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Soil fertility maps as a tool for Precision Agriculture

Mapas de fertilidade do solo como ferramenta para Agricultura de Precisão

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Abstract

The advancement of Brazilian agriculture in recent years has been driven by progress in research on soil fertility and applied technologies, which have enabled the efficient use of soil amendments and fertilizers, improving soil quality and agricultural productivity. Soil chemical analysis is essential, but not exclusive; in this context, Digital and Precision Agriculture have revolutionized agricultural practices. The use of sensors, fertility maps, geolocation, and homogeneous management zones has proven effective in increasing resource use efficiency, optimizing input recommendations, and minimizing environmental impacts. In this context, this study aimed to develop soil fertility maps to determine and analyze management zones on a property located in the municipality of Frei Paulo, Sergipe. The characterization of the soil's chemical attributes was carried out in an experimental area of 180 ha, using a georeferenced points area and generating sampling grids in the free software

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QGIS (3.28.2), with 6 sampling points, 3 samples per hectare and two depths, 0 to 20 cm and 20 to 40 cm, and for each main sample, 4 subsamples spaced 1 meter apart were collected. The data were submitted to descriptive statistics and the maps were interpolated using the Smart-Map plugin (version 1.4). According to the generated maps, distinct patterns were revealed between the two layers analyzed; pH, calcium, phosphorus, and potassium presented higher values in the surface layer (0-20 cm), reflecting the influence of agricultural management and leaching. The essential cation saturation indicated good surface fertility; however, the low effective CEC in depth requires attention to fertilization.

Keywords: Precision Agriculture; Machine Learning; Soil Fertility; Digital Soil Mapping

Resumo

O avanço da agricultura brasileira nos últimos anos tem sido impulsionado por avanços em pesquisas sobre fertilidade do solo e tecnologias aplicadas, que permitiram o uso eficiente de corretivos e fertilizantes, melhorando a qualidade do solo e a produtividade agrícola. A análise química do solo é essencial, mas não exclusiva, nesse cenário, a Agricultura Digital e de Precisão têm revolucionado as práticas agrícolas, com o uso de sensores, mapas de fertilidade, geolocalização e zonas homogêneas de manejo, têm se mostrado eficazes para aumentar a eficiência na utilização de recursos, otimizando a recomendação de insumos e minimizando os impactos ambientais. Neste contexto, este trabalho teve como objetivo elaborar mapas de fertilidade do solo para determinação e análise de zonas de manejo em uma propriedade localizada no município de Frei Paulo, Sergipe. A caracterização dos atributos químicos do solo foi realizada em uma área experimental de 180 ha, sendo adotado uma área com pontos georreferenciados e gerado grades amostrais em software livre QGIS (3.28.2), sendo 6 pontos amostrais, com 3 amostras por hectare e duas profundidades, 0 a 20 cm e 20 a 40 cm, e para cada amostra principal foram coletadas 4 subamostras distanciadas de 1 metro. Os dados foram submetidos à estatística descritiva e os mapas interpolados através do plugin Smart-Map (versão 1.4). De acordo com os mapas gerados foram revelados padrões distintos entre as duas camadas analisadas, o pH, o cálcio, o fósforo e o potássio apresentaram valores mais elevados na camada superficial (0-20 cm), refletindo a influência do manejo agrícola e da lixiviação. A saturação por cátions essenciais indicou boa fertilidade superficial, entretanto a baixa CTC efetiva em profundidade requer atenção à adubação.

Palavras-chave: Agricultura de Precisão; Machine Learning; Fertilidade do Solo; Mapeamento Digital do Solo.

INTRODUCTION

In recent decades, Brazilian agriculture has shown significant progress in the productive performance of the most economically important crops, such as soybeans, which, according to the Ministry of Agriculture and Livestock (MAPA, 2024), represent R$ 348.6 billion of the total agricultural production value, followed by corn, which represents R$ 101.8 billion, and sugarcane with R$ 101.9 billion. Among the determining factors for this progress, research on the productive potential of the soil and the technologies applied to agriculture stand out, with emphasis on the management of the chemical, physical, and biological fertility of the soil, to increase nutrient availability and reduce limiting factors to deep root development. Thus, it is necessary to improve technical evaluations to enable proper fertilization management, with rationalization of fertilizer use (Oliveira *et al.*, 2023).

The interrelationship between soil fertility and agricultural productivity is fundamental, as a productive soil does not guarantee high productivity; there are other factors that limit productivity. Assessing the nutritional status of the soil is essential for agricultural planning and can be carried out through chemical analyses and visual monitoring of nutritional deficiencies in plants. Parameters such as pH (hydrogen potential), exchangeable aluminum, aluminum saturation, exchangeable sodium, and sodium saturation index are soil characteristics that indicate conditions of stress or chemical hindrance, as well as the results of exchangeable calcium and magnesium, which indicate chemical hindrances, results primarily used to determine corrective doses (Mendes, 2007; Silva, 2009).

Digital Agriculture and Precision Agriculture have been revolutionizing soil management practices, providing greater efficiency in the use of fertilizers and soil amendments. Technologies such as remote sensors, fertility maps, and geolocation systems enable the localized application of inputs, optimizing productivity and reducing environmental impacts. Since the arrival of Precision Agriculture in the market, changes have been noticed in various management methods; one example is the collection method for soil analyses. The sample grid was widely used, but it lost prominence after soil analyses based on geolocated data were implemented, which aim to analyze the areas that are actually being impacted by low productivity, biomass index, among others. Thus, it is possible to assess where soil nutritional deficiencies may be occurring (Ramos and Oliveira, 2021).

