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Critical levels and fertility classes of soils with high-activity clay in the Brazilian semi-arid region

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ABSTRACT: Soil fertility evaluation is important for adopting conservation management and adequate nutrient supply. The objective of this study was to identify critical levels and soil fertility classes using the boundary line method for rainfed crops (corn, cowpea and sabiá [*Mimosa caesalpiniifolia*]) in the Brazilian semi-arid region. A database of 226 soil fertility analyses of samples from the 0.00-0.20 m soil layer, and corn, cowpea and sabiá yields from Ceará State was used to generate interpretation classes (at 80 and 95 % of maximum yield). In a scatter plot, soil nutrient concentrations (x-axis) and relative crop yields (y-axis) were correlated, and the border points fitted to a quadratic model. Proposed interpretation classes were classified as very low, low, adequate, high and very high, except for Na^+, whose adequate class was considered tolerable. Generated models showed coefficients of determination (R^2) for the chemical properties ranging from 0.54 to 0.92. Based on the interpretation classes, the critical level was determined as 6.3 for pH, 10.8 g dm^{-3} for OM, 20.9 mg dm^{-3} for P, 81 mg dm^{-3} for K, 55 $mmol_c$ dm^{-3} for Ca^{2+}, 24 $mmol_c$ dm^{-3} for Mg^{2+} and 8 mg dm^{-3} for S-SO_4^{2-}. Interpretation classes for soils with high-activity clay in the Brazilian semi-arid region were superior to those in the reference literature. Boundary line method established fertility classes and critical levels for soil chemical properties in more than one crop, using the concept of relative yield.

Keywords: boundary line, rainfed agriculture, soil fertility.

INTRODUCTION

Soil management directly influences crop yields, and the use of fertilizers is essential to ensure compensatory yield levels. In regions with a semi-arid climate, where low and irregular rainfall modulate the agriculture type carried out, inputs such as soluble fertilizers become secondary in the face of climate uncertainties for rainfed agriculture. Thus, crop productivity is limited by inappropriate agronomic practices, even in years with occasional well-distributed rainfall (Mupangwa et al., 2012). Conversely, not replenishing nutrients exported by harvests causes soil degradation in agricultural areas (Tittonell et al., 2008).

Brazilian semi-arid soils have low natural fertility and high environmental variability. Little information is available on technologies adapted to regional ecosystems. Fires, soil erosion, surface runoff, harvests, and animal husbandry are the main processes of nutrient and water losses in this region (Menezes et al., 2012). Synthetic/mineral, organomineral, organic fertilizers, green manure, cover crops and byproducts are accessible strategies for replenishing soil nutrients, regardless of investment capacity (Mutuku et al., 2020). Family-oriented, less capitalized growers generally use organic fertilizers, waste material from breeding small ruminants, biofertilizers and green manure, which are effective ways to supply nutrients, especially in semi-arid regions (Souza et al., 2016; Mukai, 2019).

Different edaphoclimatic conditions of each location must be considered for adequate soil fertility management, especially in the state of Ceará, Northeastern Brazil. The semi-arid region of Ceará has agriculture predominantly based on extensive livestock (sheep, goats, and cattle) and grain production. This region has little or no use of fertilizers and is prone to desertification (Sousa et al., 2012; Souza et al., 2014; Martins et al., 2019). In addition, there is a predominance of *Luvisssolo* (Luvisol), *Planossolo* (Planosol) and *Cambissolo* (Cambisol), which are characterized by having high-activity clay, with high cation exchange capacity (CEC) and base saturation (BS), values greater than 50 % (Araújo Filho et al., 2022; Câmara et al., 2021). Another representative soil in cultivated areas in the semi-arid region is the *Neossolo Flúvico* (Fluvisol), which evolved from recent alluvial sediments, so that the horizons may not exhibit a pedogenetic relationship with other soil classes (Araújo Filho et al., 2022).

In a survey about soil fertility in the semi-arid region of Ceará, the greatest soil deficiencies were organic matter and phosphorus. On the other hand, pH, calcium, magnesium and BS showed high values, as well as low aluminum concentrations (Souza et al., 2015). In the countryside of the state of Ceará, there is a predominance of the orders *Luvissolo* and *Planossolo*. Under these soil orders, the main exploited agricultural products are grains such as corn and cowpea, as the state has the fourth largest area planted with corn and the largest planted area and overall production of cowpea recorded in the 2021/2022 harvest when compared with the other states in the Northeast region of Brazil (Conab, 2023).

As soil management is important to achieve high crop yields, monitoring soil fertility is essential for the proper use of fertilizers and amendments; however, there is little research on the interpretation of soil analysis results, mainly for grain agriculture practiced by smallholding farmers in semi-arid regions. The results are often interpreted using critical levels and fertility classes from the other areas (Souza et al., 2014). In some cases, farmers use the recommendation manual for soils from Minas Gerais State (Alvarez et al., 1999) or the recommendation manual for soils from Ceará (Aquino et al., 1993), even though this manual may consider edaphoclimatic characteristics contrasting with those from the semi-arid region.

Some tools are available to generate critical nutrient levels and fertility classes. Of the methods employed, the boundary line (BL) stands out, consisting of plotting yields in a scatter plot as a function of nutrient concentrations, removing outliers, and fitting polynomial models to the upper points on the boundary line to obtain a sufficiency range

(Webb, 1972; Walworth et al., 1986). Sufficiency ranges for assessing crop nutritional status were constructed using this method for melon (Maia and Morais, 2016), dragon fruit (Almeida et al., 2016), mango (Ali, 2018), cowpea (Melo et al., 2020), soybean (Souza et al., 2020), and olive (Ali, 2023). However, other studies have used this methodology to generate interpretation classes using soil chemical properties for soybean (Evanylo and Sumner, 1987), coffee (Sousa et al., 2018), and eucalyptus (Lima Neto et al., 2020).

Using relative yield to generate sufficiency ranges along the boundary line reduces the influence of possible particularities (cultivars, management, etc.), allowing the use of a greater amount of data. This strategy allows the input of crops into the model with different characteristics, as long as their yield data are transformed into relative yield, an innovative characteristic as traditional studies with the boundary line method consider only specific crops (Guedes Filho et al., 2019; Hernández-Vidal et al., 2021; Smith and Hardie, 2022).

With the results from field surveys, conducted in different locations and with standardized information, it is possible to structure a database to generate updated interpretation classes for soil fertility in the semi-arid region of Ceará, using the boundary line method in soils with high-activity clay. In the present study, we tested two hypotheses: (i) it is possible to apply the boundary line method to generate soil fertility classes for more than one crop, using the concept of relative yield; and (ii) soils with high-activity clay have different fertility classes than the suggested interpretations for orders and classes of low-activity clay soils in the semi-arid region of Ceará. This study aimed to identify fertility critical levels and classes using the boundary line method for rainfed crops, based on chemical soil properties with a predominance of high-activity clay, in the northeastern semi-arid region.

