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Temporal changes in basic cations in soils under cocoa cultivation in the Brazilian Atlantic forest

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Abstract: Low base saturation causes abiotic stress in crops. However, it can be a significant factor for increasing yields when adjusted to appropriate levels. This study aimed to assess the temporal alterations of basic cations in two soil layers under cocoa tree cultivation in the Brazilian Atlantic Forest biome. For this purpose, a seven-year field experiment was established, consisting of 19 experimental areas (EAs), each of which received superficial applications of lime and agricultural gypsum. The changes on basic cations levels were measured at doses of 0.36-1.09 and 0.29-2.69 t ha^{-1} limestone and gypsum, respectively, after 0, 40, 52, 72, and 87 months of application. In the first two years, the cocoa trees were fertilized with the N-P-K 16-16-16 formula in doses of 640 and 1,025 kg, respectively, divided into four applications. Nutrition was done with monoammonium phosphate, urea, triple superphosphate and potassium chloride as source. The results suggests that in most EAs, lime did not affect Ca^{2+} and Mg^{2+} levels, consequently, causing no difference on the base sum and base saturation in the 0–20 cm layer. However, gypsum led to increase of Ca^{2+} levels in both soil layers, as well as an increase of Mg^{2+} and K^{+} levels in the 20–40 cm layer. Variations in K^{+} levels were associated with potassium fertilization. Cocoa producers should apply gypsum to enhance the chemical properties of poor soils by increasing exchangeable base levels at greater depths. This improvement promotes deeper root growth, enabling cocoa trees to access a larger soil volume and better withstand water stress during drought periods.

Keywords: Gypsum mobility, soil base, superficial liming.
Abbreviations: EAs_Experimental Areas

Introduction

The cocoa tree (*Theobroma cacao* L.) has been used since 1100 BC. It is native to South America which then introduced to Central America, Africa, and Asia, (Motamayor, 2002; Henderson et al., 2007). Currently, cocoa is an agricultural commodity that generates an annual revenue over than US$120 billion (FAOSTAT, 2024). The species grows only in tropical regions, engaging six million farmers for its cultivation (Olwig et al., 2024), primarily in highly weathered soils (Fageria and Baligar, 2008).

Soil acidity is the main constraint to plant production in tropical regions (Hue, 2022; Anbessa, 2023). In Africa the soil acidity has been increasing regularly, affecting large agricultural regions of Ivory Coast and Ghana (Agegnehu et al., 2021) and other main cocoa producers worldwide (ICCO, 2024). Acidic soils have low pH, high Al^{3+} levels, and low levels of basic cations such as Ca^{2+}, Mg^{2+}, and K^{+} (Rheinheimer et al., 2018; Basak et al., 2022). Higher Al^{3+} levels promote disruption of leaf cell nuclear membranes and deformity of root epidermis cells (de Almeida et al., 2015). The low base saturation observed in acidic soils is a major cause of abiotic stress in cultivated plants (Andrade et al., 2021). Low basic cations levels associated with the Al^{3+} toxicity reduces water and nutrient uptake rates (Shetty and Prakash, 2020; Bolan et al., 2023), exposing the crops to abiotic stress mainly during drought periods (Zandoná, 2015.

Soil superficial acidity can be mitigated by lime, which is also a source of Ca^{2+} and Mg^{2+}. For sub superficial acidity, the improvement of chemical environment has been achieved by agricultural gypsum, increasing Ca^{2+} level and reducing Al^{3+} saturation, which consequently enhances productivity, especially during drought periods (Bossolani et al., 2022a, b; Caires et al., 2023). Some studies have shown that gypsum reduces Cd^{2+} bioavailability in soils with high CEC, probably due to ions Ca^{2+} from gypsum to have a counteracting effect on cadmium Cd^{2+} mobilization and ion competition at the root surface (Argüello et al., 2022). The Cd^{2+} high level is harmful for human health. It also poses a challenge to the economies of cocoa-producing countries by reducing their competitiveness in the international market

Table 1. Initial values of pH and chemical attributes[1/] used to calculate the lime and gypsum amendment of two soil layers and the respective lime and gypsum doses applied in 19 experimental areas (EAs), 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[2/]	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	375	---	---
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	---

1/ pH in H_20; T (cation-exchange capacity (CEC) at pH 70); V (base saturation); Al^{3+} (exchangeable aluminum); and t (effective CEC) 2/ humid to subhumid.

(Maddela et al., 2020; Santander Ruiz et al., 2021, Reyes-Pérez, et al., 2023).