The generation of maps of soil chemical attributes provides a diagnosis of the spatial variability of fertility classes and of regions with lower and higher nutrient levels (Morato *et al.*, 2021). In this context, the use of geotechnologies contributes to the optimization of resources, making it possible, through soil analyses, to interpret the sampling grids and make specific input recommendations, ensuring a more rational optimization and use of inputs at the right time, place, and doses, providing economic and environmental benefits (Bassoi *et al.*, 2019).

In Brazil, the digital mapping of soil attributes constitutes an ongoing demand from various institutions, which seek greater accuracy in the characterization and delimitation of soils to support localized decisions, optimize management practices, and reduce production costs (Ribeiro *et al.*, 2024). Although this demand is high, there are some limitations, such as the high costs of acquiring and implementing technologies, especially for small and medium producers. Even though there are free software options like QGIS, specialized knowledge and training are required, which can impact costs for producers (Inamasu, 2024).

Varvel *et al.* (1999) used an aerial camera equipped with 35 mm color film (Kodak Ektachrome), flying at about 2,130 m, to obtain images of non-vegetated soil. From these photographs, they extracted brightness values in the blue, green, and red bands and found significant statistical correlations between these values and the organic matter and phosphorus contents obtained through intensive fine-grid sampling. Although the correlations were not extremely high, especially when extreme soil values were included, the study showed that aerial images can more efficiently guide sampling strategies, reducing costs without losing the quality of soil characterization.

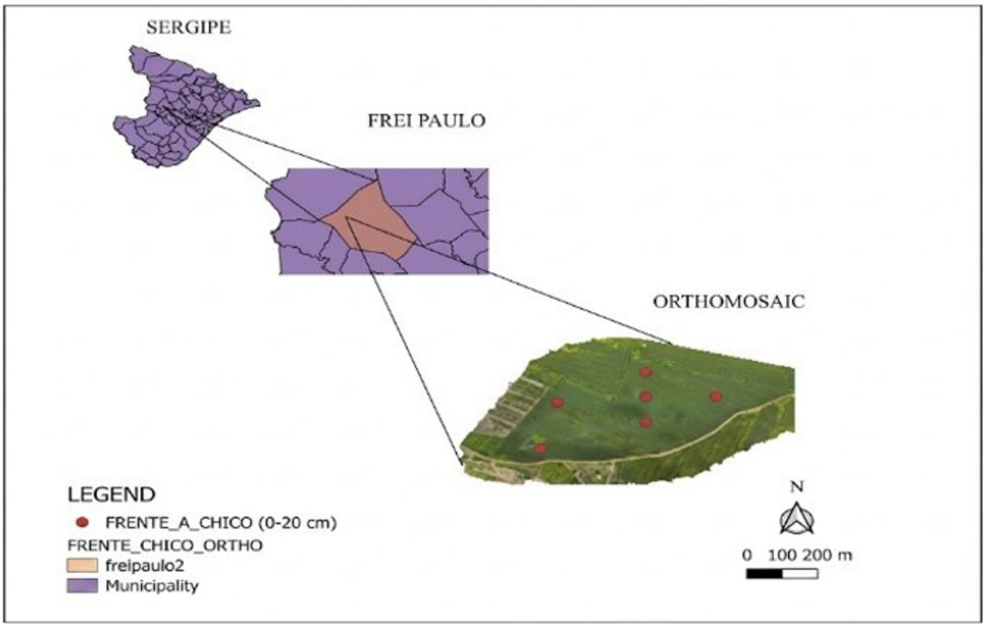
New approaches, such as homogeneous management zones, have proven to be promising in indicating the locations where sampling should be carried out. Luchiari Junior *et al.* (2000) define management zones as areas of land with equal potential production, input use efficiency, and environmental impact risk. The use of management zones is a valid strategy to increase the efficiency of natural resource use and reduce the impact of agriculture on the environment (Luchiari Junior *et al.*, 2011).

The city of Frei Paulo stands out for corn production, with 9,100 ha of harvested area, ranking 5th in the state of Sergipe. According to IBGE (2017), corn is the most cultivated grain in the SEALBA region (Sergipe, Alagoas, and Bahia), with the main production hub being the Agreste of Sergipe, since in addition to being a basis for animal feed, corn is widely used in human food in the region, especially in the form of flaked flour. This crop has significantly driven the economy of this region; however, the fact that it is cultivated in monoculture has raised concerns regarding its sustainability (Procópio *et al.*, 2019). It is hypothesized that the chemical attributes of the soil show significant variation between layers and sectors of the area, allowing for the identification of distinct management zones. Thus, the present study aimed to develop and interpret soil fertility maps at two depths to determine and analyze these management zones on a property located in the SEALBA region.

MATERIAL AND METHODS

The study was conducted in an area located in the municipality of Frei Paulo, in the western region of the state of Sergipe (Figure 1). The area comprises 180 hectares situated at 220 meters above sea level, with coordinates 10° 33’ 04’’ south latitude and 37° 32’ 01’’ west longitude. According to the Köppen classification (1961), the climate of the region is tropical with winter rains, annual temperatures of 24.8°C, and an average annual precipitation of 809.8 mm.

Figure 1. Geographical location of the study area and distribution of sampling points in Frei Paulo, Sergipe, Brazil.



Source: Jorge, 2025.

The experimental area was delineated by a plot of 18 ha consisting of 6 points (Figure 1), and each collection point had its information georeferenced using the GNSS (Global Navigation Satellite System) EMLID RS2 with 10-minute tracking at each point using the IBGE (*Instituto Brasileiro de Geografia e Estatística* / Brazilian Institute of Geography and Statistics) NTRIP (Networked Transport of RTCM via Internet Protocol) positioning system, which provides the GNSS data flow and corrections from the RBMC (*Rede Brasileira de Monitoramento Contínuo dos Sistemas GNSS* / Brazilian Network for Continuous Monitoring of GNSS Systems) stations in real time (IBGE, 2017).

