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Temporal variation of soil acidity attributes in cocoa-growing areas

Variación temporal de los atributos de acidez del suelo en zonas cacaoteras

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Abstract

Soil acidity is one of the main constraints to agricultural production in tropical regions. The objective of this study was to assess the variability of chemical attributes related to soil acidity in two layers (0-20 cm and 20-40 cm) across nineteen experimental areas where cocoa was cultivated following surface liming and gypsum application. After 87 months, no association was observed between soil acidification and soil buffering capacity indicators. Surface liming did not affect the acidity attributes within the 0-20 cm layer, suggesting that its impact was limited to upper soil layers. In contrast, gypsum amendment reduced Al^{3+} saturation in the 20-40 cm layer.

Keywords: aluminum, aluminum toxicity, gypsum amendment, gypsum mobility, surface liming.

Resumen

La acidez del suelo es la principal limitación para la producción agrícola en las regiones tropicales. El objetivo de este estudio fue evaluar la variabilidad de los atributos químicos relacionados con la acidez del suelo en dos capas (0-20 cm y 20-40 cm), en diecinueve áreas experimentales donde se cultivó cacao después de la aplicación de encalado superficial y yeso. Después de 87 meses, no se observó ninguna asociación entre la acidificación y los indicadores de amortiguación del suelo. El encalado superficial no afectó los atributos de acidez dentro de la capa de 0-20 cm, lo que indica que su impacto se limitó a las capas superiores del suelo. Por su parte, la enmienda con yeso resultó en una reducción en la saturación de Al^{3+} dentro de la capa de 20-40 cm.

Palabras clave: aluminio, encalado superficial, enmienda de yeso, movilidad del yeso, toxicidad del aluminio.

Introduction

Soil acidity is one of the main constraints to global agricultural production (Gurmessa, 2021; Rheinheimer *et al.*, 2018). About 40 % of the world's arable land is affected by high acidity, particularly in Africa, Asia, and South America (Sumner and Noble, 2003). Acidic soils are characterized by low nutrient availability and cation exchange capacity dominated by H^+ and Al^{3+} (Shetty and Prakash, 2020), which toxicity impairs root development reducing nutrient uptake, crop growth, and yield (Borges *et al.*, 2020).

The cocoa tree is tolerant to Al^{3+}, however, this element reduces the root and shoot dry weight of cocoa seedlings (Baligar and Fageria, 2005). Liming enhances biomass production in cocoa seedlings and boosts cocoa bean yield. It also increases soil pH, as well as Ca^{2+} and Mg^{2+} levels, and lowers Al^{3+} saturation (Hirzel *et al.*, 2020; Souza Júnior *et al.*, 2018). However, this input has low mobility in the soil. Therefore, its corrective effect is restricted to topsoil layers (Li *et al.*, 2019; Rheinheimer *et al.*, 2018).

Agricultural gypsum is a good alternative to reduce subsoil acidity, especially aluminum saturation (m%). Its mobility in the soil profile reduces Al^{3+} toxicity and increases Ca^{2+} and SO_4^{2-} concentrations in deeper soil layers (Enesi *et al.*, 2023). Consequently, water and nutrient absorption in deep layers increases (Bossolani *et al.*, 2020). However, the specific effects of gypsum amendment on cocoa trees are still not fully understood, highlighting the need for further research. Nevertheless, in their pioneering study, Nakayama (1986) showed that gypsum amendment improved the development and distribution of the root system of cocoa seedlings.

This study aimed to assess changes in chemical attributes of soil acidity resulting from lime and gypsum surface application in no-till systems cultivated with cocoa tress in the southeastern region of the state of Bahia, Brazil.

