0.03	75.63	0	0.25	1.00	Weak	0.18	0
Al (cmol$_c$ dm^{-3})	EPP	0	0	86.64	-	-	-	-	-	-
H+Al (cmol$_c$ dm^{-3})	LP	0.15	0.19	91.75	0	0.75	0.79	Weak	0.42	0.03
K (mg dm^{-3})	ESF	762.04	1092.71	69.55	62319.97	0.31	0.70	Moderate	33.36	0
S (mg dm^{-3})	LP	26.16	35.81	113.54	14.65	0.79	0.73	Moderate	5.56	0.07
P Mehlich (mg dm^{-3})	LP	0.23	0.31	53.2	0	0.82	0.74	Moderate	0.54	0.01
MO (dag/dm^{3})	LIN	0.08	0.08	71.67	0	0.18	1.00	Weak	0.28	0.14
Zn (mg dm^{-3})	LP	1.55	2.28	59.41	0.12	0.62	0.68	Moderate	1.38	0.13
B (mg dm^{-3})	EPP	0	0	127.71	-	-	-	-	-	-
Cu (mg dm^{-3})	LP	0.5	1.15	97.44	0.02	0.93	0.43	Moderate	0.83	0.27
Fe (mg dm^{-3})	LP	907.21	2374.36	57.7	410401.8	0.65	0.38	Moderate	37.68	0.31
Mn (mg dm^{-3})	ESF	224.29	793.72	44.4	2658.38	0.92	0.28	Moderate	23.23	0.25
Sum of Bases (cmol$_c$ dm^{-3})	LIN	0.36	0.34	69.53	0.01	0.16	1.06	Weak	0.61	0.01
CTC (cmol$_c$ dm^{-3})	LIN	0.36	0.43	127.7	0.02	-0.3	0.84	Weak	0.66	0.11
Sat Bases %	LP	39.55	54.33	40.8	119.31	0.26	0.73	Moderada	7.19	0.06
Sat Alum (saturation of Al)	ESF	3.35	4.48	86.9	0.2	0.75	0.75	Weak	2.01	0.06
Ca/Mg	LP	0.15	0.45	66.87	0	0.95	0.33	Moderate	0.47	0.43
Ca/K	ESF	42.74	69.59	54.71	269.94	0.3	0.61	Moderate	8.23	0.02
Mg/K	LP	11.84	12.66	45.03	1.14	0.12	0.94	Weak	3.68	0.01

All soil attributes that presented R² greater than 0.75 were submitted to the cross-validation test, to validate the method used. Elements that had R² greater than 0.25 in cross-validation were interpolated to generate spatial distribution maps of soil attributes. In this test, only the Cu, Fe, Mn, and Ca+Mg analyses passed (Figure 3).