Six samples were collected, with three per hectare, at depths of 0 to 20 cm and 20 to 40 cm, and for each main sample, four sub-samples were collected at a distance of 1 meter. The samples were submitted to chemical analysis at the soil analysis laboratory, Solos & Plantas Laboratory (ABNT NBR ISO/IEC 17025), located in the municipality of Luís Eduardo Magalhães, Bahia. The attributes analyzed were: pH in calcium chloride, phosphorus (P), potassium (), Organic matter, calcium (), magnesium (), calcium and magnesium ratio, CEC to pH 7,0, effective CEC.

After the laboratory analyses, a table was prepared containing the information on depth and nutrient quantity at each sampling point and the respective geographic coordinates converted to the

UTM (Universal Transverse Mercator) system, a standardization necessary to perform interpolations using the Smart-Map plugin (version 1.4) in QGIS (3.28.2). To operationalize spatial predictions, the Smart-Map plugin was used, registered with the National Institute of Industrial Property (INPI) under number BR 51 2021 000002-1. The plugin was developed in Python 3.7, with a graphical interface built in PyQt5, being compatible with Windows, Linux, and macOS operating systems, and operating on QGIS versions from 3.10 onwards. Its most recent version is available both in the official QGIS repository (https://plugins.qgis.org/plugins/Smart_Map/, accessed on March 15th, 2024) and on the project's GitHub (https://github.com/gustavowillam/SmartMapPlugin, accessed on March 15th, 2024). This infrastructure enabled the application of SVM as an interpolation method, integrating raster and vector covariates in the QGIS environment for generating prediction maps of soil chemical attributes (Pereira *et al.*, 2022).

The sample data were imported in ".csv" format into QGIS and processed through the plugin. After reading the table and recognizing the georeferenced attributes, the interpolation grid was defined, setting the pixel size X and Y to 10 and -10, respectively, thus establishing the spatial resolution of the map. For the modeling step, the Support Vector Machine (SVM) method from Smart-Map was selected. In this procedure, the SVM adjusts a model of the spatial relationship between the samples, learning the patterns present in the data to predict the nutrient values in the area. With the model adjusted, the plugin performed the interpolation on the defined grid, resulting in the generation of interpolated maps for each nutrient and providing the resulting maps for visualization and analysis.

The Support Vector Machine (SVM) method was employed for the interpolation of soil chemical attributes. SVM, developed in the 1990s, is a machine learning algorithm widely used for both regression and classification, being recognized for its ability to handle smaller or larger datasets without significant loss of performance. Its choice in this study is due to the robustness of the method and its efficiency in modeling complex relationships between variables even when data availability is limited (Zhang *et al.*, 2020; Liu *et al.*, 2015). As is characteristic of machine learning algorithms, SVM requires the tuning of hyperparameters, among them C and gamma (γ), which were optimized through a systematic grid search, allowing the selection of the values most suitable for the data used.

The results obtained through soil analysis were analyzed and discussed through the generation of fertility maps and the descriptive statistics of the chemical soil attributes (Tables 1 and 2). The statistical analysis includes parameters such as mean, standard deviation, variance, coefficient of variation, minimum and maximum values, skewness, and kurtosis, which are fundamental tools to describe the variability of the data and assess the uniformity of the attributes among the samples (Gomes and Garcia, 2002).

Table 1. Descriptive statistics of the chemical attributes of the soil (0-20 cm layer).

Attributes	Unit	Average	DP	V	CV	Mn	Md	Mx	AMP	ASS	K
pH		6.34	0.29	0.08	4.62	5.9	6.3	6.8	0.9	0.15	-0.60
P Res	mg/dm^3	121.25	51.8	2687.64	42.76	73	101.5	200	127	0.70	-1.33
K+	mg/dm^3	153.7	53.0	2803.51	34.45	97.1	138.8	249.7	152.6	0.78	-0.17
Ca+	cmol/dm^3	14.58	2.14	4.56	14.65	12.8	13.75	19.4	6.6	1.99	4.34
Mg^{2}+	cmol/dm^3	2.84	0.65	0.42	22.76	2	2.6	4	2	0.75	0.01
M.O	g/Kg	29.11	1.95	3.81	6.70	26.8	29.25	31.7	4.9	-0.05	-1.85
T	cmol/dm^3	22.02	3.07	9.45	13.96	17.23	21.15	26.52	9.29	0.12	-0.62
t	cmol/dm^3	17.80	2.31	5.35	12.99	15.97	17.005	22.83	6.86	1.74	3.16
Ca/Mg		5.31	1.06	1.12	19.91	3.5	5.25	6.7	3.2	-0.38	-0.46

DP: standard deviation; V: variance; CV (%): coefficient of variation; Mn: minimum; Md: median; Mx: maximum; AMP: amplitude; ASS: skewness; K: kurtosis. Hydrogen potential (pH); phosphorus (P Res); potassium (K+); calcium (Ca+); magnesium (Mg^{2}+); organic matter (M.O); CEC at pH 7,0 (T); effective CEC (t); calcium to magnesium ratio (Ca/Mg).

Table 2. Descriptive statistics of the chemical attributes of the soil (20-40 cm layer).