Materials and methods

Data collection

Soil samples were collected from nineteen experimental areas (EAs) located in fifteen municipalities across two climate zones: humid and humid-to-subhumid (SEI-BA, 2022), in the southeastern region of Bahia, Brazil (Figure 1). In total, 20 simple samples were collected for each composite sample. The analysis of the 0–20 cm and 20–40 cm layers were used to calculate the doses of lime and gypsum, respectively (Table 1). The study period was 87 months. Time zero (T0) refers to the month of liming and gypsum amendment, followed by subsequent sampling at T40, T52, T72, and T87 months after fertilization. Samples were collected in 0–10 cm, 10–20 cm, and 20–40 cm layers at these four times, and the values for the 0–20 cm layer were calculated by averaging the values of the 0–10 cm and 10–20 cm layers. Two composite samples were collected per EA at T40, while six composite samples were collected per EA at T52, T72, and T87.

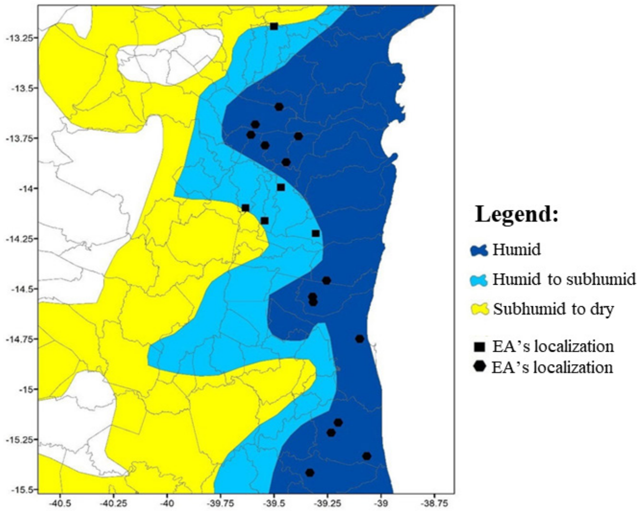

Figure 1. Location and climate type (according to Thornthwaite and Matter) of the nineteen experimental areas under study (SEI-BA, 2022).

Soil attributes

The following soil attributes were analyzed: pH in H_2O; Al^{3+}, Ca^{2+}, and Mg^{2+} extracted with 1.0 mol L^{-1} KCl; potential acidity (H+Al) extracted with 0.5 mol L^{-1} $Ca(CH_3COO)_2$; organic matter (OM) determined using the Walkley–Black method; and remaining P (P-rem), assessed by stirring 60 mg L^{-1} P in a 0.01 mol L^{-1} $CaCl_2$ solution (Teixeira *et al.*, 2017). The sand, silt, and clay contents were determined according to Teixeira *et al.* (2017). The aluminum saturation was calculated as follows (Eq. 1):

$$m\% = \frac{Al^{3+}}{Al^{3}+(Ca^{2}+Mg^{2}+K^{+})} \times 100 \quad \textbf{(Eq. 1)}$$

The results of the preliminary chemical analysis and the respective lime and gypsum doses are outlined in Table 1.

Calculation of lime and gypsum doses

Lime doses were calculated using the base saturation method (Eq. 2). The objective was to increase base saturation (V%) to 75 % in EAs with initial V% values below 65 % in the 0–20 cm layer, considering a reaction depth (d) of 5 cm and 90 % relative Total Neutralizing Power (RTNP) of the soil corrective. For this purpose, the amount was calculated as follows:

$$LD = \frac{(V_2 - V_1) \times T}{10 \times PRNT} \times \frac{d}{20} \quad \textbf{(Eq. 2)}$$

Where:

LD = lime dose, in tons per hectare (t ha^{-1});

V_2 = target base saturation (75 %);

V_1 = base saturation of the 0-20 cm layer, in %;

T = CEC at pH 7.0, in $mmol_c\ dm^{-3}$;

RTNP = relative total neutralizing power (90 %);

d = lime reaction depth (5 cm).