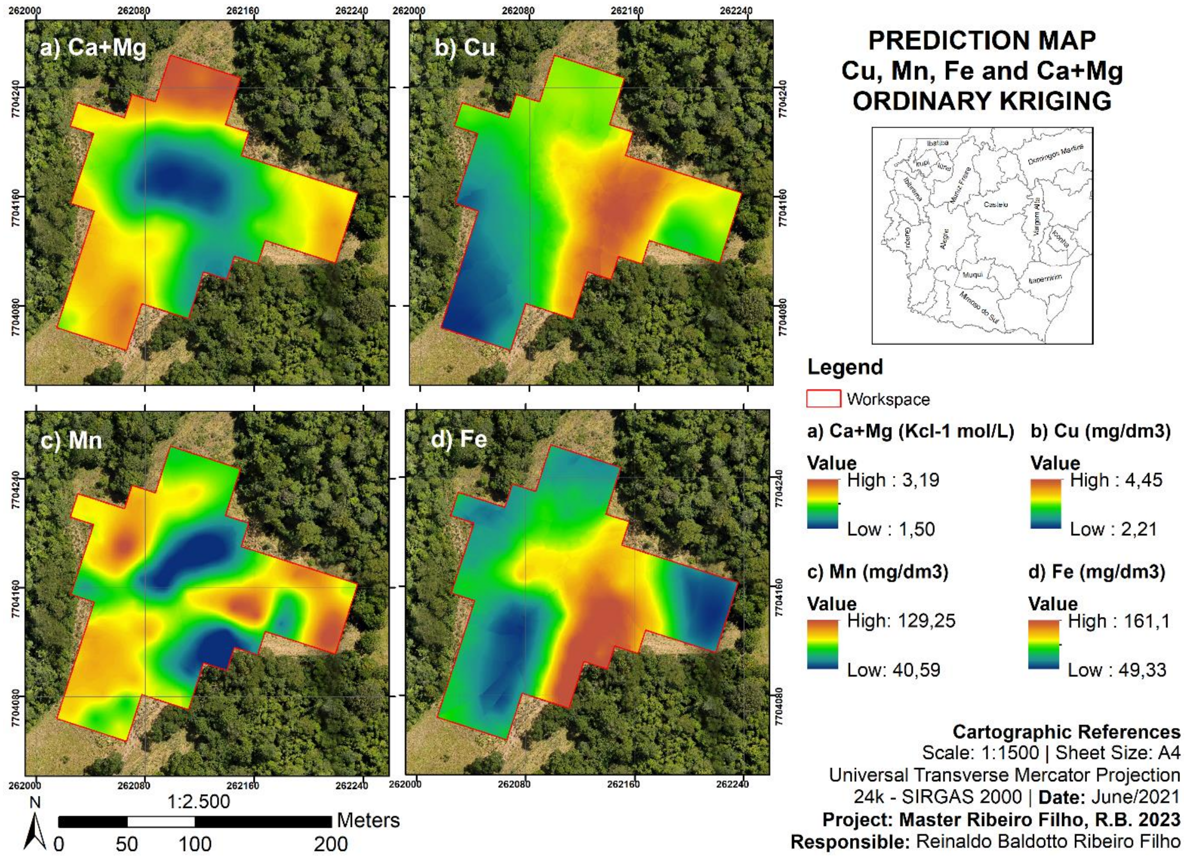

Figure 3. Map of the spatial distribution of nutrients in the soil by the geostatistical method of ordinary kriging for the elements Ca+Mg, Cu, Mn, and Fe, at the Fazenda Experimental Bananal do Norte, Pacotuba, in Cachoeiro de Itapemirim, ES.

In Figure 3, it is possible to identify that the soil attributes are distributed heterogeneously throughout the work area, and it is possible to find zones with higher or lower concentrations. Thus, through visual evaluation, it is possible to find lower concentrations of Ca+Mg in the central part of the work area, which increases towards the north, and towards the forest. Orthogonally to the crop line, between the plots with columns 7 to 9, there is a zone with enrichment of Cu and Fe. In the northeast and southeast portions of the area, depletion of the amount of Mn was identified.

3.4. Current soil nutrient conditions showing management zones

With the information regarding the nutritional contents of the soil per plot and with the interpolation of the data, either by the IDW method or by Kriging, it is possible to have an overview of the local conditions and identify the areas that need corrections to improve productivity. Of the main factors that control nutrient availability in soils, adsorption by plants, increase or decrease in solubility, and cation exchange capacity (CEC), pH is one of the main regulators. In the pH management map (Figure 4), it is possible to identify that the minimum pH value found was 4.8 in the F5 plot and the maximum value of 6.3 was found in the D2 plot.

In general, the area has an average pH represented by the green color with some portions in the central and eastern parts with acidic pH conditions.