Cocoa trees experience reduced nutrient uptake, translocation, and accumulation, when grown in acidic soils (Ribeiro et al, 2013; Rosas-Patiño et al., 2017). The species has higher nutritional requirements compared to perennial tropical crops such as coffee and rubber trees (Baligar and Fageria, 2005; Souza Júnior et al., 2018). Cocoa high productivity is related to high levels of foliar nutrients, which are seriously affected by acidity, leading to loss of productivity (Marrocos et al., 2020).

To meet the cocoa nutritional demands and avoid soil depletion, it is necessary to increase productivity in existing areas instead of deforesting to establish new plantations. The Brazilian Atlantic Forest biome is home to 500 thousand hectares of cocoa (Chiapetti, 2018), cultivated in an agroforestry system called "cabruca", which consisted of planting cocoa trees under native trees presenting rich biodiversity (Sambuichi et al., 2012).

These plantations have great potential to produce sustainable cocoa beans, but soil fertility management remains a challenge to overcome. Seeking to develop strategies to manage the soil fertility of local plantations, this study aimed to evaluate the temporal alterations on chemical attributes related to exchangeable basic cations (Ca^{2+}, Mg^{2+}, K^+, base sum, and saturation) in two soil layers (0–20 cm and 20–40 cm). This study was conducted in the Brazilian Atlantic Forest across 19 experimental areas (EAs) cultivated with cocoa trees, after superficial application of lime and agricultural gypsum.

Results

Temporal alterations for Ca^{2+}

There was no substantial alteration in Ca^{2+} levels over time across eight EAs at 0–20 cm layer (Table 2). Three of experimental areas (EAs) received lime ranging from 0.54 to 0.98 t ha^{-1}, two received lime + gypsum from 0.46 to 1.09 t ha^{-1} and from 0.60 to 1.06 t ha^{-1}, respectively, while one received 0.73 t ha^{-1} gypsum, and two did not receive any inputs (Table 1).

In 0–20 cm layer, 10 EAs exhibited significant alteration in Ca^{2+} levels over time. All of them had the same behavior, exhibiting a quadratic regression with a positive linear coefficient and a negative quadratic coefficient. (Table 2). Among these EAs, three received limes at rates between 0.36 and 0.54 t ha^{-1}, five received both lime and gypsum at rates of 0.62 to 1.04 t ha^{-1} and 0.29 to 2.39 t ha^{-1}, respectively, and two did not receive the inputs (Table 1). The Ca^{2+} levels decreased over time only in EA 19. For the 20–40-cm layer, there was no considerable alteration in Ca^{2+} levels over time at 12 EAs. Six EAs exhibited an increase, followed by a decrease in Ca^{2+} levels over time. All received gypsum ranging from 0.29 to 2.39 t ha^{-1}. The Ca^{2+} levels showed a linear reduction only in EA 9 did over time.

Temporal alterations for Mg^{2+}

For the 0–20-cm layer, no significant variations were observed in the Mg^{2+} levels in 10 EAs (Table 3). Among these, five received lime ranging from 0.36 to 0.98 t ha^{-1}, three received lime plus gypsum from 0.46 to 1.04 t ha^{-1} and from 0.60 to 2.39t ha^{-1},m respectively, one EA received 0.73 t ha^{-1} gypsum, and one EA did not receive any inputs (Table 1).

Table 2. Regression equations for Ca^{2+} levels over time1/ in two layers from soils cultivated with cocoa trees across 19 experimental areas (EAs) in Bahia, Brazil.