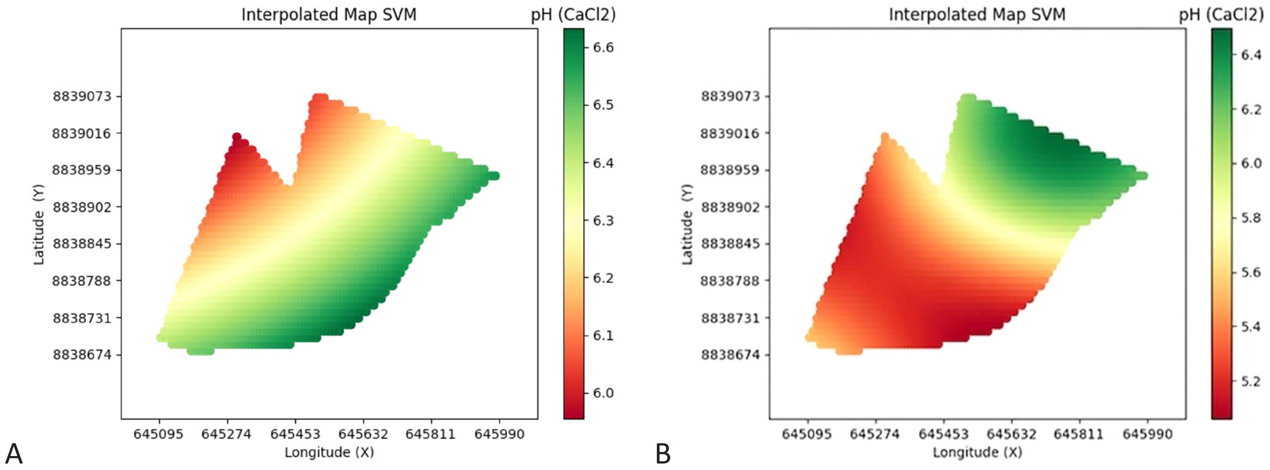
Attributes	Unit	Average	DP	V	CV	Mn	Md	Mx	AMP	ASS	K
pH		5.75	0.44	0.19	7.61	5.2	5.75	6.3	1.1	0	-2.34
P Res	mg/dm³	76.12	32.6	1063.27	42.83	33	69.5	128	95	0.47	-0.77
K+	mg/dm³	91.5	37.8	1431.30	41.35	54.9	83.15	161	106.1	0.86	-0.06
Ca+	cmol/dm³	11.25	1.08	1.16	9.57	10.2	11.05	13.5	3.3	1.40	2.23
$Mg^{2}+$	cmol/dm³	2.52	0.58	0.34	23.17	1.9	2.45	3.8	1.9	1.59	3.52
M.O	g/Kg	18.44	4.49	20.13	24.33	11.2	19.3	25.6	14.4	-0.13	-0.02
T	cmol/dm³	15.85	1.04	1.07	6.53	14.05	15.7	17.58	3.53	-0.06	1.05
t	cmol/dm³	14.02	1.02	1.04	7.28	12.95	13.82	16.28	3.33	1.75	3.92
Ca/Mg		4.62	1.06	1.13	23.02	2.7	4.5	6	3.3	-0.49	0.33

DP: standard deviation; V: variance; CV (%): coefficient of variation; Mn: minimum; Md: median; Mx: maximum; AMP: amplitude; ASS: skewness; K: kurtosis. Hydrogen potential (pH); phosphorus (P Res); potassium (K+); calcium (Ca+); magnesium ($Mg^{2}+$); organic matter (M.O); CEC at pH 7,0 (T); effective CEC (t); calcium to magnesium ratio (Ca/Mg).

RESULTS AND DISCUSSION

The pH CaCl is considered a more precise determination than the pH in water, represented by the activity of the ion in the soil solution and is greatly affected by small amounts of salts present in the soil (Shofield and Taylor, 1955; Davey and Conyers, 1988). The 0-20 cm layer (Figure 2A) showed pH values between 5.9 and 6.8 (Table 1), indicating a possible influence of external factors, such as the localized application of agricultural liming, which is responsible for neutralizing aluminum and providing calcium and magnesium as nutrients (Sousa and Lobato, 2004). These patterns are confirmed by the statistical results in Table 1, which show an average of 6.34 and a low coefficient of variation (4.61%), indicating uniformity, but with small local fluctuations, consistent with the variation spots observed on the map. The 20-40 cm layer (Figure 2B) had values between 5.2 and 6.3, with a more continuous distribution and a well-defined acidity gradient, possibly related to leaching processes that increase in areas with low CEC and reduce the residual effects of soil acidity amendments (Sousa and Lobato, 2004).

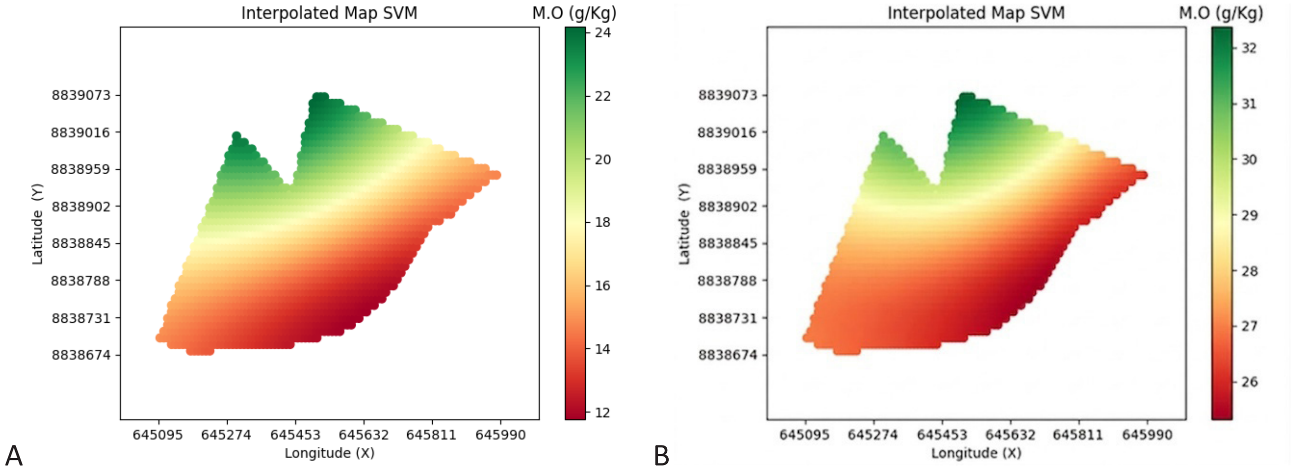
Figure 2. Maps of pH CaCl levels in the 0-20 cm (A) and 20-40 cm (B) layers.