MATERIALS AND METHODS

Used data came from soil fertility analyses of fertilization trials on corn (*Zea mays*), cowpea (*Vigna unguiculata*), and sabiá (*Mimosa caesalpiniifolia*) grown in monoculture and intercropped (corn + forage). Trials were conducted under rainfed conditions in the municipalities of Sobral and Ibaretama, in Ceará (Northeast Brazil), from 2013 to 2019 (Figure 1).

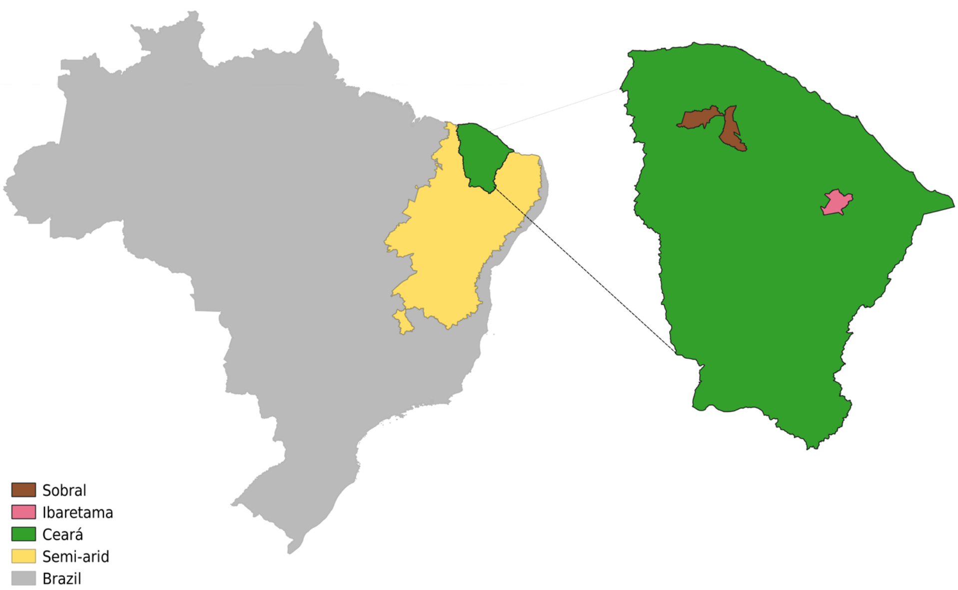

Figure 1. Geographic location of Sobral and Ibaretama municipalities, Ceará State, Brazil.

Trials in Sobral were carried out on the experimental fields of Embrapa Goats and Sheep, on *Luvissolo Háplico* and *Neossolo Flúvico* (Santos et al., 2018). These soil classes correspond to Luvisol and Fluvisol (WRB/FAO). Region climate is classified as hot semi-arid (BShw), according to Köppen classification system. Annual average temperature is 28 °C and the average annual precipitation is 759 mm yr^{-1}. Experiments in Ibaretama were carried out at Fazenda Triunfo in soil classified as *Planossolo Háplico* (Santos et al., 2018), corresponding to Planosol (WRB/FAO). Ibaretama also has a hot semi-arid climate (BShw), according to Köppen classification system, with annual average temperatures of 27 °C and average precipitation of 838 mm yr^{-1}. Our database comprised 226 samples from experimental plots (Table 1). Soil samples from all experiments were collected in the 0.00-0.20 m layer. Samples comprised soil from different cultivation practices, such as agroforestry systems, grass intercrops and monocultures. Sampling of the 0.00-0.20 m layer was established due to the standardization of soil depth in the selected studies and the recommendation for soil chemical analysis, as also established in the reference literature (Aquino et al., 1993; Alvarez et al., 1999). Grain yield was used for corn and cowpea, whereas for sabiá yields, we considered the dry mass of the whole plant after 22 months of planting. Soil sampling was always performed after measuring the yield (harvest).

Soil samples were analyzed for pH (1:2.5 soil:water); organic matter (OM), determined by organic carbon analysis by wet digestion with potassium dichromate and multiplication by the factor 1.724; potassium (K^+), phosphorus (P), sodium (Na^+), copper (Cu^{2+}), iron (Fe^{2+}), manganese (Mn^{2+}) and zinc (Zn^{2+}) extracted by Mehlich-1 (H_2SO_4 0.0125 mol L^{-1} and HCl 0.05 mol L^{-1}), with K^+ and Na^+ determined using a flame photometer, P by colorimetry, and cationic micronutrients using an atomic absorption spectrophotometer; calcium (Ca^{2+}) and magnesium (Mg^{2+}) were extracted with 1 mol L^{-1} KCl and determined using atomic absorption spectrophotometry; potential acidity (H+Al) was extracted with 0.5 mol L^{-1} calcium acetate and quantified by titration; sulfur (S) was extracted using barium chloride, with subsequent reading in a spectrophotometer; boron (B) was determined by hot water (Teixeira et al., 2017). At last, sum of bases ($SB = K^+ + Ca^{2+} + Mg^{2+} + Na^+$), cation exchange capacity (CEC = SB + H+Al) and base saturation (BS = SB/CEC × 100) were calculated.

Boundary line calculations were performed according to Quesnel et al. (2006), Blanco-Macías et al. (2009), Lafond (2009, 2013) and Bhat and Sujatha (2013). Relative yield approach was used to compare the yield of different experiments and crops, in which the yield of the selected sample is divided by the maximum yield (Equation 1):

$$RY(\%) = \frac{Y\,sample}{Y\,high\,yield} \times 100 \qquad \text{Eq. 1}$$

in which: RY is the relative yield; Y sample is the highest yield in the range of a given class; and Y high yield is the maximum yield of a population (Ali, 2018, 2023; Sousa et al., 2018; Lima Neto et al., 2020). For the Ibaretama experiment, identified with the number 7 (Table 1), the sum of corn and cowpea grain yields was considered. Before starting the calculations, possible outliers were checked and removed via box-plot, always considering the normal distribution (Shapiro-Wilk) for crop yield.

First step consisted of plotting the soil nutrient concentration data (x-axis) against relative yield (y-axis). Second step was selecting the points located at the upper limit of the scatter plot. Maximum and minimum concentration value verification was determined using the difference between them, then divided by "n" classes, thereby selecting the highest point (concentration) within each interval (Blanco-Macías et al., 2009).