EAs	Layer			
	---------------- 0–20-cm ----------------		---------------- 20–40-cm ----------------	
	Equation	R^2	Equation	R^2
1	$\hat{Y} = 28.3 + 0.510t - 0.006°t^2$	0.65	$\hat{Y} = 4.8 + 0.404^{*}t - 0.005^{*}t^2$	0.78
2	$\hat{Y} = \bar{Y} = 76.4$	-	$\hat{Y} = \bar{Y} = 58.0$	-
3	$\hat{Y} = 27.3 + 0.618^{**}t - 0.008^{**}t^2$	0.94	$\hat{Y} = 2.8 + 0.442^{**}t - 0.005^{**}t^2$	0.95
4	$\hat{Y} = 32.8 + 0.901^{*}t - 0.011^{*} t^2$	0.84	$\hat{Y} = 8.2 + 0.742^{**}t - 0.009^{**}t^2$	0.95
5	$\hat{Y} = \bar{Y} = 37.8$	-	$\hat{Y} = \bar{Y} = 16.0$	-
6	$\hat{Y} = \bar{Y} = 33.0$	-	$\hat{Y} = \bar{Y} = 23.4$	-
7	$\hat{Y} = 28.7 + 0.464^{**}t - 0.007^{**}t^2$	0.96	$\hat{Y} = 11.1 + 0.363^{*}t - 0.005^{**}t^2$	0.82
8	$\hat{Y} = \bar{Y} = 33.0$	-	$\hat{Y} = \bar{Y} = 9.1$	-
9	$\hat{Y} = \bar{Y} = 18.1$	-	$\hat{Y} = 10.3 - 0.070°t$	0.51
10	$\hat{Y} = \bar{Y} = 31.6$	-	$\hat{Y} = \bar{Y} = 11.6$	-
11	$\hat{Y} = 45.1 + 0.770t^{*} - 0.010^{**}t^2$	0.65	$\hat{Y} = \bar{Y} = 17.7$	-
12	$\hat{Y} = 20.4 + 0.342t - 0.003°t^2$	0.77	$\hat{Y} = 6.9 + 0.117t - 0.001^{*}t^2$	0.93
13	$\hat{Y} = \bar{Y} = 33.2$	-	$\hat{Y} = \bar{Y} = 11.0$	-
14	$\hat{Y} = 34.4 + 0.708°t - 0.010^{*}t^2$	0.68	$\hat{Y} = \bar{Y} = 20.3$	-
15	$\hat{Y} = 35.5 + 0.373t - 0.006^{*}t^2$	0.59	$\hat{Y} = \bar{Y} = 11.0$	-
16	$\hat{Y} = 38.1 + 0.779^{**}t - 0.010^{**}t^2$	0.88	$\hat{Y} = \bar{Y} = 22.2$	-
17	$\hat{Y} = \bar{Y} = 38.8$	-	$\hat{Y} = 6.0 + 0.646^{*}t - 0.007^{**}t^2$	0.51
18	$\hat{Y} = 32.6 + 0.331^{*}t - 0.005^{**}t^2$	0.74	$\hat{Y} = \bar{Y} = 14.4$	-
19	$\hat{Y} = 35.7 - 0.153^{*}t$	0.69	$\hat{Y} = \bar{Y} = 10.0$	-

1/ Ca^{2+} level in $mmol_c\ dm^{-3}$; time in months.

**, *, °, significant at 001, 005, and 010, respectively, as per the F test.

In this layer, five EAs exhibited significant variations in Mg^{2+} levels over time. All of them exhibited a positive linear coefficient and a negative quadratic coefficient, indicating an initial increase followed by a subsequent decrease in Mg^{2+} levels over time (Table 3). Among these five EAs, two received lime (0.62 and 1.09 t ha^{-1}) plus gypsum (1.06 and 1.96 t ha^{-1}), one EA received 0.54 t ha^{-1} lime, and two EAs received none of the inputs. Finally, in four EAs, the Mg^{2+} levels decreased linearly over time, even in three EAs that received lime doses ranging from 0.70 to 1.04 ha^{-1} (Table 1).

For the 20–40-cm layer, there was greater consistency in the Mg^{2+} levels over time compared to the superficial layer, as in 13 EAs, a significant variation in the Mg^{2+} levels were observed over the 87 months of evaluation (Table 3). Six of these EAs exhibited a quadratic model fit. It is essential to note that all six EAs received gypsum, with doses ranging from 0.29 to 2.69 t ha^{-1} (Table 1). There was a linear reduction in Mg^{2+} levels over time only in EA 13.

Temporal alterations for K^+

The K^+ levels in the 0–20-cm layer did not vary significantly across nine EAs. For five EAs, a quadratic behavior was observed, indicating an initial increase followed by a later decrease in K^+ levels over time. In four EAs, a positive linear behavior was observed. Finally, in just one EA, the K^+ levels decreased linearly over time (Table 4).

In the 20–40 cm soil layer, K^+ levels mostly presented no significant change over time. There was positive linear behavior only in three EAs and only one EA exhibited a quadratic behavior for the K^+ level over time.

Temporal alterations for sum of base (SB)

The temporal behavior SB was similar to those observed for Ca^{2+} and Mg^{2+} (Tables 2 and 3). Thus, there was a prevalence of no variation in SB over time, especially in the subsurface layer. In contrast, the predominant significant model was quadratic with a positive linear coefficient and a negative quadratic coefficient, when there was variation.

V% is the percentage of the CEC at pH 7.0 (T) that is occupied by basic cations (SB), with the remaining portion occupied by potential acidity ($H+Al^{3+}$). In other words, V% is highly dependent on SB, but also on potential acidity. Therefore, the behavior of both variables is similar, with the 20–40-cm layer exhibiting identical behavior across all 19 EAs, 14 of which exhibited no variation over time and five of which exhibited significant quadratic models (Tables 5 and 6), with these five EAs having received gypsum (Table 1).