Gypsum doses were calculated according to the stochiometric equation proposed by Souza Júnior *et al*. (2018) (Equation 3). The objective was to reduce Al^{3+} saturation (m%) to 20 % in EAs with m% higher than 20 %, considering a layer thickness (LT) of 30 cm and a gypsum percentage ($\%Ca_{ges}$) of 16 %. For this purpose, the amount was calculated as follows:

$$GD = \left[Al^{3+} - \left(\frac{m_t \times t}{100} \right) \right] \times \frac{0.2 \times LT}{\%\ Ca_{gyp}} \quad \textbf{(Eq. 3)}$$

where:

GD = gypsum dose, in tons per hectare (t ha^{-1});

Al^{3+} = Al^{3+} concentration in the 20–40 cm layer, in $mmol_c\ dm^{-3}$;

m_t = tolerable Al^{3+} saturation (cocoa tree = 20 %);

t = effective CEC in the 20–40 cm layer, in $mmol_c\ dm^{-3}$;

LT = layer thickness (30 cm);

$\%Ca_{gyp}$ = percentage of Ca in gypsum (16 %).

Lime and gypsum amendment method

The lime and gypsum doses (Table 1) were converted to grams per plant and manually broadcast, covering the entire soil surface in a no-till system. To enhance contact between the inputs and the soil, the organic mulch was turned over using a leaf blower.

Statistical analysis

To assess the homogeneity of error variances, a one-way ANOVA was performed for each chemical attribute within each EA, subsequently calculating the ratio of the largest to the smallest mean square residual. The values were well above 7, indicating a lack of homogeneity of variances. Therefore, each EA was considered as an individual experiment. Finally, a regression analysis was performed to evaluate the variation of chemical attributes over time (0, 40, 52, 72, and 87 months), testing linear and quadratic coefficients using the mean square error from the ANOVA of each EA. Significance was assessed at up to 10 % probability, according to the F-test. All statistical tests were performed using the R software (R Core Team, 2023).

Results

The pH values of the 0-20 cm layer remained stable over time in eleven of the EAs (Table 2), seven of which had received surface liming at doses ranging from 0.36 to 1.09 t ha^{-1} (Table 1). The pH of the 0-20 cm layer decreased over time in eight EAs, seven of which had received surface liming at doses ranging from 0.54 to 1.04 t ha^{-1}. In contrast, the pH of the 20-40 cm layer remained stable in twelve EAs, while it decreased in seven EAs over time (Table 2).

Al^{3+} concentration in the 0-20 cm layer did not decrease in any of the fourteen EAs that received surface liming; however, Al^{3+} concentration increased over time in ten EAs (Table 3), nine of which had received liming ranging from 0.54 to 1.09 t ha^{-1} (Table 1). The nine EAs where Al^{3+} concentration did not change were the same ones where the pH did not change either.

Al^{3+} concentrations in the 20–40 cm layer varied in three of the eight EAs that received gypsum amendment (Table 3). The quadratic models were significant, indicating a decrease in Al^{3+} concentrations, which reached minimum values and subsequently increased over time. In these EAs, the effect of gypsum on reducing Al^{3+} concentrations peaked at 38, 52, and 25 months in EAs 3, 4, and 7, respectively. Al^{3+} concentration increased linearly over time in the 20–40 cm layer in five EAs (Table 3); however, gypsum was applied in only one of them, i.e., EA 12, which received a dose of 2.39 t ha^{-1} gypsum (Table 1). Al^{3+} concentrations did not change in eleven EAs, four of which had received gypsum amendment at doses ranging from 0.60 to 1.06 t ha^{-1}.

m% in the 0–20 cm layer did not vary over time in eleven EAs, seven of which received doses of lime ranging from 0.36 to 1.04 t ha^{-1} (Tables 1 and 4). Al^{3+} concentrations did not change either in nine of the eleven EAs mentioned above (Tables 4 and 5). m% increased over time in eight EAs, all of which had received surface liming at doses ranging from 0.54 to 1.09 t ha^{-1}, except for EA 6.

Aluminum saturation in the 20–40 cm layer varied over time in ten EAs (Table 5), increasing in five of them. In these EAs, gypsum was not applied. m% variation over time was described using a quadratic equation in the five EAs. All of them received gypsum amendments (Table 5 and Figure 2). The mean minimum m% ($m\%_{min}$) was 15.6 %, reached, on average, 41 months after applying gypsum.