The study was carried out with 226 samples; therefore, a maximum value of 15 classes was used because less than 25 % of the observations were used to develop the model to limit the selection of points on the upper limit of the scatter data, and to maximize

Table 1. Soil fertility and yield database for the municipalities of Sobral and Ibaretama, Ceará, Brazil

Local	Crop	Year	Experiment	Soil characterization	Number of samples (soil and yield)	Reference
Sobral (1)	Corn (Gorutuba variety)	2013 and 2014	Evaluation of base organic compost rates and residues from the production and slaughter of small ruminants in the corn crop	Haplic Luvisol (0.00-0.20 m: 80 g kg^{-1} clay, 19.5 $cmol_c$ kg^{-1} of CEC (Ta = 243 $cmol_c$ kg^{-1}) /0.20-0.40 m: 180 g kg^{-1} clay, 20.0 $cmol_c$ kg^{-1} of CEC (Ta = 111 $cmol_c$ kg^{-1}))	48	Souza et al. (2016)
Sobral (2)	Corn (Robusto variety)	2013 and 2014	Evaluation of sources (organic compost and mineral fertilizer) and nitrogen rates in the corn crop	Haplic Luvisol (0.00-0.20 m: 80 g kg^{-1} clay, 19,5 $cmol_c$ kg^{-1} of CEC (Ta = 243 $cmol_c$ kg^{-1}) / 0.20-0.40 m: 180 g kg^{-1} clay, 20,0 $cmol_c$ kg^{-1} de CEC (Ta = 111 $cmol_c$ kg^{-1}))	54	Araújo et al. (2023)
Sobral (3)	Corn (BRS2020 hybrid)	2017	Evaluation of corn intercropped with buffel and massai forages with different planting times	Haplic Luvisol (0.00-0.20 m: 80 g kg^{-1} clay, 19.5 $cmol_c$ kg^{-1} of CEC (Ta = 243 $cmol_c$ kg^{-1}) / 0.20-0.40 m: 180 g kg^{-1} clay, 20.0 $cmol_c$ kg^{-1} of CEC (Ta = 111 $cmol_c$ kg^{-1}))	27	Ponte Filho et al. (2023)
Sobral (4)	Corn (Gorutuba variety)	2015	Evaluation of corn intercropped with buffel or massai forages and nitrogen rates	Fluvic Neosol (0.00-0.20 m: 250 g kg^{-1} clay and 13.5 $cmol_c$ kg^{-1} of CEC (Ta = 54 $cmol_c$ kg^{-1}) / 0.20-0.40 m: 230 g kg^{-1} clay and 13.5 $cmol_c$ kg^{-1} of CEC (Ta = 59 $cmol_c$ kg^{-1}))	21	Unpublished data
Ibaretama (5)	Sabiá	2016	Evaluation of sheep manure rates in sabiá plants	Haplic Planosol (0.00-0.20 m: 50 g kg^{-1} clay and 10.0 $cmol_c$ kg^{-1} of CEC (Ta = 200 $cmol_c$ kg^{-1}) / 0.20-0.40 m: 100 g kg^{-1} clay and 14.0 $cmol_c$ kg^{-1} de CEC (Ta = 140 $cmol_c$ kg^{-1}))	20	Souza et al. (2021)
Ibaretama (6)	Sabiá	2016	Evaluation of phosphorus rates in sabiá plants	Haplic Planosol (0.00-0.20 m: 50 g kg^{-1} clay and 10.0 $cmol_c$ kg^{-1} of CEC (Ta = 200 $cmol_c$ kg^{-1}) / 0.20-0.40 m: 100 g kg^{-1} clay and 14.0 $cmol_c$ kg^{-1} de CEC (Ta = 140 $cmol_c$ kg^{-1}))	20	Souza et al. (2022)
Ibaretama (7)	Corn (AL Piratininga variety) / Cowpea (Xiquexique variety)	2015, 2017 and 2019	Evaluation of organic fertilizers applied in crop-forest interaction (sabiá) with corn and cowpea grown in the same plot	Haplic Planosol 0.00-0.20 m: 50 g kg^{-1} clay and 10.0 $cmol_c$ kg^{-1} of CEC (Ta = 200 $cmol_c$ kg^{-1}) / 0.20-0.40 m: 100 g kg^{-1} clay and 14.0 $cmol_c$ kg^{-1} of CEC (Ta = 140 $cmol_c$ kg^{-1}))	36	Pompeu et al. (2023)

CEC: cation exchange capacity; Ta: clay fraction activity (Ta = CEC × 1000/clay content).

the probability of developing statistically significant models, increasing the number of observations (Vizcayno-Soto and Côté, 2004). The number of classes considered the square root of the number of samples, after verifying outliers; some authors suggest the number of classes be greater than 10 or even 20 (Vizcayno-Soto and Côté, 2004; Blanco-Macías et al., 2009; Bhat and Sujatha, 2013).

This method indicated samples with discrepant differences in yield. Therefore, the samples with the lowest yield were not in adequate nutritional conditions (Vizcayno-Soto and Côté, 2004; Quesnel et al., 2006; Bhat and Sujatha, 2013). Thus, the classes were excluded, considering the construction of a new concave quadratic model, that is, with an ascending curve until the maximum point. Exclusions from classes occurred as adapted by Quesnel et al. (2006) and Vizcayno-Soto and Côté (2004), according to equations 2, 3, 4, 5 and 6:

$$RY > RY_{-1} \text{ and } RY_{+1} \quad \text{Eq. 2}$$

$$RY < RY_{-1} \text{ and } RY_{+1} \quad \text{Eq. 3}$$

$$RY < (RY_{-1} \text{ and } RY_{+1})/2 \quad \text{Eq. 4}$$

$$\frac{RY}{\left[\frac{RY_{-1}+RY_{+1}}{2}\right]} < 90\ \% \quad \text{Eq. 5}$$

$$RY > RY_{-1} \text{ and } RY_{+1} \quad \text{Eq. 6}$$

in which: RY, RY_{-1} and RY_{+1} were the relative yields and adjacent points, lower and higher, respectively.

Class samples were excluded when the criteria were met (Vizcayno-Soto and Côté, 2004; Quesnel et al., 2006). Generation of the sample selected from the initial class cannot be higher than the second class; when this occurred, the first class was discarded and taken up by the second class. Analogical reasoning was carried out for the last selected class, discarding it when the relative performance was higher than the previous class. Also, as the relative yield of different crops and trials was considered if the first class showed the relative yield of 100 % as the highest value, the value was excluded, and the second highest yield was used as the relative yield of the first class, if the second class also had a relative yield of 100 %.

After the exclusion process, a second-degree polynomial function is generated. Optimal concentration or critical level (NC) was determined by solving the first derivative of the quadratic regression equation (Equation 7):

$$NC = \frac{-b}{2a} \quad \text{Eq. 7}$$

in which: a and b are coefficients of the quadratic equation.

Thus, two fertility classes were generated, whose values correspond to 80 and 95 % of the maximum relative yield: Y = 0.80 or 0.95 × RY, with subsequent substitution in equation 8 (Quesnel et al., 2006; Blanco-Macías et al., 2009).

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad \text{Eq. 8}$$

in which: a, b and c are coefficients of the quadratic equation, and x is the corresponding value of the nutrient concentration in soil for the generation of fertility classes. Interpretation classes were established: very low (RY <80 % to the left of the maximum), low (80≤ RY <95 % to the left of the maximum), adequate (95≤ RY ≤95 % to the left and right of the maximum, respectively), high (95< RY ≤80 % to the right of the maximum) and very high (RY <80 % to the right of the maximum). Specifically, for Na^+, the term tolerable was used instead of adequate.