Discussion

Alterations in Ca^{2+} and Mg^{2+} levels

Out of the 15 EAs that received lime and/or gypsum, eight exhibited significant changes in Ca^{2+} levels within the 0–20-cm layer throughout the study, exhibiting quadratic models. This indicates the importance of these two inputs as sources of Ca^{2+} with temporally limited effects, as demonstrated by the decrease in Ca^{2+} levels after the inflection point of the quadratic models, which varied

Table 3. Regression equations for Mg^{2+} levels over time[1/] in two layers from soils cultivated with cocoa trees across 19 experimental areas (EAs) in Bahia, Brazil.

EA	Layer			
	---------------- 0–20 cm ----------------		---------------- 20–40 cm ----------------	
	Equation	R^2	Equation	R^2
1	$\hat{Y} = \bar{Y} = 14.6$	-	$\hat{Y} = 3.9 + 0.145t - 0.002^{\circ}t^2$	0.91
2	$\hat{Y} = \bar{Y} = 24.4$	-	$\hat{Y} = \bar{Y} = 25.4$	-
3	$\hat{Y} = 19.4 - 0.122^{**}t$	0.95	$\hat{Y} = 3.2 + 0.158^{**}t - 0.002^{**}t^2$	0.99
4	$\hat{Y} = 14.5 + 0.093t - 0.002^{\circ}t^2$	0.77	$\hat{Y} = 2.7 + 0.218^{**}t - 0.003^{**}t^2$	0.94
5	$\hat{Y} = \bar{Y} = 14.3$	-	$\hat{Y} = 4.7 + 0.178^{\circ}t - 0.002^{\circ}t^2$	0.55
6	$\hat{Y} = 25.2 - 0.169^{**}t$	0.58	$\hat{Y} = \bar{Y} = 13.6$	-
7	$\hat{Y} = 25.6 - 0.215^{**}t$	0.70	$\hat{Y} = 7.0 + 0.135^{**}t - 0.002^{*} t^2$	0.93
8	$\hat{Y} = \bar{Y} = 20.2$	-	$\hat{Y} = \bar{Y} = 6.4$	-
9	$\hat{Y} = \bar{Y} = 8.9$	-	$\hat{Y} = \bar{Y} = 3.9$	-
10	$\hat{Y} = \bar{Y} = 14.3$	-	$\hat{Y} = \bar{Y} = 5.2$	-
11	$\hat{Y} = \bar{Y} = 17.4$	-	$\hat{Y} = \bar{Y} = 7.7$	-
12	$\hat{Y} = \bar{Y} = 14.3$	-	$\hat{Y} = \bar{Y} = 4.3$	-
13	$\hat{Y} = \bar{Y} = 13.4$	-	$\hat{Y} = 6.9 - 0.034^{\circ}t$	0.48
14	$\hat{Y} = 15.2 + 0.159t - 0.002^{*}t^2$	0.55	$\hat{Y} = \bar{Y} = 10.0$	-
15	$\hat{Y} = 26.1 + 0.215t - 0.004^{\circ}t^2$	0.59	$\hat{Y} = \bar{Y} = 7.4$	-
16	$\hat{Y} = 21.6 + 0.195^{\circ}t - 0.003^{**}t^2$	0.89	$\hat{Y} = \bar{Y} = 12.8$	-
17	$\hat{Y} = 15.6 + 0.287^{*}t - 0.004^{**}t^2$	0.70	$\hat{Y} = 4.4 + 0.231^{*}t - 0.003^{**}t^2$	0.61
18	$\hat{Y} = \bar{Y} = 23.3$	-	$\hat{Y} = \bar{Y} = 15.8$	-
19	$\hat{Y} = 18.5 - 0.083^{\circ}t$	0.93	$\hat{Y} = \bar{Y} = 5.0$	-

1/ Mg^{2+} level in $mmol_c\ dm^{-3}$; time in months

**, *, °, significant at 001, 005, and 010, respectively, as per the F test

between 32 to 53 months. In the 0–20-cm layer, the increase in Ca^{2+} levels, has been documented particularly in no-till farming (NTF) due to surface liming, where there is no soil disturbance (Caires et al., 2015; Crusciol et al., 2016; Fontoura et al., 2019; Crusciol et al., 2022). In NTF, the influence of plant residues on the dynamics of Ca^{2+} has also been observed through the formation of organometallic complexes, which can enhance the mobility of the nutrient (Miyazawa et al., 2002; Pavinato et al., 2017; Rheinheimer et al., 2018).