Discussion

The pH in the 0–20 cm layer did not increase in the EAs that received surface liming (Table 2). This result suggests that the corrective effect was restricted to the topsoil layers, which were not assessed in this study. Furthermore, this result corroborates the

Table 1. Initial pH and chemical attribute* values used to calculate the lime and gypsum amendments for two soil layers and the respective lime and gypsum doses applied across nineteen experimental areas under cocoa cultivation, in the state of Bahia, Brazil

EA	Climate zone	0–20 cm layer			20–40 cm layer			Input	
		pH	T	V	pH	Al^{3+}	t	Lime	Gypsum
			$mmol_c\ dm^{-3}$	%		$mmol_c\ dm^{-3}$		$t\ ha^{-1}$	
1	humid	5.56	101.7	44.9	4.59	6.8	16.6	0.80	1.31
2	humid	6.51	104.1	87.5	6.50	0.0	78.5	---	---
3	humid	5.61	91.8	47.7	4.67	10.7	17.6	0.70	2.69
4	humid	5.81	91.0	50.5	4.91	8.8	17.9	0.62	1.96
5	humid	5.88	49.4	73.6	4.78	5.9	19.8	---	0.73
6	humid	6.01	80.2	70.0	5.51	4.9	37.8	---	---
7	humid	5.27	114.2	42.2	4.68	4.9	20.7	1.04	0.29
8	humid	5.84	73.0	52.0	4.90	4.0	12.0	0.46	0.60
9	humid	5.31	79.4	30.0	5.15	3.9	18.4	0.98	---
10	humid	5.83	123.0	59.3	5.14	5.0	28.2	0.54	---
11	humid	6.08	99.8	59.9	5.42	2.0	27.7	0.42	---
12	humid	4.95	90.2	33.4	4.75	10.7	21.7	1.04	2.39
13	humid	5.52	86.3	50.1	5.22	0.0	16.6	0.54	---
14	humid	6.50	60.3	81.7	4.76	0.0	19.4	---	---
15	hs[1]	5.69	102.3	56.0	4.99	4.9	26.8	0.54	---
16	hs	7.34	73.1	86.3	6.63	0.0	37.5	---	---
17	hs	5.35	115.4	41.0	4.17	6.8	19.9	1.09	1.06
18	hs	5.63	92.3	61.0	5.11	4.0	24.3	0.36	---
19	hs	5.55	110.8	49.4	4.90	1.0	24.7	0.78	---

* pH in H_2O. T: cation-exchangeable capacity (CEC) at pH 7.0; V: base saturation; Al^{3+}: exchangeable aluminum; t: effective CEC. [1] Humid to subhumid.

Table 2. Regression equations of pH variation over time* in two soil layers across nineteen experimental areas under cocoa cultivation in the state of Bahia, Brazil

AE	Layer 0–20 cm Equation	R^2	Layer 20–40 cm Equation	R^2
1	$\hat{Y} = \bar{Y} = 5.38$	-	$\hat{Y} = \bar{Y} = 4.83$	-
2	$\hat{Y} = \bar{Y} = 6.11$	-	$\hat{Y} = \bar{Y} = 5.92$	-
3	$\hat{Y} = 5.69 - 0.013^{**}t$	0.80	$\hat{Y} = 4.70 - 0.004^{*}t$	0.46
4	$\hat{Y} = 5.76 - 0.009^{**}t$	0.83	$\hat{Y} = 4.98 - 0.005^{*}t$	0.69
5	$\hat{Y} = \bar{Y} = 5.54$	-	$\hat{Y} = \bar{Y} = 5.01$	-
6	$\hat{Y} = 6.05 - 0.013^{**}t$	0.74	$\hat{Y} = \bar{Y} = 5.16$	-
7	$\hat{Y} = 5.45 - 0.013^{**}t$	0.74	$\hat{Y} = 4.78 - 0.007^{**}t$	0.80
8	$\hat{Y} = \bar{Y} = 5.44$	-	$\hat{Y} = \bar{Y} = 4.72$	-
9	$\hat{Y} = 5.38 - 0.008^{**}t$	0.97	$\hat{Y} = 5.03 - 0.006^{**}t$	0.93
10	$\hat{Y} = 5.22 - 0.008^{*}t$	0.48	$\hat{Y} = 4.69 - 0.004^{\circ}t$	0.42
11	$\hat{Y} = \bar{Y} = 5.35$	-	$\hat{Y} = \bar{Y} = 4.86$	-
12	$\hat{Y} = \bar{Y} = 4.89$	-	$\hat{Y} = \bar{Y} = 4.40$	-
13	$\hat{Y} = 5.56 - 0.007^{**}t$	0.99	$\hat{Y} = 5.18 - 0.006^{**}t$	0.92
14	$\hat{Y} = \bar{Y} = 6.23$	-	$\hat{Y} = \bar{Y} = 5.72$	-
15	$\hat{Y} = 5.77 - 0.010^{**}t$	0.62	$\hat{Y} = 5.05 - 0.008^{**}t$	0.79
16	$\hat{Y} = \bar{Y} = 6.09$	-	$\hat{Y} = \bar{Y} = 5.46$	-
17	$\hat{Y} = \bar{Y} = 4.91$	-	$\hat{Y} = \bar{Y} = 4.34$	-
18	$\hat{Y} = \bar{Y} = 5.16$	-	$\hat{Y} = \bar{Y} = 4.75$	-
19	$\hat{Y} = \bar{Y} = 5.33$	-	$\hat{Y} = \bar{Y} = 4.75$	-