With the critical levels and fertility classes in hand, analogous reasoning was used; that is, samples of each attribute were classified as excessive, sufficient or deficient based on the recommendation manual of correctives and fertilizers for the state of Ceará (Aquino et al., 1993); however, for the classes of micronutrients (B, Cu, Fe, Mn, and Zn), we used the recommendation manual for the state of Minas Gerais instead (Alvarez et al., 1999). Reference literature (Aquino et al., 1993) shows no fertility classes for micronutrients. Therefore, for comparative purposes, we used the fertility manual of Minas Gerais (Alvarez et al., 1999), which is traditionally used in the Northeast region of Brazil, because this manual uses the same extractors for micronutrients (Cu, Fe, Mn, and Zn – Mehlich-1 and B – hot water).

RESULTS

The yields obtained in the trials were considered satisfactory because they were higher than the averages for the state of Ceará in the 2021/2022 season, which were 929 kg ha^{-1} of corn grains and 289 kg ha^{-1} of cowpea grains. The difference verified between state data and those obtained from the experiments may be explained by using fertilizers (organic and mineral) in the experiments, justifying the importance of using these inputs (Table 2). The variability verified in yield between different years, but with the application of the same treatments is explained by the variation in precipitation in each agricultural year, which significantly affects crop production.

Considering the experimental sites, average values obtained for soil chemical properties justify the soil characterization as eutrophic because the average base saturation (BS) equals 78 % and a minimum greater than 61 % (Table 3).

Classes interval number used for the analyzed chemical properties, after exclusions (Equations 2 to 6), was 9 for pH (Figure 2a), 8 for OM (Figure 2b), 9 for P (Figure 2c), 10 for K (Figure 2d), 9 for Ca^{2+} (Figure 2e) and 10 for Mg^{2+} (Figure 2f), considering a total of 14, 14, 15, 15, 15 and 15 initial classes, respectively. For H+Al, SB, CEC, BS, $S\text{-}SO_4^{2-}$ and Na, the number of classes was 8 (Figure 3a), 10 (Figure 3b), 8 (Figure 3c), 9 (Figure 3d), 8 (Figure 3e) and 7 (Figure 3f) for 15, 15, 15, 14, 14 and 13 initial classes, respectively. As for micronutrients B, Cu, Fe, Mn and Zn, the number of classes was 11 (Figure 4a), 9 (Figure 4b), 8 (Figure 4c), 10 (Figure 4d) and 9 (Figure 4e), for 15 initial classes, respectively. Coefficient of determination (R^2) values ranged from 0.54 to 0.92.

The use of the 80 and 95 % ranges, based on the maximum yield, allowed the generation of five interpretation classes: very low, low, adequate, high and very high for soil chemical properties. This method improves the data interpretation over the reference literature (Aquino et al., 1993), which shows only three interpretation classes for some properties (OM, Ca^{2+}, Mg^{2+}, and Al^{3+}) and four classes for others (P and K) (Table 4).

Table 2. Descriptive statistics (mean, maximum, minimum, standard deviation and coefficient of variation) and number of samples (n) referring to the yield of rainfed crops, in experiments carried out in soils with high-activity clay. Sobral and Ibaretama, Ceará, Brazil

Site/ Experiment	Year	Crop	Average	Maximum	Minimum	δ	CV	n
							%	
Sobral 1	2013	Corn (kg ha^{-1})	1897	3015	628	676	35.6	24
Sobral 1	2014	Corn (kg ha^{-1})	5329	7550	3331	1456	27.3	24
Sobral 2	2013	Corn (kg ha^{-1})	1654	5520	533	1209	73.1	27
Sobral 2	2014	Corn (kg ha^{-1})	5588	11369	147	3009	53.9	27
Sobral 3	2017	Corn (kg ha^{-1})	3096	5532	482	1226	39.6	27
Sobral 4	2015	Corn (kg ha^{-1})	1383	1894	748	385	27.9	21
Ibaretama 5	2016	Sabiá (g $plant^{-1}$)	392	649	160	97	24.8	20
Ibaretama 6	2016	Sabiá (g $plant^{-1}$)	480	673	311	98	20.3	20
Ibaretama 7	2015	Corn (kg ha^{-1})	2834	3364	1748	851	30.0	12
		Cowpea (kg ha^{-1})	1478	2901	791	615	41.6	12
Ibaretama 7	2017	Corn (kg ha^{-1})	1354	2255	397	614	45.4	12
		Cowpea (kg ha^{-1})	536	842	88	227	42.3	12
Ibaretama 7	2019	Corn (kg ha^{-1})	1640	3126	703	769	46.9	12
		Cowpea (kg ha^{-1})	421	687	199	170	40.3	12

δ: standard deviation; CV: coefficient of variation; n: number of samples. Ibaretama (7): corn and cowpea yields were added together. n: number of samples used in the boundary line method of each agronomic test.

Table 3. Descriptive statistics and number of samples (n) of chemical properties for rainfed agriculture, in experiments carried out in soils with high-activity clay in Sobral and Ibaretama, Ceará, Brazil

Attribute	Average	Maximum	Minimum	δ	CV	N
					%	
pH(H_2O) (1:2.5)	6.50	7.30	5.70	0.33	5.1	208
OM (g kg^{-1})	8.9	18.5	2.0	3.9	43.8	220
P (mg dm^{-3})	16.1	42.0	3.0	9.8	60.9	199
K (mg dm^{-3})	78	147	23	27	34.6	218
Ca^{2+} ($mmol_c$ dm^{-3})	39	84	8	19	48.7	226
Mg^{2+} ($mmol_c$ dm^{-3})	19	42	3	9	47.4	214
H+Al ($mmol_c$ dm^{-3})	19	31	11	4	21.1	216
SB ($mmol_c$ dm^{-3})	61	127	14	26	42.6	222
CEC ($mmol_c$ dm^{-3})	79	153	25	29	36.7	224
BS (%)	78	95	62	6	7.7	201
S-SO_4^{2-} (mg dm^{-3})	6	14	1	3	50.0	204
Na (mg dm^{-3})	11	24	3	5	45.5	170
B (mg dm^{-3})	0.26	0.51	0.10	0.09	34.6	221
Cu (mg dm^{-3})	0.6	1.3	0.1	0.3	55.4	226
Fe (mg dm^{-3})	30	66	5	16	53.3	223
Mn (mg dm^{-3})	22	56	3	14	60.9	224
Zn (mg dm^{-3})	0.9	2.0	0.1	0.5	55.6	210

n: number of samples used in the boundary line method after excluding outliers.

With regard to the interpretation classes generated, the frequency of distribution of samples among the classes lower than the properties pH, OM, K, Ca^{2+}, H+Al, SB, CEC, BS, S-SO_4^{2-}, Cu, Fe, and Zn is mainly included in the adequate range (and for Na^+ as tolerable). Only P and Mg^{2+} were classified as low, according to the interpretation classes proposed in the present study (Table 4). However, in the reference literature, only K, Fe and Zn were frequently classified as suitable. Previously considered low in the generated interpretation class, Mg was considered high in the reference literature (Table 5). For the critical level generated, the properties with the highest frequency below the optimal values (critical level), in descending order, were: Ca^{2+} (81 %) = S-SO_4^{2-} (81 %) >Mn (78 %) >SB (75 %) >H+Al (73 %) >Mg^{2+} (72 %) >Fe (66 %) = OM (66 %) = P (66 %) > Zn (62 %) > Cu (60 %)> K (57 %) > CEC (54 %) = B (54 %) > BS (37 %) > pH (34 %) (Table 5).