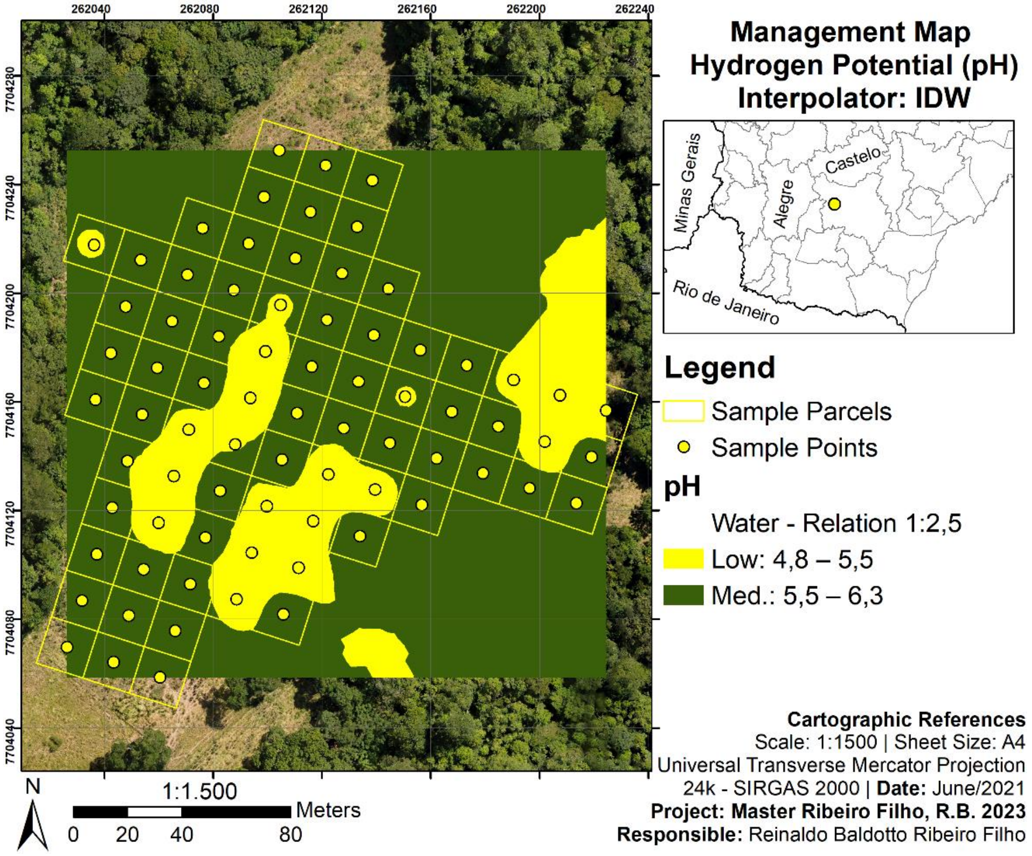

Figure 4. Map of spatial distribution with reference values for pH, showing the predominant acidity in the work area, identifying in yellow the areas with deficiency of this element that need management and in green areas with average values, at the Fazenda Experimental Bananal do Norte, Pacotuba, in Cachoeiro de Itapemirim, ES.

As for Organic Matter (Figure 5), only 5 plots show deficiency. The movement of cattle within the working area is one of the factors that increase the availability of organic matter through manure, but it is not always distributed homogeneously. Thus, the application of organic fertilizer to increase the availability of organic matter in areas with values below the average may be suggested.

Analyzing the K conditions (Figure 6) in the SSP-FEBN, it is possible to identify plots with values below the average in the yellow color (C6, C7, D2, D9, E8, D11, F12, G3, H3, H4, and J4) and plots with values considered high in the central region represented by the color orange, requiring management of these areas.

In this work, the only nutrient that could be compared using the IDW and the Kriging methods was Ca+Mg. All the other nutrients presented high values in the entire work area, and it wasn’t possible to compare them with the IDW and the Kriging methods.

Figure 7 presents the Ca+Mg interpolation with IDW (left) and with the Kriging methods (right). In general, the two maps are very similar, with an area predominantly with average Ca+Mg values and deficiency in the central portion that goes towards the south. The main differences were found in plots C6, E8, E9, G7, and I7, where in some cases the value is considered low, and in others medium. According to Prezotti and Garçoni (2013), liming is a technique that can be used to correct the levels of calcium and magnesium in soils.