* Time in months.

'**,' '*,' and '°' are significant at 0.01, 0.05, and 0.1, respectively, according to the F-test.

Table 3. Regression equations of the variation of Al^{3+} concentration over time* in two soil layers of nineteen experimental areas under cocoa cultivation in the state of Bahia, Brazil

AE	Layer 0–20 cm Equation	R^2	Layer 20–40 cm Equation	R^2
1	$\hat{Y} = -0.6 + 0.030^{\circ}t$	0.82	$\hat{Y} = \bar{Y} = 6.1$	-
2	$\hat{Y} = \bar{Y} = 0.0$	-	$\hat{Y} = \bar{Y} = 0.0$	-
3	$\hat{Y} = -0.2 + 0.076^{**}t$	0.57	$\hat{Y} = 10.4 - 0.176t^{**} + 0.002^{**}t^2$	0.94
4	$\hat{Y} = -0.4 + 0.019^{**}t$	0.81	$\hat{Y} = 8.6 - 0.256^{**}t + 0.003^{**}t^2$	0.99
5	$\hat{Y} = \bar{Y} = 0.2$	-	$\hat{Y} = \bar{Y} = 2.0$	-
6	$\hat{Y} = -0.8 + 0.049^{\circ}t$	0.51	$\hat{Y} = \bar{Y} = 6.7$	-
7	$\hat{Y} = -3.9 + 0.141^{**}t$	0.65	$\hat{Y} = 5.0 - 0.124^{*}t + 0.003^{**}t^2$	0.67
8	$\hat{Y} = \bar{Y} = 0.5$	-	$\hat{Y} = \bar{Y} = 4.2$	-
9	$\hat{Y} = 1.8 + 0.040^{\circ}t$	0.57	$\hat{Y} = \bar{Y} = 7.7$	-
10	$\hat{Y} = -0.2 + 0.075^{*}t$	0.36	$\hat{Y} = 5.7 + 0.098^{**}t$	0.66
11	$\hat{Y} = \bar{Y} = 0.5$	-	$\hat{Y} = \bar{Y} = 3.8$	-
12	$\hat{Y} = \bar{Y} = 3.7$	-	$\hat{Y} = 9.0 + 0.057^{\circ}t$	0.72
13	$\hat{Y} = -0.3 + 0.021^{\circ}t$	0.68	$\hat{Y} = 0.04 + 0.038^{*}t$	0.67
14	$\hat{Y} = \bar{Y} = 0.0$	-	$\hat{Y} = \bar{Y} = 0.1$	-
15	$\hat{Y} = -1.4 + 0.054^{**}t$	0.70	$\hat{Y} = -0.2 + 0.112^{**}t$	0.46
16	$\hat{Y} = \bar{Y} = 0.03$	-	$\hat{Y} = \bar{Y} = 0.8$	-
17	$\hat{Y} = 0.2 + 0.029^{*}t$	0.56	$\hat{Y} = \bar{Y} = 7.1$	-
18	$\hat{Y} = \bar{Y} = 0.9$	-	$\hat{Y} = \bar{Y} = 3.6$	-
19	$\hat{Y} = \bar{Y} = 0.7$	-	$\hat{Y} = 1.0 + 0.048^{\circ}t$	0.99

* Al^{3+} concentration in $mmol_c\ dm^{-3}$; time in months.