DISCUSSION

Low grain productivity in the Sertão (hinterland) of Ceará is generally due to rainfall irregularity of the semi-arid climate of the mesoregion (Vasconcelos et al., 2019; Rocha et al., 2020). However, aspects related to soil fertility still lack investigations that allow farmers to sustain agricultural production of subsistence crops, despite soil vulnerability. Soils of the Sertão are characterized as having low to high natural fertility in a semi-arid tropical environment (Souza and Oliveira, 2003; Brandão and Freitas, 2014). Despite this, the soils have agricultural potential for livestock and grain cultivation, though still little exploited in a context of sustainable agriculture.

In comparing the adequate ranges of this study with those in the reference literature (Aquino et al., 1993), OM concentration decreased in amplitude and limits of the classes; for P and Mg^{2+}, there was an opposite response, with an increase in the amplitude and limits of the concentrations; for K and Ca^{2+}, the amplitude remained close to the reference,

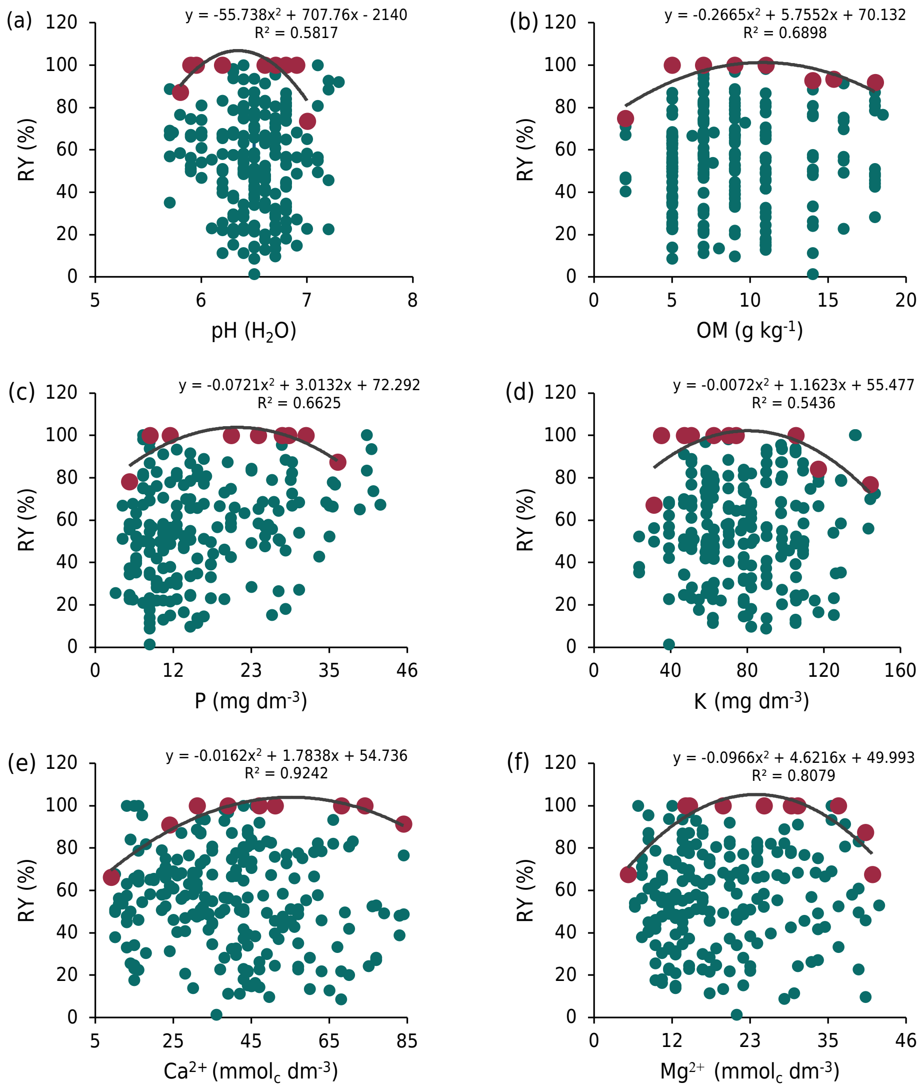

Figure 2. Relationship between pH (a), organic matter (b), phosphorus (c), potassium (d), calcium (e), and magnesium (f) concentrations and relative yield, plotted by the boundary line method for rainfed agriculture in soils with high-activity clay in Sobral and Ibaretama, Ceará, Brazil.

but the limits were higher (Table 4). These differences can be explained by the fact the reference literature proposes fertility classes for the entire state of Ceará, not considering the different production systems, environments, and soils.

Soils from *Luvissolo* and *Planossolo* classes, which form the basis of the database used in this study, are characterized by the Bt horizon, containing clay with high activity and high BS and are representative of the Brazilian semi-arid region (Barbosa et al., 2015; Câmara et al., 2021; Santos et al., 2022). This characteristic helps to justify the differences between the proposed interpretation classes and the reference literature (Aquino et al., 1993).

In the equations obtained by the boundary line method, the models revealed coefficients of determination (R^2) for routinely tested properties in soil chemical analysis ranging from 0.54 (K) to 0.92 (Ca^{2+}). As for Na^+, S and the micronutrients, the R^2 values ranged from 0.65 (Zn) to 0.91 (B). In a study evaluating soil fertility in coffee areas (Mata Mineira zone, Brazil) using the boundary line, R^2 values ranged from 0.69 to 0.98 (Sousa et al., 2018); for eucalyptus, R^2 values ranged from 0.89 to 0.98 for OM and macronutrients (Lima Neto et al., 2020). One of the limitations of the method used in this research is based