Source: Jorge, 2025.

The experimental area showed organic matter values between 26.8 and 31.7 g/kg in the 0-20 cm layer (Figure 3A), and between 11.2 and 25.6 g/kg in the 20-40 cm layer (Figure 3B), suggesting that the soil was tilled during its preparation. These results support the studies by Embrapa (2023), which demonstrated that the accumulation of organic matter in the soil's surface layer is characteristic of no-tillage systems, in which surface deposition of crop residues predominates.

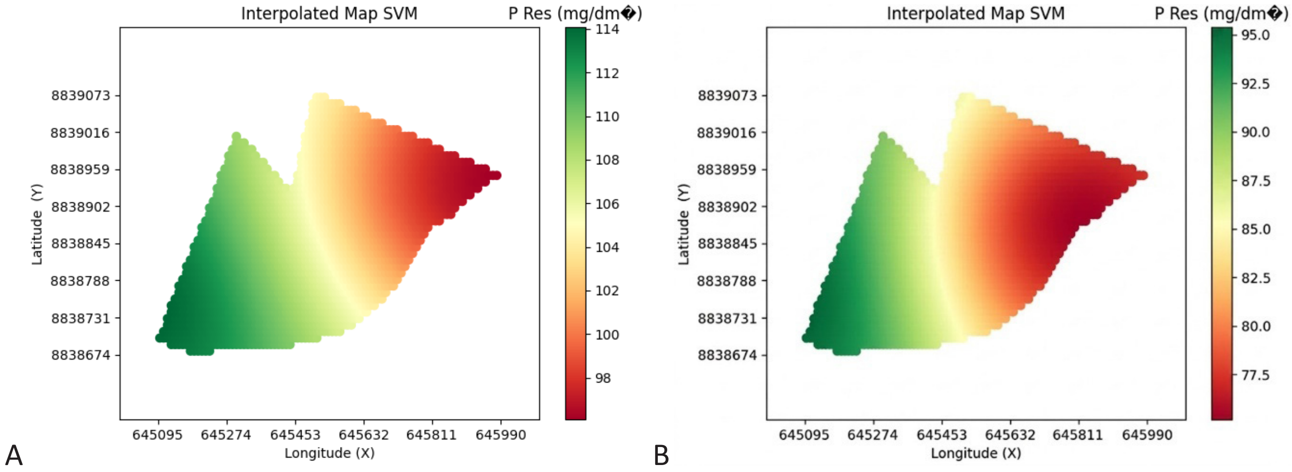
Figure 3. Maps of Organic Matter content in g/kg in the 0-20 cm (A) and 20-40 cm (B) layers.



Source: Jorge, 2025.

Phosphorus (P) is the most complex element in the soil, being influenced by several factors such as pH and the levels of other nutrients. Analyzing the phosphorus (P) distribution map, it can be seen that in the 0-20 cm layer (Figure 4A) the values range from 73 mg/dm³ to 200 mg/dm³. This variation is reflected in the statistical data (Table 1), which indicate an average of 121.25 mg/dm³, a high coefficient of variation (42.76%), and positive skewness (0.69), suggesting localized fertilizer application. The 20-40 cm layer (Figure 4B) ranges from 33 to 128 mg/dm³, with a high coefficient of variation (42.83%) according to Table 2. The lower phosphorus values in the 20-40 cm layer, compared to the 0-20 cm layer, corroborate the studies by Hauschild (2013), where phosphorus levels decrease with depth, being directly related to soil pH and its low mobility, meaning that soil acidity reduces the availability of phosphorus in the soil. Despite the significant variation among the layers analyzed, all observed values are within the appropriate parameters for clay-textured soils, according to the criteria established by Sobral *et al.* (2015), which indicate values above 8 mg/dm³ as sufficient for this type of soil.

Figure 4. Maps of Phosphorus (P) content in mg/dm³ in the 0-20 cm (A) and 20-40 cm (B) layers.

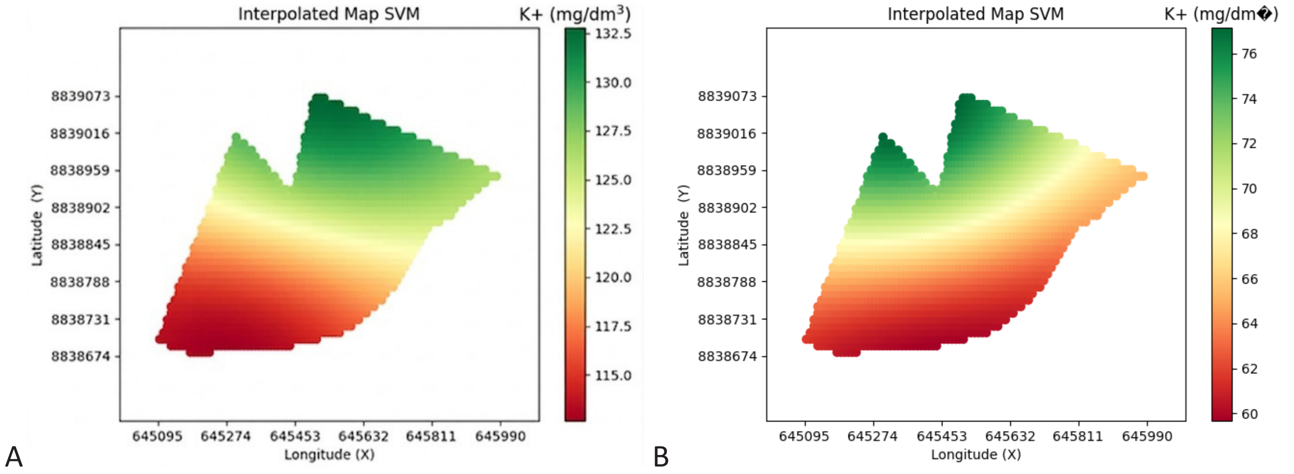


Fonte: Jorge, 2025.