'**,' '*,' and '°' are significant at 0.01, 0.05, and 0.1, respectively, according to the F-test.

Table 4. Regression equations of Al^{3+} saturation over time* in two soil layers of nineteen experimental areas under cocoa cultivation in the state of Bahia, Brazil

EA	Layer			
	0–20 cm		20–40 cm	
	Equation	R^2	Equation	R^2
1	$\hat{Y}$= - 2.2 + 0.088°t	0.81	$\hat{Y}$= 41.0 – 1.102t + 0.013*t^2	0.98
2	$\hat{Y}$= $\bar{Y}$= 0.0	-	$\hat{Y}$= $\bar{Y}$= 0.0	-
3	$\hat{Y}$= - 3.5 + 0.229**t	0.54	$\hat{Y}$= 62.1 – 1.667**t + 0.019**t^2	0.98
4	$\hat{Y}$= - 1.1 + 0.042**t	0.77	$\hat{Y}$= 49.0 – 1.635**t + 0.016**t^2	0.99
5	$\hat{Y}$= $\bar{Y}$= 0.6	-	$\hat{Y}$= $\bar{Y}$= 9.5	-
6	$\hat{Y}$= - 2.4 + 0.119°t	0.52	$\hat{Y}$= $\bar{Y}$= 14.7	-
7	$\hat{Y}$= - 15.6 + 0.470**t	0.61	$\hat{Y}$= 23.9 – 1.001**t + 0.018**t^2	1.00
8	$\hat{Y}$= $\bar{Y}$= 1.4	-	$\hat{Y}$= $\bar{Y}$= 25.3	-
9	$\hat{Y}$= $\bar{Y}$= 14.9	-	$\hat{Y}$= 25.4 + 0.289°t	0.73
10	$\hat{Y}$= - 2.0 + 0.195*t	0.35	$\hat{Y}$= 11.2 + 0.480**t	0.58
11	$\hat{Y}$= $\bar{Y}$= 0.8	-	$\hat{Y}$= $\bar{Y}$= 13.9	-
12	$\hat{Y}$= $\bar{Y}$= 8.3	-	$\hat{Y}$= $\bar{Y}$= 50.0	-
13	$\hat{Y}$= $\bar{Y}$= 2.7	-	$\hat{Y}$= 0.3 + 0.232°t	0.55
14	$\hat{Y}$= $\bar{Y}$= 0.0	-	$\hat{Y}$= $\bar{Y}$= 0.4	-
15	$\hat{Y}$= - 3.5 + 0.126**t	0.64	$\hat{Y}$= - 11.4 + 0.666**t	0.49
16	$\hat{Y}$= $\bar{Y}$= 0.1	-	$\hat{Y}$= $\bar{Y}$= 2.4	-
17	$\hat{Y}$= - 0.7 + 0.071*t	0.62	$\hat{Y}$= 38.4 – 1.042t* + 0.013*t^2	0.55
18	$\hat{Y}$= $\bar{Y}$= 1.6	-	$\hat{Y}$= $\bar{Y}$= 11.2	-
19	$\hat{Y}$= $\bar{Y}$= 1.8	-	$\hat{Y}$= - 0.4 + 0.375**t	0.96

* Al^{3+} saturation in percentage; time in months.