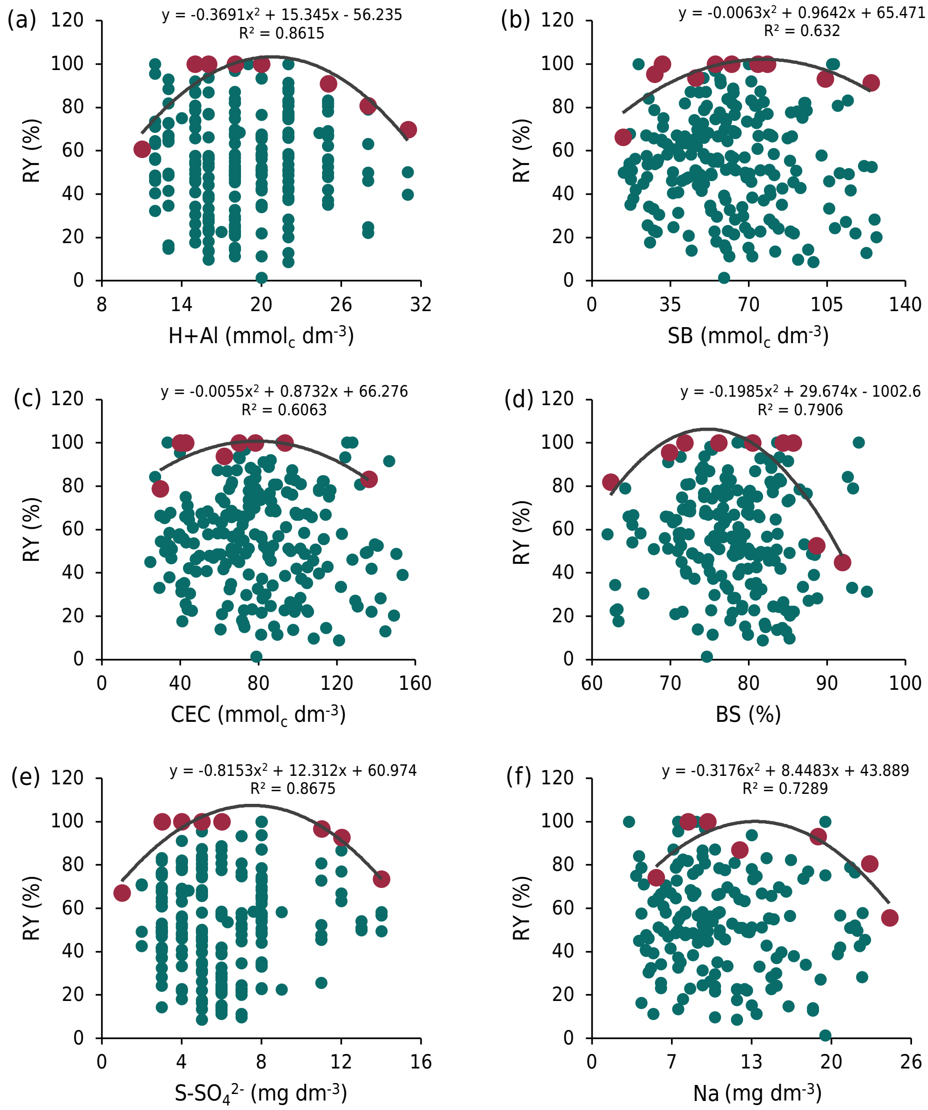

Figure 3. Relationship between soil properties H+Al (a), sum of bases (b), cation exchange capacity (c), base saturation (d), sulfur (e) and sodium (f) and relative yield, plotted by the boundary line method for rainfed agriculture in soils with high-activity clay in Sobral and Ibaretama, Ceará, Brazil.

on the possibility of reducing the robustness of the method when using a database with a limited sample number. However, there was an adequate fit between crop yield and soil chemical properties, except for some properties that had poorer adjustment due to data variability, since the studies took place under uncontrolled conditions (Iheshiulo et al., 2018). Besides, this is essential to obtain reliable standards (Lima Neto et al., 2024).

When analyzing the studies using the boundary line for soil physical properties (density, penetration resistance, water content, aggregate stability, etc.) for soybean and corn cultivation, R^2 values were between 0.59 and 0.91 (Guedes Filho et al., 2019), indicating the model is influenced by the selection of points that form the quadratic equation. However, in the present study, the selection of points allowed the generation of quadratic curves, considering the exclusion of high amplitudes between classes (Vizcayno-Soto and Côté, 2004; Quesnel et al., 2006; Bhat and Sujatha, 2013).

According to the fertility classes (Table 4), specifically for Na, very low, low and tolerable concentrations should be considered as adequate in the verification of this nutrient, given its negative impacts when at high concentrations in soil, such as sodicity, that hampers plant development (Aquino et al., 1993). Based on the results, the value of 13 mg dm^{-3} was established as the critical level for Na in soils from the semi-arid region of Ceará.

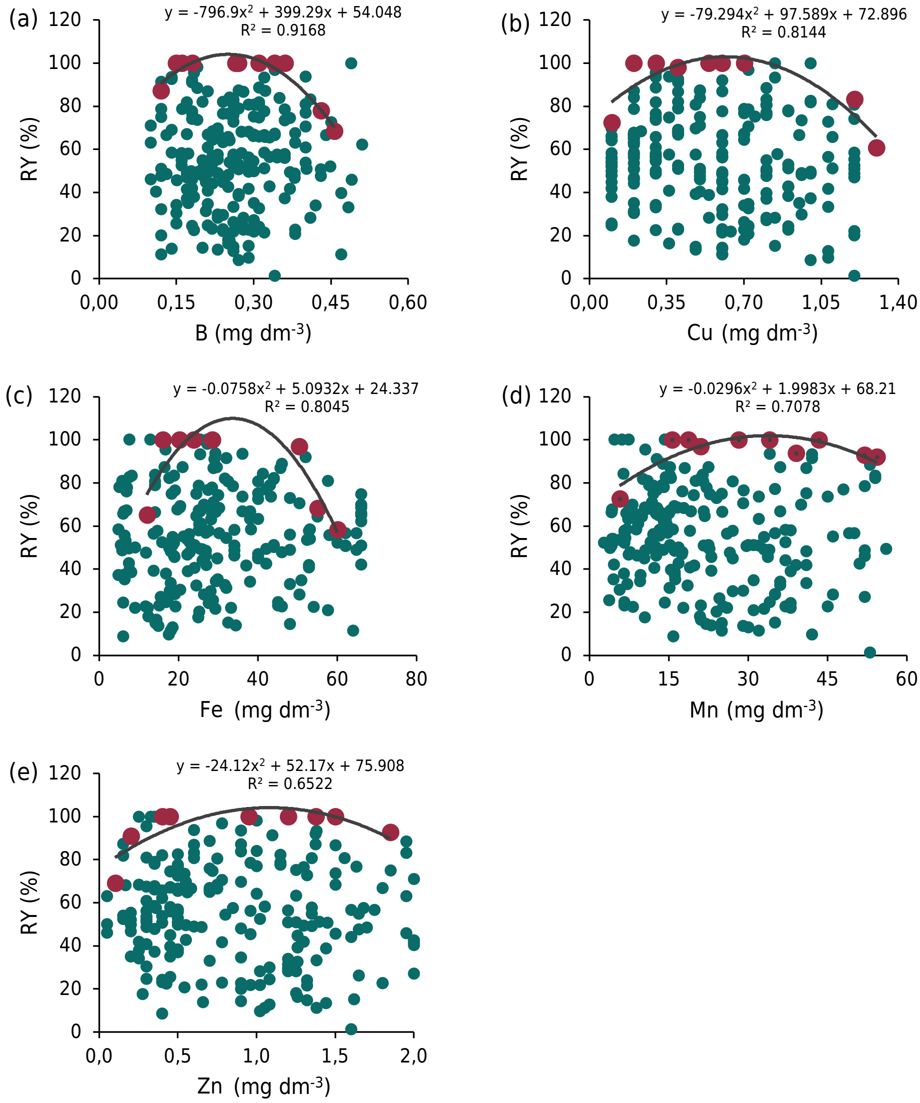

Figure 4. Relationship between boron (a), copper (b), iron (c), manganese (d) and zinc (e) concentrations and relative yield, plotted by the boundary line method for rainfed agriculture in soils with high-activity clay in Sobral and Ibaretama, Ceará, Brazil.