Several arguments could be presented that may act independently or in conjunction for the The lack of temporal variations in EAs that exhibited no in Ca^{2+} levels despite receiving lime and/or gypsum such as small doses of these inputs (Auler et al., 2019; Li et al., 2019) could be attributed to the following circumstances: concentration of Ca^{2+} from lime in the more superficial layers, thereby diluting the sample from the 0–20-cm layer (Hume et al., 2023); the loss of Ca^{2+} from gypsum through leaching to layers at depths greater than 0–20 cm (Araújo et al., 2016; Rusyanto et al., 2017) dynamic equilibrium in biogeochemical cycling due to natural nutrient inputs (mineralization from the large influx of organic matter from the removal of old cocoa trees and pruning of branches from trees in the cocoa-cabruca agroforestry system which, in some EAs, led to excessive shading); nutrient extraction by the crop (formation of new cocoa trees over the years, immobilizing nutrients in living plant biomass) and export through harvests (some EAs have exhibited yields exceeding 3,000 kg ha^{-1} $year^{-1}$ of dried almonds in recent years) (Snoeck et al., 2016; Van Vliet and Giller, 2017).

In the 20–40-cm layer, the dynamics of Ca^{2+} appear to be linked to the application of gypsum on the surface, as all six EAs that exhibited a quadratic behavior (an increase followed by a decrease in Ca^{2+} levels over time) received gypsum. The application of gypsum has proven effective in increasing subsurface Ca^{2+} levels due to the formation of an ionic pair with SO_4^{2-} (Ramos et al., 2013). In contrast, Butterly et al. (2021) suggested that the presence of plant-derived organic ligands can influence the mobility of Ca^{2+} in the soil. Therefore, this possibility cannot be dismissed in this study, considering the high input of plant material in the EA resulting from the renewal of old cocoa crops. It should be noted that among the EAs that received gypsum, only in two of them (EA 5 and 8) there were no significant changes in Ca^{2+} levels over time in the 20–40-cm layer. This is likely due to the relatively low doses of gypsum used in these EAs, which were 0.73 and 0.60 t ha^{-1}, respectively (Auler et al., 2019). In this layer, for all EAs that did not receive gypsum, there was no significant variation in Ca^{2+} levels over time, indicating stability over a time frame of 87 months, except for EA 9, which exhibited a linear reduction in Ca^{2+} over time (Table 3), likely because it had the lowest surface Ca^{2+} level, which would allow plants to absorb Ca^{2+} from deeper subsoil layers.

In the 0–20 cm layer, among the 14 EAs that received lime, only three exhibited a quadratic trend of Mg^{2+} levels, with peak achieved between 29 to 40 months. In eight EAs, the Mg^{2+} level was not significantly affected over the months, indicating a balance between the nutrient

Table 4. Regression equations for K^+ levels over time[1] in two layers from soils cultivated with cocoa trees across 19 experimental areas (EAs) in Bahia, Brazil.

EAs	Layer 0–20 cm Equation	R^2	Layer 20–40 cm Equation	R^2
1	$\hat{Y} = \bar{Y} = 93.1$	-	$\hat{Y} = \bar{Y} = 55.7$	-
2	$\hat{Y} = \bar{Y} = 96.8$	-	$\hat{Y} = \bar{Y} = 81.7$	-
3	$\hat{Y} = 7.8 + 1.439^{**}t$	0.83	$\hat{Y} = - 1.6 + 0.818^{**}t$	0.83
4	$\hat{Y} = 56.0 + 3.530^{*}t - 0.035^{**}t^2$	0.91	$\hat{Y} = 29.5 + 0.584^{\circ}t$	0.88
5	$\hat{Y} = \bar{Y} = 94.3$	-	$\hat{Y} = \bar{Y} = 53.1$	-
6	$\hat{Y} = \bar{Y} = 111.5$	-	$\hat{Y} = \bar{Y} = 64.8$	-
7	$\hat{Y} = \bar{Y} = 52.8$	-	$\hat{Y} = \bar{Y} = 23.8$	-
8	$\hat{Y} = \bar{Y} = 33.0$	-	$\hat{Y} = \bar{Y} = 8.9$	-
9	$\hat{Y} = 13.3 + 0.568^{**}t$	0.87	$\hat{Y} = \bar{Y} = 29.2$	-
10	$\hat{Y} = 192.5 - 1.425^{**}t$	0.77	$\hat{Y} = \bar{Y} = 57.3$	-
11	$\hat{Y} = \bar{Y} = 100.1$	-	$\hat{Y} = \bar{Y} = 45.4$	-
12	$\hat{Y} = 9.5 + 0.845^{**}t$	0.97	$\hat{Y} = - 7.6 + 0.594^{**}t$	0.89
13	$\hat{Y} = 13.9 + 0.878^{**}t$	0.97	$\hat{Y} = \bar{Y} = 32.1$	-
14	$\hat{Y} = 21.9 + 2.367^{*}t - 0.029^{**}t^2$	0.94	$\hat{Y} = \bar{Y} = 21.2$	-
15	$\hat{Y} = \bar{Y} = 70.4$	-	$\hat{Y} = \bar{Y} = 32.7$	-
16	$\hat{Y} = 80.2 + 4.458^{**}t - 0.049^{**}t^2$	0.96	$\hat{Y} = \bar{Y} = 83.9$	-
17	$\hat{Y} = 36.1 + 2.611^{*}t - 0.029^{*}t^2$	0.92	$\hat{Y} = 10.7 + 1.158^{*}t - 0.012^{*}t^2$	0.75
18	$\hat{Y} = 49.6 + 2.199t - 0.026^{\circ}t^2$	0.88	$\hat{Y} = \bar{Y} = 28.6$	-
19	$\hat{Y} = \bar{Y} = 64.8$	-	$\hat{Y} = \bar{Y} = 33.6$	-