The analysis of the fertility maps will indicate a marked vertical gradient in potassium levels (K^+), with significantly higher concentrations in the 0-20 cm layer, ranging from 97.1 to 249.7 mg/dm³ (Figure 5A and Table 1) compared to the 20-40 cm layer, ranging from 54.9 to 161 mg/dm³

(Figure 5B and Table 2). This pattern is consistent with studies indicating that potassium levels tend to be higher in the surface layers due to fertilizer application, decomposition of plant residues, which promote greater availability of the nutrient to plants, and low leaching (Schmidt and Hughes-Games, 2010). The average reduction of 45% in the 20-40 cm layer suggests a limitation in vertical mobility of K^+, feature observed in soils managed under conservation systems, such as no-till, where potassium accumulates in the upper layers due to low leaching (Artuso *et al.*, 2023). This retention is directly related to the CEC (Cation Exchange Capacity) of the soil, being responsible for regulating the relationship between K^+ exchangeable and K^+ in the solution, optimizing storage and reducing losses by leaching (Werle *et al.*, 2008).

Figure 5. Maps of Potassium (K+) content in mg/dm³ in the 0-20 cm (A) and 20-40 cm (B) layers.

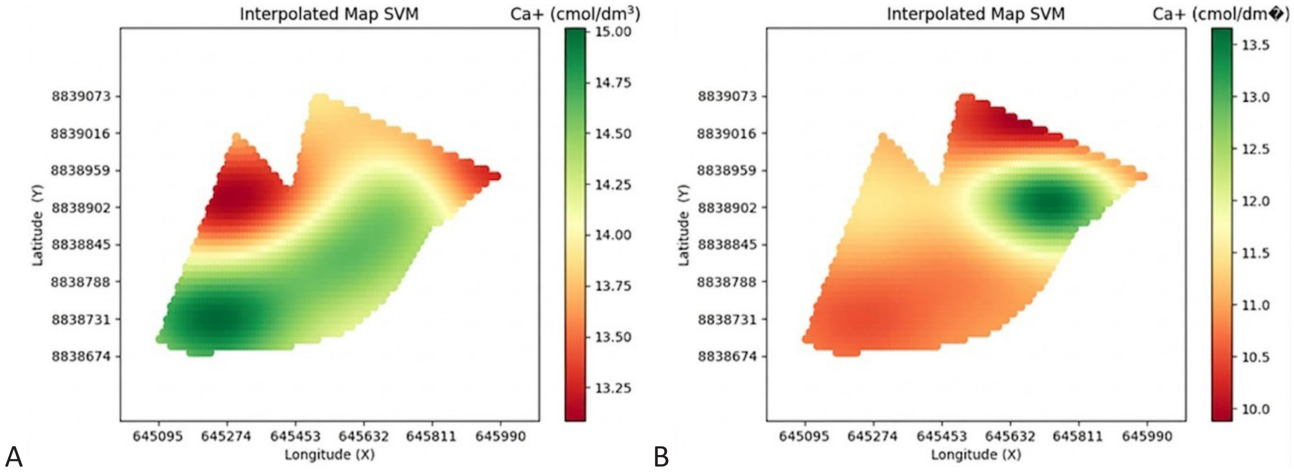


A B

Source: Jorge, 2025.

Calcium (Ca) is a primary essential element; it improves soil structure, permeability, and water infiltration, as well as helps the plant withstand soil salinity stress (Daba, 2024). Analyzing the calcium content maps, higher levels are observed in the 0-20 cm layer, between 12.8 and 19.4 cmol/dm³ (Figure 6A and Table 1) compared to the 20-40 cm layer, where values range from 10.2 to 13.5 cmol/dm³ (Figure 6B and Table 2). Sousa and Lobato (2002) recommend applying gypsum when calcium content in the lower layers is below 0.5 cmol/dm³. Although calcium values are lower in the 20-40 cm layer compared to the 0-20 cm layer, the values are above the recommended level for the use of gypsum.

Figure 6. Calcium Content Maps (Ca) in cmol/dm³ in the 0-20 cm (A) and 20-40 cm layers (B).