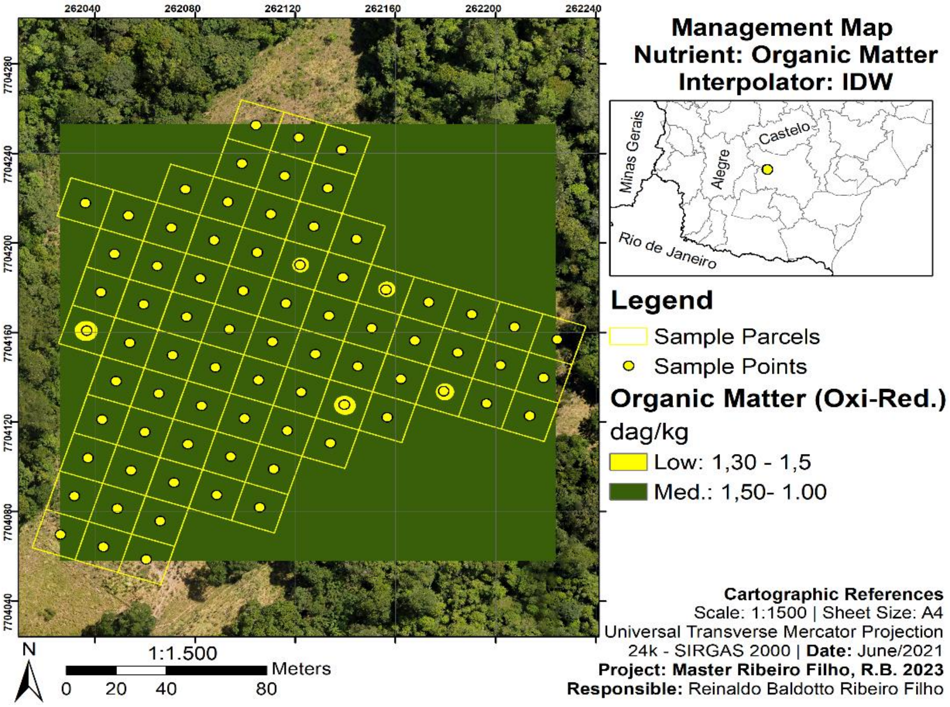

Figure 5. Map of spatial distribution with reference values for organic matter, identifying in yellow the areas with deficiency of this element that need management and in green areas with average values, at the Fazenda Experimental Bananal do Norte, Pacotuba, in Cachoeiro de Itapemirim, ES.

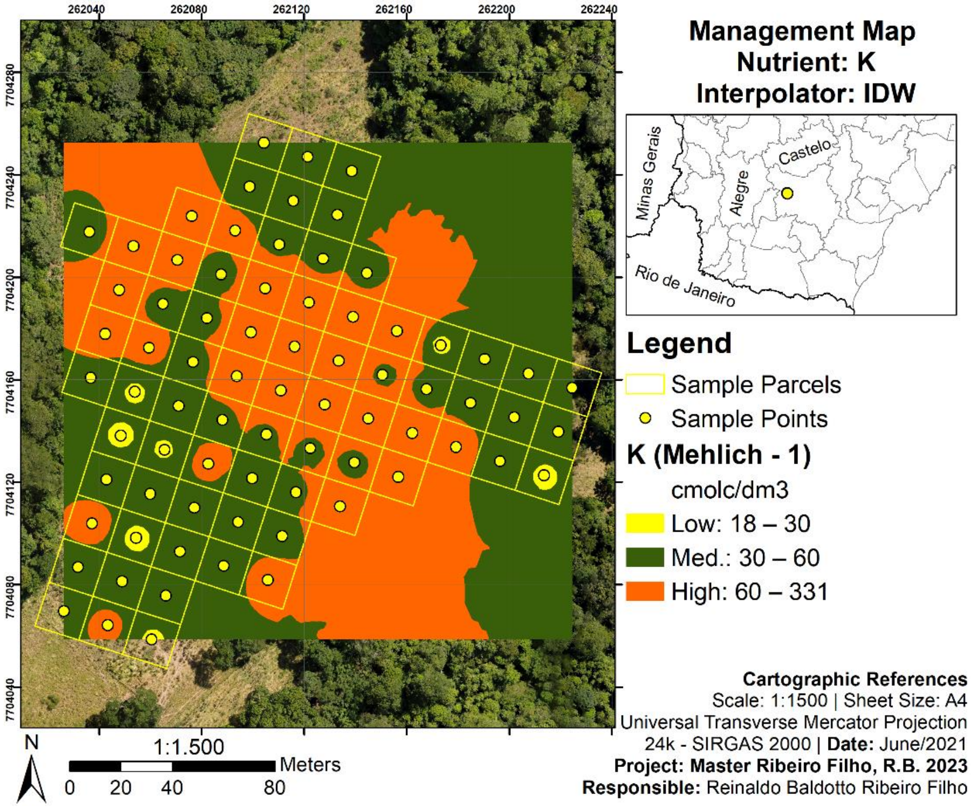

Figure 6. Map of spatial distribution with reference values for potassium at depths of 0-0.10 m, where areas in orange indicate high values, areas in yellow indicate low values, and areas in green indicate medium values, at Fazenda Experimental Bananal do Norte, Pacotuba, in Cachoeiro de Itapemirim, ES.