1/ K^+ level in mg dm^{-3}; time in months
**, *, °, significant at 001, 005, and 010, respectively, as per the F test

supplied by the lime and its absorption by plants. In three EAs, the Mg^{2+} level decreased over time, suggesting that plant absorption exceeded the supply from the lime. Particularly, for EA 3, the decrease in Mg^{2+} levels in the surface layer may also have been affected by a higher dose of gypsum, which could have contributed to the leaching of Mg^{2+} to subsurface layers (Alves et al., 2021; Tiecher et al., 2019; Vicensi et al., 2020). The Mg^{2+} content may result from the mineralization of organic matter from the removal of old cocoa trees and the pruning of shade tree branches. It would help to explain the initial increases in Mg^{2+} levels in the three EAs that received lime (Agbotui et al., 2024; Asigbaase et al., 2021), as well as in EA 14 and 16, which did not receive lime. In these latter EAs, the peak Mg^{2+} occurred at around 34 months. The lack of significant variation in Mg^{2+} was also observed in two of the five EAs that did not receive lime.

In the 20–40-cm layer, the quadratic behavior of Mg^{2+} levels were observed only in the EA that received gypsum. This indicates that the gypsum applied to the surface promoted the leaching of Mg^{2+} to the subsurface layer, with peak concentrations that were achieved between 29 and 47 months. Changes in subsurface levels of Mg^{2+} are reported in studies involving the surface application of gypsum, due to the formation of an ionic pair with SO_4^{2-} which imparts mobility to the cation in the soil profile (Bossolani et al., 2020; Vicensi et al., 2020). This growth in subsurface Mg^{2+} levels allowed the expansion of the soil volume by the root system, leading to improved water and nutrient uptake (Bossolani et al., 2022). For cocoa cultivation, this fact is highly significant, as the species is considered demanding in Mg^{2+} (Souza Júnior et al., 2018).

In the 20–40-cm layer, among 10 EAs that did not receive gypsum and two that did, there was no significant change in Mg^{2+} levels over time. Only in EA 13 the Mg^{2+} level decrease linearly over time, possibly because this EA had a low surface level of Mg^{2+}, requiring plants to absorb Mg^{2+} from deeper subsurface layers.

Variation in K^+ levels

Although lime and gypsum are not sources of K^+, these inputs can affect the dynamics of this nutrient in soils, either by increasing the CEC of the soil through lime, which enhances K^+ retention, or by enhancing K^+ leaching, facilitated by the addition of Ca^{2+} and Mg^{2+} from lime and, particularly, by the addition of Ca^{2+} and SO_4^{2-} from gypsum (Fageria and Knupp, 2014). It should be noted that the EAs were fertilized with K^+, with the doses determined based on the planting age, expected productivity, and the most recent soil analyses for each EA, following the criteria suggested by Souza Júnior et al. (2018). The four factors that most profoundly influenced the temporal variations of K^+ were: specific potassium fertilizations for each EA, natural K^+ input through the mineralization of organic matter from the thinning of old cocoa trees and pruning of shade tree branches (Asigbaase et al., 2021), K^+ extraction for the formation of new cocoa trees, and K^+ export through harvests (Kone et al., 2020). It is noteworthy that K^+ is the mineral nutrient that accumulates the most in the plant biomass of the cocoa tree, as well as in the cocoa itself (Anokye et al., 2021; Souza Júnior et al., 2018).