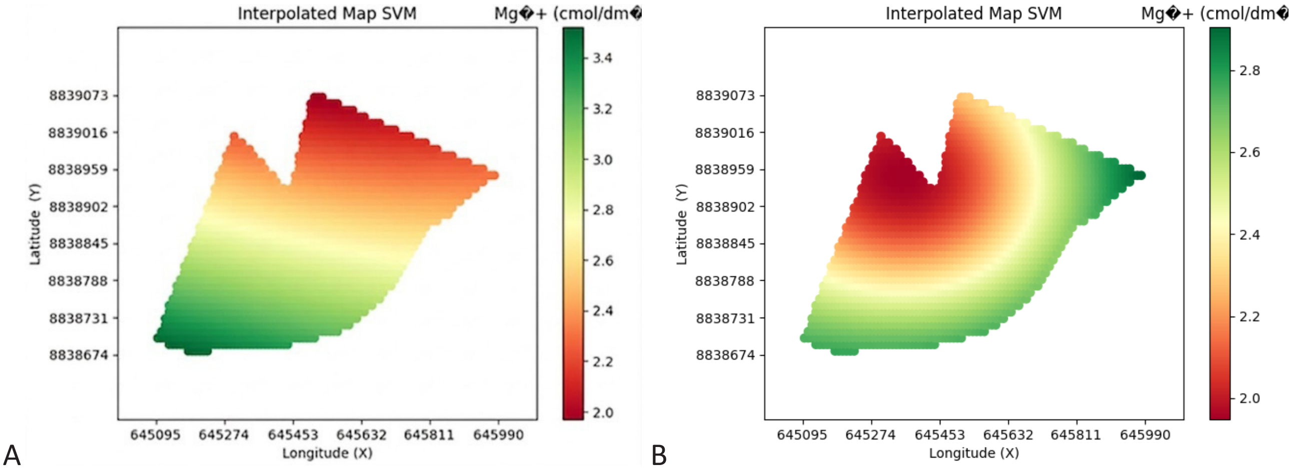


A B

Source: Jorge, 2025.

Magnesium shows higher values in the 20-40 cm layer, between 1.9 and 3.8 cmol/dm³ (Figure 7B and Table 2) compared to the 0-20 cm layer (Figure 7A), where the values range from 2 to 4 cmol/dm³ (Table 1). This effect can be explained by the hydrated ionic radius: The larger the radius, the lower the adsorption force and, therefore, the greater the mobility in the soil (Benites, *et al.*, 2010). Magnesium is a secondary macronutrient used by plants, and its main function is to serve as the central atom of the chlorophyll molecule, which is responsible for light absorption and energy transfer in photosynthesis (Oliveira *et al.*, 2024).

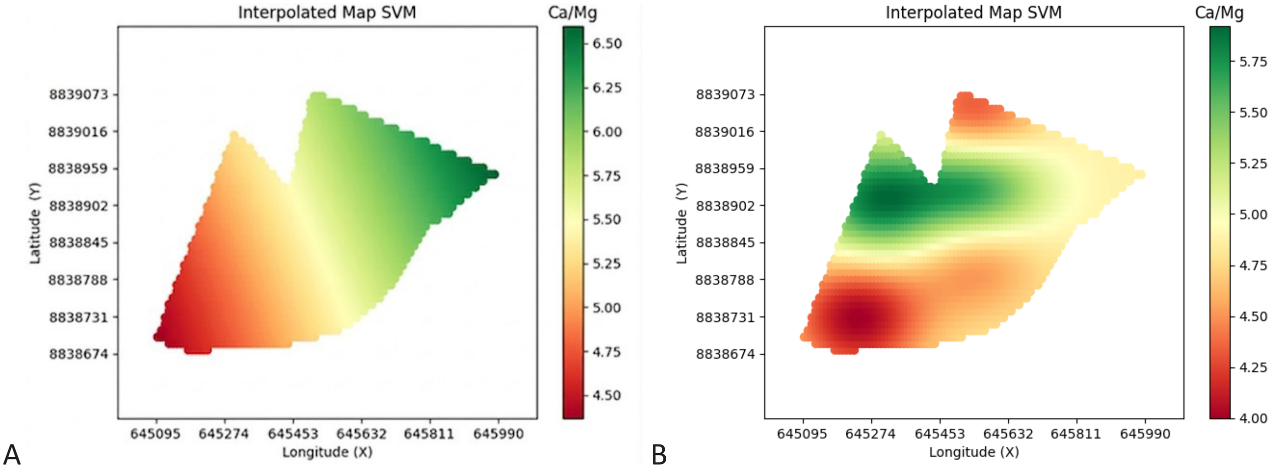
Figure 7. Magnesium Content Maps (Mg) in cmol/dm³ in the 0-20 cm (A) and 20-40 cm layers (B).



Source: Jorge, 2025.

The Ca/Mg ratio (Figure 8A and 8B) remains between 3:1 and 5:1, indicating favorable conditions for the accumulation of root and shoot dry mass of soybean and corn, increasing soybean production (Lange *et al.*, 2021).

Figure 8. Maps of the Ca/Mg ratio content in the 0-20 cm (A) and 20-40 cm (B) layers.

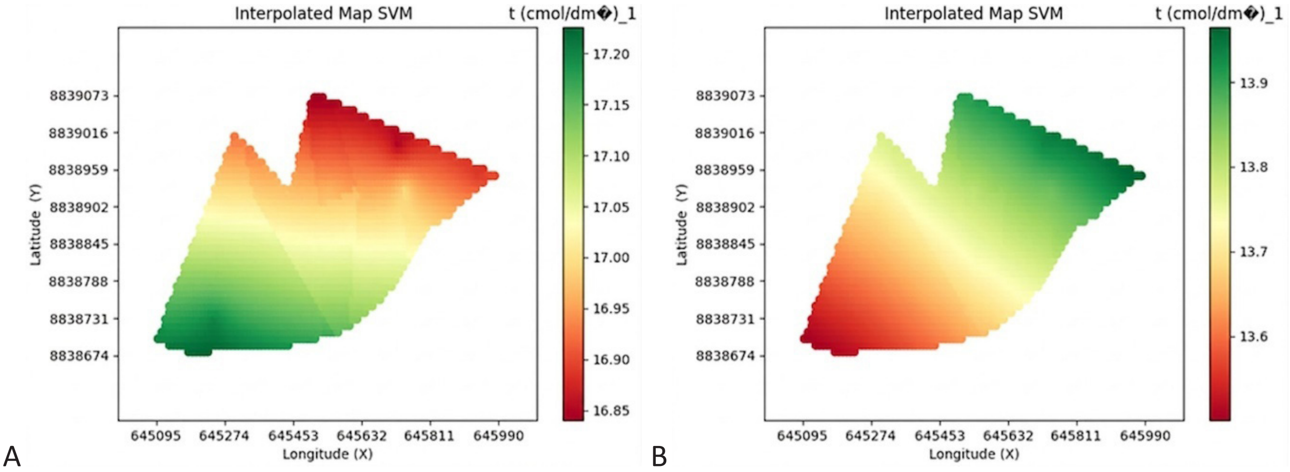


Source: Jorge, 2025.