The critical level values for pH and base saturation determined by the reduced normal distribution method for the cultivation of corn and cowpea in the Inhamuns region of Ceará (Souza et al., 2014) presented critical level values similar to the present study. In this case, the critical level for pH proposed in the present study for corn and cowpea were 6.6 and 6.5, respectively. While it was established as 73 and 71 %, respectively, the critical level for corn and cowpea. However, for OM, P, Ca^{2+}, and Mg^{2+}, the levels proposed in this study were higher; for K, they were lower than those suggested by these authors, both for corn and cowpea. This result can be explained by the difference in the management system, fertilization and cultivars, as in the present study, the time interval was quite long. In contrast, that of Souza et al. (2014) considered data from only one season.

Proposed classes for organic matter were lower than those in the reference literature (Aquino et al., 1993), in which the appropriate OM class varied between 16 and 30 g dm^{-3}. However, the data suggest a reduction in the lower and upper limits of OM, with a variation between 6.4 and 15.2 g dm^{-3} in the appropriate class. This can be partly explained by the inclusion of *Planossolo* in the database, which, compared to other soils in the Brazilian semi-arid region, have low C and N concentrations due to the

Table 4. Interpretation classes, critical level and reference literature for chemical properties for rainfed agriculture in soils with high-activity clay in Sobral and Ibaretama, Ceará, Brazil

Property	Interpretation Classes					Critical level
	Very low	Low	Adequate	High	Very high	
Present study						
pH $_{(H2O)}$	<5.7	5.7-5.9	6.0-6.7	6.8-7.0	>7.0	6.3
OM (g dm^{-3})	<2.1	2.1-6.3	6.4-15.2	15.3-19.5	>19.5	10.8
P (mg dm^{-3})	<3.9	3.9-12.3	12.4-29.4	29.5-37.9	>37.9	20.9
K (mg dm^{-3})	<27	27-53	54-107	108-134	>134	81
Ca^{2+} (mmol$_c$ dm^{-3})	<19	19-36	37-73	73-91	>91	55
Mg^{2+} (mmol$_c$ dm^{-3})	<9	09-16	17-31	32-39	>39	24
H+Al (mmol$_c$ dm^{-3})	<13	13-16	17-25	26-28	>28	21
SB (mmol$_c$ dm^{-3})	<20	20-47	48-105	106-134	>134	77
CEC (mmol$_c$ dm^{-3})	<19	19-48	49-110	111-140	>140	79
BS (%)	<64	64-69	70-80	81-85	>85	75
S-SO_4^{2-} (mg dm^{-3})	<2	2-4	5-10	11-13	>13	8
B (mg dm^{-3})	<0.09	0.09-0.17	0.18-0.34	0.35-0.43	>0.43	0.26
Cu (mg dm^{-3})	<0.1	0.1-0.3	0.4-0.9	1.0 -1.10	>1.10	0.6
Fe (mg dm^{-3})	<17	17-24	25-42	43-51	>51	34
Mn (mg dm^{-3})	<8	8-20	21-47	48-60	>60	34
Zn (mg dm^{-3})	<0.2	0.2-0.5	0.6-1.5	1.6-2.0	>2.0	1.1
	Very low	Low	Tolerable	High	Very high	Critical level
Na (mg dm^{-3})	<5	5-8	9-17	18-21	>21	13
Literature[1,2]						
	Acidity			Neutrality	Alkalinity	Critical level
	High	Average	Low		Low	
pH[1]	<5.1	5.1-5.9	6.0-6.9	7.0	7.1-7.4	-
	Very low	Low	Adequate	High	Very High	Critical level
OM[1] (g dm^{-3})	-	0-15	16-30	>30	-	-
P[1] (mg dm^{-3})	-	0-10	11-20	21-40	>40	-
K[1] (mg dm^{-3})	-	0-45	46-90	91-180	>180	-
Ca^{2+}[1] (mmol$_c$ dm^{-3})	-	0-15	16-40	>40	-	-
Mg^{2+}[1] (mmol$_c$ dm^{-3})	-	0-5	6-10	>10	-	-
Al^{3+}[1] (mmol$_c$ dm^{-3})	-	0-5	6-10	>10	-	-
B[2] (mg dm^{-3})	<0.16	0.16-0.35	0.36-0.60	0.61-0.90	>0.90	0.60
Cu[2] (mg dm^{-3})	<0.4	0.4-0.7	0.8-1.2	1.3-1.8	>1.8	1.2
Fe[2] (mg dm^{-3})	<9	9-18	19-30	31-45	>45	30
Mn[2] (mg dm^{-3})	<3	3-5	6-8	9-12	>12	8
Zn[2] (mg dm^{-3})	<0.5	0.5-0.9	1.0-1.5	1.6-2.2	>2.20	1.5

[1] Adapted from Aquino et al. (1993). [2] Adapted from Alvarez et al. (1999).

high sand content in the surface layer (Santana et al., 2019). In relation to *Luvissolo*, OM concentrations vary depending on soil management and use; in degraded areas, OM concentrations are around 8.3 g kg^{-1}. However, preserved areas can exhibit values of 47.0 g kg^{-1} in topsoil (Santos et al., 2022), demonstrating soil use and management influence organic matter contents in this region (Gava et al., 2022).

Mehlich-1 was used to determine P in the soil. Although this method presents some known limitations in neutral or slightly alkaline soils, such as those from the semi-arid region (Medeiros et al., 2021), it is still the most widely used method in laboratories in

Table 5. Frequency (%) of samples according to the different interpretation classes of the present study and reference literature, and frequency (%) of samples with values below the critical level for chemical properties for rainfed agriculture soils with high-activity clay in Sobral and Ibaretama, Ceará, Brazil

Property	**Interpretation Classes**					**Critical Level**
	Very low	**Low**	**Adequate**	**High**	**Very high**	
	%					
Present study						
pH	8	8	64	16	4	34
OM	3	23	62	10	3	66
P	0	43	37	5	15	66
K	1	17	64	11	7	57
Ca^{2+}	18	28	49	5	0	81
Mg^{2+}	9	40	33	10	8	72
H+Al	11	31	54	3	1	73
SB	5	26	60	8	1	75
CEC	0	18	67	11	4	54
BS	13	4	50	20	13	37
$S\text{-}SO_4^{2-}$	0	28	52	7	12	81
B	0	17	63	13	7	54
Cu^{2+}	0	33	53	8	6	60
Fe^{2+}	23	16	37	9	15	66
Mn^{2+}	14	39	39	8	0	78
Zn^{2+}	4	31	46	12	7	62
	Very low	Low	Tolerable	High	Very high	Critical level
Na	7	20	37	5	32	53
			Literature[1,2]			
		Acidity		Neutrality	Alkalinity	Critical level
	High	Average	Low		Low	
pH[1]	1	15	77	3	4	
	Very low	Low	Tolerable	High	Very high	Critical level
OM[1]	-	88	12	0	-	-
P[1]	-	35	31	21	13	-
K[1]	-	7	62	31	0	-
Ca^{2+} [1]	-	13	41	46	-	-
Mg^{2+} [1]	-	1	17	81	-	-
Al^{3+} [1]	-	4	0	96	-	-
B[2]	12	69	19	0	0	81
Cu[2]	33	36	31	0	0	67
Fe[2]	11	16	32	20	21	26
Mn[2]	0	5	8	11	77	5
Zn[2]	25	26	29	13	7	52

Critical level: the percentage considers the number of samples below and equal to the critical level value presented in table 4. [1] Aquino et al. (1993). [2] Alvarez et al. (1999).

the Brazilian Northeast and referenced in literature (Aquino et al., 1993). Despite that, the interpretation classes for P (Table 4) presented higher concentrations in relation to the sufficiency ranges of the reference literature, which can be partly justified by the fact the database of the present study comes from phosphate and organic material fertilization experiments. Another reason for this difference is the *Luvissolo* of the Brazilian semi-arid being formed from mafic rocks, which are more fertile than felsic rock soils and, therefore, exhibit higher values of P and other elements, in addition to high base saturation (Câmara et al., 2021; Santos et al., 2022).