Table 5. Regression equations for the sum of bases (SB) over time1/ in two layers from soils cultivated with cocoa trees across 19 experimental areas (EAs) in Bahia, Brazil.

EAs	Layer			
	--------------- 0–20 cm ---------------		--------------- 20–40 cm ---------------	
	Equation	R^2	Equation	R^2
1	$\hat{Y} = \bar{Y} = 49.6$	-	$\hat{Y} = 8.9 + 0.580^{\circ}t - 0.006^{*}t^2$	0.81
2	$\hat{Y} = \bar{Y} = 103.2$	-	$\hat{Y} = \bar{Y} = 85.6$	-
3	$\hat{Y} = 45.4 + 0.604^{*}t - 0.009^{**}t^2$	0.96	$\hat{Y} = 5.9 + 0.623^{**}t - 0.007^{**}t^2$	0.97
4	$\hat{Y} = 48.7 + 1.084^{*}t - 0.013^{**}t^2$	0.84	$\hat{Y} = 11.3 + 0.989^{**}t - 0.011^{**}t^2$	0.95
5	$\hat{Y} = \bar{Y} = 54.5$	-	$\hat{Y} = \bar{Y} = 25.1$	-
6	$\hat{Y} = \bar{Y} = 50.2$	-	$\hat{Y} = \bar{Y} = 38.7$	-
7	$\hat{Y} = 48.6 + 0.571^{*}t - 0.010^{**}t^2$	0.93	$\hat{Y} = 18.7 + 0.482^{*}t - 0.007^{**}t^2$	0.84
8	$\hat{Y} = \bar{Y} = 55.9$	-	$\hat{Y} = \bar{Y} = 15.7$	-
9	$\hat{Y} = \bar{Y} = 28.2$	-	$\hat{Y} = \bar{Y} = 10.4$	-
10	$\hat{Y} = \bar{Y} = 48.0$	-	$\hat{Y} = \bar{Y} = 18.3$	-
11	$\hat{Y} = 63.2 + 0.871^{\circ}t - 0.011^{*}t^2$	0.61	$\hat{Y} = \bar{Y} = 26.6$	-
12	$\hat{Y} = \bar{Y} = 43.3$	-	$\hat{Y} = 11.2 + 0.151t - 0.002^{\circ 2}$	0.98
13	$\hat{Y} = \bar{Y} = 48.4$	-	$\hat{Y} = \bar{Y} = 16.5$	-
14	$\hat{Y} = 50.2 + 0.928^{\circ}t - 0.013^{*}t^2$	0.68	$\hat{Y} = \bar{Y} = 30.9$	-
15	$\hat{Y} = 61.5 + 0.650t - 0.010^{*}t^2$	0.61	$\hat{Y} = \bar{Y} = 19.2$	-
16	$\hat{Y} = 61.7 + 1.088^{**}t - 0.015^{**}t^2$	0.91	$\hat{Y} = \bar{Y} = 37.2$	-
17	$\hat{Y} = 45.2 + 1.141^{*}t - 0.014^{*}$	0.50	$\hat{Y} = 10.7 + 0.907^{*}t - 0.010^{**}t^2$	0.54
18	$\hat{Y} = \bar{Y} = 59.8$	-	$\hat{Y} = \bar{Y} = 30.7$	-
19	$\hat{Y} = 55.74 - 0.235^{*}t$	0.76	$\hat{Y} = \bar{Y} = 15.8$	-

1/ Sum of bases in $mmol_c\ dm^{-3}$; time in months.

**, *, °, significant at 001, 005, and 010, respectively, as per the F test.

K^+ in the 0–20-cm layer exhibited distinct behaviors over time among the 19 studied EAs due to the presented factors. In nine EAs, there was no significant variation in K^+ levels, indicating a balance between the intake and output of the nutrient (Hafizal et al., 2023). In five EAs, quadratic behavior was observed, which can be comprehended by the initial increase in K^+ due to the addition of K^+ through fertilization and the mineralization of biomass from the crop renewal process (Agbotui et al., 2024). This was followed by a subsequent decrease in K^+ levels caused by the extraction and export of K. It is noteworthy that in many EAs, productivity in recent years has surpassed 3,000 kg ha^{-1} $year^{-1}$, with some reaching close to 5,000 kg ha^{-1} of dried cocoa beans. In four EAs, a positive linear trend was observed, with coefficients ranging from +0.568 to +1.439 (Table 4). These coefficients correspond to annual increases of 6.8 to 17.3 mg dm^{-3} of K^+. These EAs initially had the lowest soil K^+ levels and consequently received the highest annual K_2O doses, which in recent years ranged from 280 to 320 kg ha^{-1} $year^{-1}$. In contrast, there was a negative linear trend only in EA 10 with a coefficient of -1.425 (Table 4). This indicates an annual decrease of 17.1 mg dm^{-3} of K^+. This EA received lower K_2O applications of just 40 kg ha^{-1} $year^{-1}$ in recent years due to initially very high soil K^+ levels in the early years of the experiment.