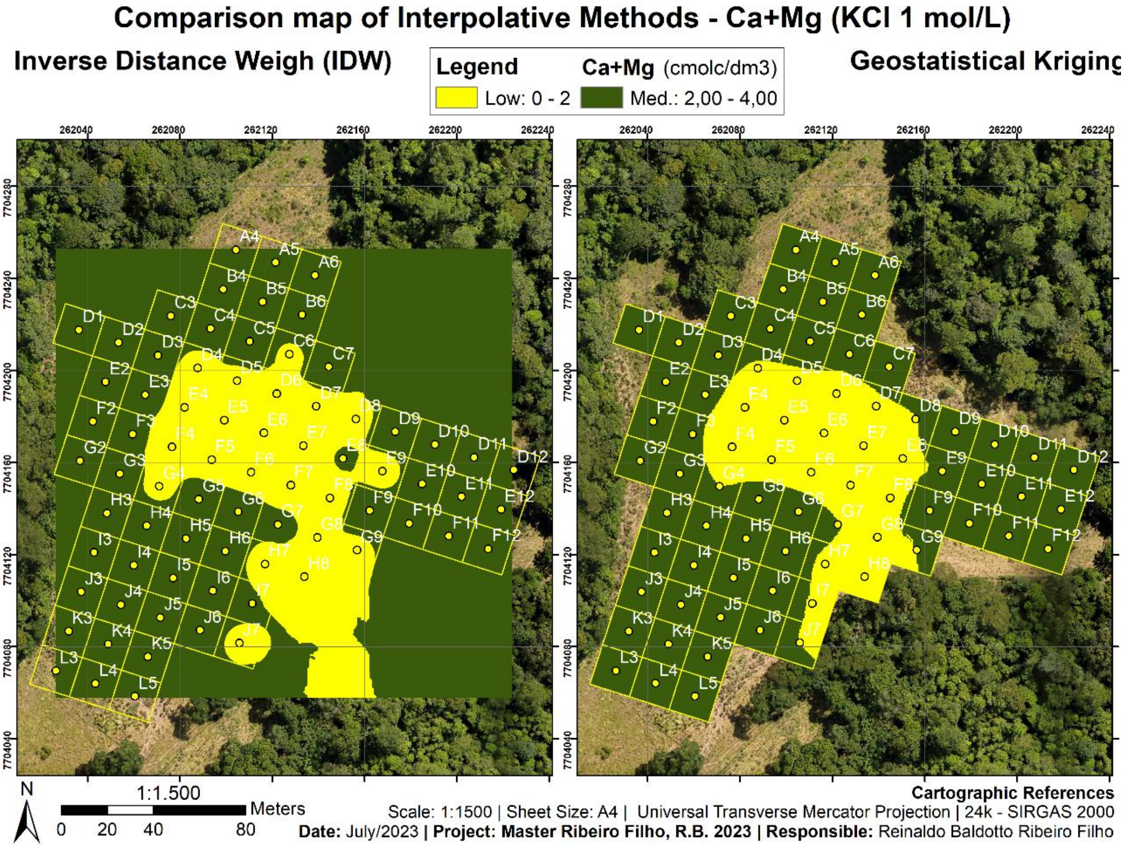

Figure 7. The spatial distribution map referred to the values of the Ca+Mg ratio at depths of 0-0.10 m using IDW interpolation (left) and Geostatistical Kriging (right) in the Fazenda Experimental Bananal do Norte, Pacotuba, in Cachoeiro de Itapemirim, ES. The yellow area indicates low values of the Ca+Mg ratio, while the green area indicates medium values.

4. CONCLUSION

The cultivation of jacarandá-da-bahia intensified land use over time in the area where this research was conducted. Also, it probably increased the contribution of biomass and supply of organic matter to the pasture, as well as the appearance of new shaded areas for the well-being of animals. Based on the analysis of descriptive statistics, it was identified that pH, P, and B present concentrations below those desired to increase productivity. Organic Matter, Calcium, and Magnesium showed average concentrations. Zones with low amounts of nutrients were found in the work area, which can be corrected through the application of dolomitic limestone.

The spatialization of the data allowed us to obtain a comprehensive view of the work area, using two different techniques: interpolation by IDW and geostatistics by kriging. We observed that only Cu, Fe, Mn, and Ca+Mg nutrients showed significant spatial dependence. This analysis identified areas with deficiencies in nutrients K, Ca, Zn, and Fe, even when the average values indicated high or moderate levels of nutrients according to the descriptive statistics.

Thus, the interpolation of data using interpolators, or geostatistics, was essential for agrochemical assessments to improve soil quality to increase crop performance, directly identifying which plots have nutritional deficiencies. The use of remotely piloted aircraft, together with a georeferenced database, proved to be a powerful innovative tool for the production and analysis of temporal images.

5. ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to the institutions Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural (INCAPER), Fundação de Amparo à Pesquisa e Inovação do Espírito Santo (FAPES), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Universidade Federal do Espírito Santo (UFES), and Instituto Federal de Educação, Ciência e Tecnologia do Espírito Santo (IFES) for their invaluable support and funding, which greatly contributed to the successful completion of this academic research.

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