CEC represents the cation exchange capacity, that is, it represents the soil's ability to retain cations, positively charged elements. The higher the soil's CEC, the greater the amount of cations the soil can retain. Two main types of CEC were analyzed, the effective CEC and the CEC at pH 7. The effective CEC is calculated from the sum of basic cations and aluminum, which keep the soil close to its natural pH value. The CEC at pH 7 is calculated from the basic cations and acidic cations, taking into account the amount of available hydrogen. It can be said that the difference between both maps is basically the amount of hydrogen, since the amount of aluminum in the area is 0 (Scalon, 2020).

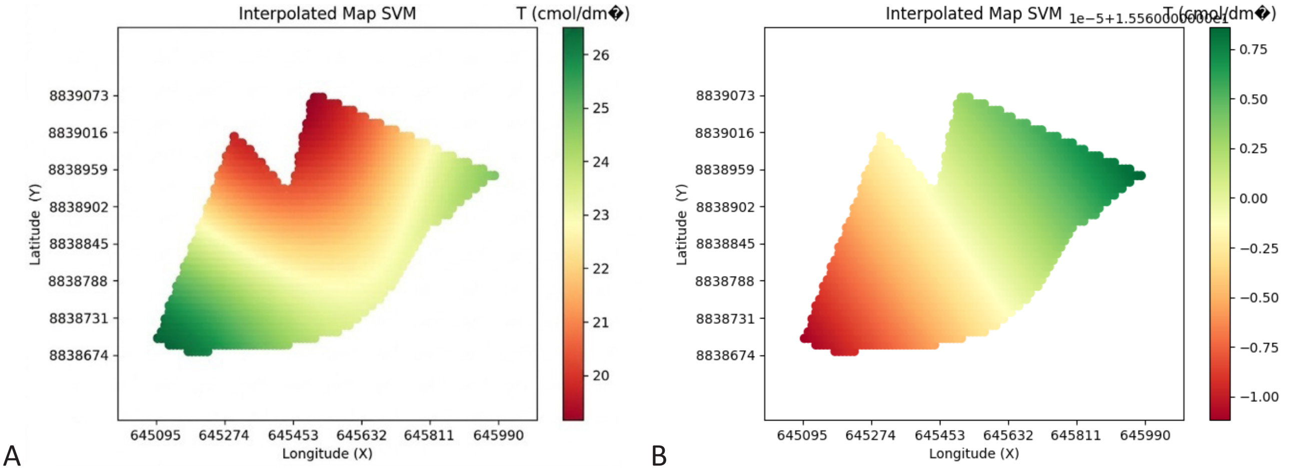
The map of effective CEC in the 0-20 cm layer (Figure 9A) shows values between 15.97 and 22.83 cmol/dm³ (Table 1). The map of CEC at pH 7.0 in the 0-20 cm layer (Figure 10A) is similar to the map of effective CEC; however, its values range from 17.23 to 26.52 cmol/dm³. The 20-40 cm layer (Figure 9B) shows effective CEC values between 12.95 and 16.28 cmol/dm³ (Table 2), whereas CEC at pH 7.0 (Figure 10B) shows slightly higher values, between 14.05 and 17.58 cmol/dm³ (Table 2). The low effective CEC in both layers indicates possible limitations to nutrient availability at depth (Souza, 2003).

Figure 9. Maps of the effective CEC content in cmol/dm³ in the 0-20 cm (A) and 20-40 cm layers (B).



Source: Jorge, 2025.

Figure 10. Maps of CEC content at pH 7.0 in cmol/dm³ in the 0-20 cm (A) and 20-40 cm layers (B).



Source: Jorge, 2025.

According to Ronquim (2020), a soil is considered good for plant nutrition when most of the soil's CEC is occupied by essential cations, such as Ca (calcium), Mg (magnesium), and K (potassium); however, if a soil is occupied by toxic cations, such as H (hydrogen) and Al (aluminum), the soil is considered nutrient-poor. Saturation by essential cations indicates good surface fertility, but low effective CEC at depth requires attention to fertilization in subsurface layers.

Among the analyzed depths (0-20 cm and 20-40 cm), a distinct behavior of the soil chemical attributes is observed, influenced both by agricultural management and by natural processes, such as leaching. In the surface layer, higher values of pH, calcium, phosphorus, and potassium are observed, while magnesium and organic matter tend to show higher concentrations in the 20-40 cm layer.

The results confirmed the hypothesis that the chemical attributes of the soil vary significantly between layers and sectors of the area, allowing the delimitation of distinct management zones. The interpolation performed with the SVM method made it possible to accurately represent the spatial patterns of nutrients, highlighting consistent differences between the depths of 0-20 cm and 20-40 cm. The development and interpretation of fertility maps met the study's objective and evidenced the influence of agricultural management, leaching, and cation exchange capacity on the distribution of chemical attributes.

The identified management zones provide important support for more efficient agronomic decisions, such as localized fertilization, targeted correction of acidity, and rational use of inputs, reinforcing the potential of digital soil mapping for precision agriculture. Despite limitations, such as the reduced sample density and the absence of formal model validation metrics, the SVM-based approach demonstrated feasibility and potential for application in the SEALBA region. Future studies may increase the number of samples, include new covariates, and compare different interpolation methods to improve the robustness of predictions.

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