'**,' '*,' and '°' are significant at 0.01, 0.05, and 0.1, respectively, according to the F-test.

findings of other studies, which have shown that the corrective effects of surface liming in a no-till system are limited to the topsoil layers, particularly at depths of 0–5 cm and 5–10 cm (Alleoni *et al.*, 2005; Zandoná *et al.*, 2015). In a field study with cocoa trees, Nakayama (1986) observed that surface liming in a no-till system corrected soil acidity up to a depth of 10 cm, six years after the application of this amendment. The effect of surface liming is restricted

Table 5. Estimates of the minimum Al^{3+} saturation and the times to reach 20 % Al^{3+} saturation, minimum m%, and 20 % Al^{3+} saturation again, in five experimental areas under cocoa cultivation in the state of Bahia, Brazil

EA	$m\%_{min}$	--------Time (months) ---------		
		T1	T2	T3
1	17.6	29	42	56
3	25.5	nd[1/]	44	nd[1]
4	7.2	23	51	80
7	10.0	04	28	52
17	17.5	26	40	54
Mean	15.6	20.5	41.0	60.5

to the topsoil layers because lime has low mobility in the soil due to the loss of the accompanying ion (CO_3^{2-}) during dissolution reactions, which consume H^+, yielding H_2CO_3. Subsequently, H_2CO_3 dissociates into H_2O and CO_2. In addition, the Al^{3+} precipitation reaction with OH^- derived from lime dissolution forms $Al(OH)_3$, contributing to the surface effect of this input (Rheinheimer *et al.*, 2018).

The coefficients of the linear regression models for the 0-20 cm layer ranged from 0.007 to 0.013 per month, corresponding to an annual pH reduction rate ranged from 0.084 to 0.156 units (Table 2). In the 20–40 cm layer, the annual pH reduction rate ranged from 0.048 to 0.096. These results suggest that the acidification process is more intense in the topsoil layer.

The soil buffering indicators T, P-rem, OM, and clay did not explain differences in pH variation between soils because their mean values were 96.6 $mmol_c\ dm^{-3}$, 37.6 mg L^{-1}, 30.1 g kg^{-1}, and 42.1 %, respectively, in the eleven EAs where the pH of the 0–20 cm layer did not change over time. These results indicate a lower acidity buffering in these soils than in the soils of the eight EAs whose pH values decreased over time, with average values of 102.0 $mmol_c\ dm^{-3}$, 31.5 mg L^{-1}, 34.8 g kg^{-1}, and 47.9 %, respectively.

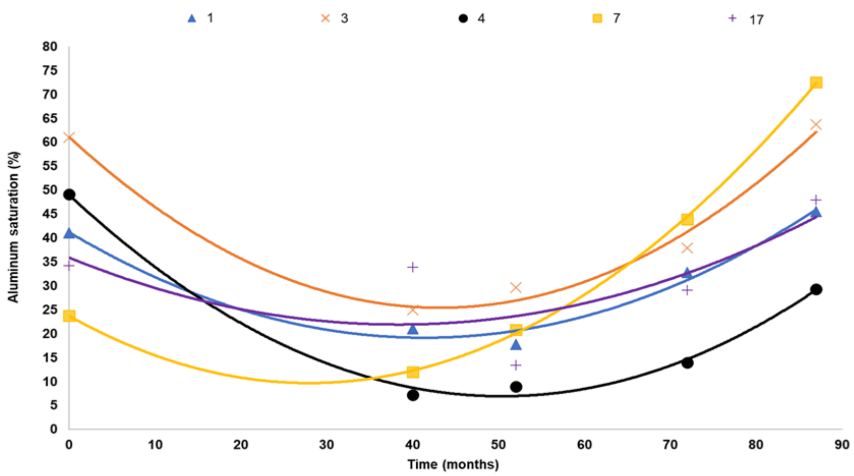

Figure 2. Variation of Al^{3+} saturation over time in five EAs under cocoa cultivation in the state of Bahia, Brazil

Climate may be useful to explain these results because seven of the eight EAs whose pH values decreased over time are located in the rainiest climate zone (Tables 1 and Figure 1). High precipitation rates promote the leaching of basic cations, thereby increasing soil acidity. In addition to climate, the decrease in pH values over time in the seven EAs that received surface liming might have been caused by interactions between factors such as the low dose of lime applied to the soil, averaging 0.71 t ha^{-1}, and OM mineralization.