Some reviews on soil fertility in the Brazilian semi-arid region mention the region has low P concentrations (Menezes et al., 2012; Souza et al., 2015). However, the diversity of soil orders in this region suggests the existence of different P forms. In a broad evaluation of ten different soil orders in the 0.00-0.20 m layer, *Luvissolo*, *Vertissolo*, *Luvissolo* and *Cambissolo* show the highest P concentrations. In turn, *Argissolo*, *Neossolo Litólico* and *Latossolo* showed intermediate P concentrations, whereas *Neossolo Regolítico*, *Planossolo*, and *Neossolo Quartzarênico* had the lowest P concentrations (Silveira et al., 2006).

The proposed classes for K concentrations had lower and upper limits above those found in the reference literature (Aquino et al., 1993) (Table 4). Our data suggest a concentration of K in the appropriate class between 54 and 107 mg dm^{-3} in soil with high-activity clay in the semi-arid region. In contrast, in the reference literature, the concentration in the appropriate class was established ranging from 46 to 90 mg dm^{-3}. However, when compared with other soil fertility manuals, in which there is a predominance of soils with 1:1 clay (Alvarez et al., 1999; Sousa and Lobato, 2004), the classes proposed in this study are higher. In soils with 2:1 clay, such as *Luvissolo* and *Planosolo*, there is significant participation of non-exchangeable K as a nutrient source, in addition to a higher exchangeable K concentration (Paiva et al., 2020; Câmara et al., 2021).

Appropriate classes of P and K in the soil with banana cultivation in a semi-arid region of Ceará were superior to the manual recommending correctives and fertilizers (Lima Neto et al., 2024). In accordance with the results found in this study, this suggests the occurrence of errors in the application of fertilizers, below the crop demands, which may lead to future declines in soil fertility and crop yields throughout cycles of nutrient extraction in the soil. As for Ca^{2+}, the classes proposed in the present study, especially for the adequate range, have an upper limit (73 $mmol_c$ dm^{-3}) above those of the reference literature (40 $mmol_c$ dm^{-3}) (Aquino et al., 1993). In a similar way, the classes proposed for Mg^{2+} in the present study are higher than those in the reference literature. The upper limit of the appropriate class in the reference literature corresponded to only 10 $mmol_c$ dm^{-3}, while in the present study, the concentration was 31 $mmol_c$ dm^{-3} (Table 4).

The difference verified for the interpretation class for K, Ca^{2+} and Mg^{2+} can be explained by the fact the database is based on *Planossolo* and *Luvissolo*, which show higher concentrations of basic cations, and the reference literature considers a greater number of soils for the interpretation composition of fertility classes, including soils with 1:1 clay, which have low concentrations of these macronutrients. Furthermore, Smith et al. (2023) suggest an underestimation of the values considered adequate by the reference literature in relation to the boundary line approach. This is because the recommendation manuals are outdated and do not keep up with the increasing nutritional requirements of agricultural crops.

For the interpretation classes of the chemical properties shown in table 4, the database was mainly obtained from *Planossolo* and *Luvissolo*, which are directly linked to their respective parent rocks. Furthermore, in *Planossolo* and *Luvissolo*, the contribution of Ca^{2+} and K is associated with changes in plagioclase; in *Planossolo*, the contribution of Fe and Mg is mainly associated with alteration of biotite; in *Luvissolo*, the input of Fe and Mg is strongly influenced by alteration of amphiboles. Thus, Ca^{2+} is the main dominant cation in the sorption complex, and both soils have low H+Al values (Câmara et al., 2021). This helps explain the findings, mainly for basic cations and micronutrients.

Adequate fertility classes were lower for B and Cu, and virtually similar for Zn, but with greater amplitude (Table 4). However, the adequate classes for Fe and Mn were higher than those proposed by Alvarez et al. (1999). Organic matter greatly influences B and Cu, either as a source of B or due to adsorption and formation of complexes with Cu

(Oliveira et al., 2018; Dhaliwal et al., 2019; Vera et al., 2021). This condition can explain the lower values found in the adequate class proposed in this study due to the lower concentrations of organic matter when generating the interpretation classes.

The difference in sufficiency ranges for Fe and Mn cannot be explained by the higher pH values proposed in our study. Higher concentrations of Fe and Mn are linked to a lower pH value, but the parent materials may have contributed to higher concentrations of these micronutrients (Biondi et al., 2011; Oliveira et al., 2018). Thus, the boundary line method is an accessible strategy for generating interpretation classes and optimal levels of soil chemical properties using a standardized database from trials in several locations (Hernández-Vidal et al., 2021), providing greater speed and lower cost than conventional methods.

Although previous studies have shown promise with the boundary line approach, to the best of our knowledge, this is the first study that proposes establishing critical level and classes of soil fertility for the cultivation of corn, cowpea and sabiá, with a boundary line approach considering exclusively the edaphoclimatic conditions of a semi- arid region of Ceará. Results for soil fertility classes and critical and optimal levels for rainfed agriculture in soils with high-activity clay represent an innovation for tailoring amendment and fertilizer management to the Brazilian semi-arid region, which exhibits a predominance of soil orders similar to those used in the database of this study.

Generation of the interpretation ranges for soil fertility in soils with high-activity clay allows more adequate monitoring of chemical properties, making it possible to verify whether the supply of nutrients is satisfactory to maintain proper fertility rates without soil degradation. Reference literature disregards regional particularities, even if they are located in the same Brazilian state. Consequently, the erroneous interpretation of soil fertility classes can promote poor management of soil nutrients, which is relevant for the Brazilian semi-arid region due to desertification spots and areas in the process of degradation, where predominates the loss of soil fertility (Martins et al., 2019).

CONCLUSIONS

Boundary line method allowed the generation of fertility classes and critical levels for soil chemical properties in more than one crop, using the concept of relative yield. The method is an effective tool for generating optimal levels and interpretation classes based on standardized databases. Fertility classes generated for soils with high-activity clay in the Brazilian semi-arid region were superior to those in the reference literature, providing more adequate recommendations and management to avoid soil fertility degradation and guarantee a more satisfactory yield.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available on request to the corresponding author.

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