Neither the Al^{3+} concentration (Table 3) nor the pH (Table 2) changed over time in the 0–20 cm layer in nine EAs, suggesting a close correlation between these two attributes. Al^{3+} solubility and, hence, toxicity, are primarily controlled by the pH. Al^{3+} availability troughs at pH levels above 5.5 (Ruíz *et al.*, 2016). Therefore, despite having received surface liming, some EAs did not show variations in Al^{3+} because the pH did not change.

The m% in the 0–20 cm layer did not change in eleven of the EAs. In ten of them, the mean m% ranged from 0 % to 8.3 % (Table 4). These m% values were low for cocoa trees, according to Souza Júnior *et al.* (2018). The mean m% was higher (14.9 %) only in EA 9; however, it was still lower than the threshold of 15 % suggested by Baligar and Fageria (2005) as the maximum m% tolerated by the crop. Nevertheless, m% increased over time in this layer in eight EAs (Table 4), reflecting a rise in Al^{3+} concentrations despite surface liming being applied in seven of them at doses ranging from 0.54 to 1.09 t ha^{-1} (Table 1). In this context, the increase in Al^{3+} and, thus, in m%, might have resulted from natural soil acidification processes such as OM mineralization, root uptake of basic cations and H^+ extrusion, leaching of bases, and H^+ and Al^{3+} accumulation in the soil profile (Li *et al.*, 2019). The low mean dose of 0.71 t ha^{-1} lime combined with the low mobility of this input might have also contributed to this result (Alleoni *et al.*, 2005; Parecido *et al.*, 2021; Zandoná *et al.*, 2015). The coefficients of the linear regression models indicated an increase in m%, ranging from 0.5 % to 5.6 % per year.

The m% in the 20–40 cm layer decreased in five EAs after surface gypsum amendment (Table 5). The minimum m% ($m\%_{min}$) reached in each EA was estimated based on quadratic models of the variation of m% over time and gypsum dose. The $m\%_{min}$ values ranged from 7.2 % to 25.5 %, averaging 15.6 %. This value is close to the target m% of 20 % which was adopted as the tolerable threshold (m_t) for cocoa cultivation and used to calculate the doses of gypsum (Equation 3).

The following time estimates were also calculated: T1, the time required to reach the target m% tolerated by the crop (m_t), set at 20 % (Equation 3); T2, the time to reach the minimum $m\%_{min}$, representing the maximum duration of gypsum effectiveness; and T3, the time until m% rises back to 20 %, indicating the need for gypsum reapplication. The mean T1, T2, and T3 values were 20.5, 41, and 60.5 months, respectively (Table 5). The maximum gypsum effectiveness on m% reduction (T2) ranged from 28 to 51 months after application. This range is higher than the maximum time of 22 months assessed by Nora and Amado (2013) and similar to the maximum time (43 months) assessed by Caires *et al.* (2000). Moreover, both studies reported that gypsum chemically improves subsurface soil layers by reducing Al^{3+} concentrations and m%. However, the periods assessed in both studies were shorter than those of this study, where the time for gypsum reapplication (T3) ranged from 52 to 80 months (Table 5). This time interval exceeded the residual effect of the gypsum amendment of 60 months reported by da Costa *et al.* (2016), and the maximum duration of 72 months observed by Pauletti *et al.* (2014).

The m% in the 20–40 cm layer increased over time in five of the EAs that were not treated with gypsum (Tables 1 and 5). Based on the linear regression models, m% increased at an annual rate ranging from 2.8 % to 8.0 %.

Conclusions

Soil acidification in experimental areas (EAs) under cocoa cultivation varied markedly over a period of 87 months, showing no correlation with soil buffering indicators.

Surface liming in a no-till system did not change the chemical attributes in the 0–20 cm layer; therefore, its effect might have been restricted to the topsoil layers.

Surface gypsum amendment in a no-till system led to a reduction in Al^{3+} concentration and, especially, Al^{3+} saturation in the 20–40 cm layer in some EAs; however, this effect diminished over time.

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