In the 20–40 cm layer, K^+ levels remained highly stable over time, as 15 EAs showed no significant fluctuations throughout the 87-month study. Despite this stability, average K^+ levels varied widely among these EAs, ranging from 8.9 to 83.9 mg dm^{-3} (Table 4). In three EAs, a positive linear trend was observed, with regression model coefficients indicating estimated annual increases in K^+ ranging from 7.0 to 9.8 mg dm^{-3}. It is essential to note that these three EAs received the highest gypsum doses, varying from 1.96 to 2.69 t ha^{-1} (Table 1), suggesting that gypsum may have enabled the translocation of K^+ from the surface to the subsurface layer (Moraes et al., 2016). Only in one EA, there was a quadratic behavior observed for the K^+ level over time, after the application of 1.06 ha^{-1} of gypsum.

Variation in sum of bases and bases saturation

The sum of bases is mainly dependent on the Ca^{2+} and Mg^{2+} levels, which represented more than 95% of variation in both layers (de Almeida et al., 2018). Hence, sum of bases tends to be an intermediate behavior between these two nutrients. This is similar to what was observed for Ca^{2+} and Mg^{2+}, in which there was predominantly no change in sum of bases over time, either due to the absence of lime and/or gypsum application or because the doses were small (Fageria and Knupp, 2014).

However, in the 0–20-cm and 20–40-cm layers there were differences in the sum of bases in nine and six EAs due to the previously discussed reasons for Ca^{2+} and Mg^{2+}. These variations primarily exhibited quadratic models, indicating that the estimated maximum sum of bases occurred between 28 to 41 months for the 0–20-cm layer and between 34 to 48 months for the 20–40-cm layer, following the application of inputs. It should be noted that for the subsurface layer, all six EAs that exhibited variations in sum of bases values received gypsum which causes cation mobility in soil profile (Rampim and Lana, 2015; Tiecher et al., 2019).

Table 6. Regression equations for base saturation (V) over time[1/] across two layers from soils cultivated with cocoa trees in 19 experimental areas (EAs) in the state of Bahia, Brazil.

EAs	Layer			
	---------------- 0–20 cm ----------------		---------------- 20–40 cm ----------------	
	Equation	R^2	Equation	R^2
1	$\hat{Y} = 45.1 + 0.682t - 0.008^{\circ}t^2$	0.93	$\hat{Y} = 17.8 + 0.855t - 0.009^{\circ}t^2$	0.65
2	$\hat{Y} = \bar{Y} = 81.2$	-	$\hat{Y} = \bar{Y} = 80.7$	-
3	$\hat{Y} = 47.8 + 0.185t - 0.004^{\circ}t^2$	0.95	$\hat{Y} = 12.7 + 0.797^{**}t - 0.009^{**}t^2$	0.89
4	$\hat{Y} = 51.0 + 0.528^{*}t - 0.007^{**}t^2$	0.84	$\hat{Y} = 15.6 + 1.022^{**}t - 0.011^{**}t^2$	0.98
5	$\hat{Y} = \bar{Y} = 67.4$	-	$\hat{Y} = \bar{Y} = 48.7$	-
6	$\hat{Y} = \bar{Y} = 60.3$	-	$\hat{Y} = \bar{Y} = 60.6$	-
7	$\hat{Y} = 40.8 + 0.489^{*}t - 0.008^{**}t^2$	0.81	$\hat{Y} = 19.5 + 0.616^{**}t - 0.009^{**}t^2$	0.99
8	$\hat{Y} = \bar{Y} = 59.2$	-	$\hat{Y} = \bar{Y} = 28.3$	-
9	$\hat{Y} = \bar{Y} = 33.0$	-	$\hat{Y} = \bar{Y} = 19.1$	-
10	$\hat{Y} = \bar{Y} = 42.3$	-	$\hat{Y} = \bar{Y} = 23.2$	-
11	$\hat{Y} = \bar{Y} = 61.1$	-	$\hat{Y} = \bar{Y} = 39.3$	-
12	$\hat{Y} = 32.6 + 0.469^{*}t - 0.004\ t^2$	0.86	$\hat{Y} = 15.4 + 0.287^{\circ}t - 0.003^{*}t^2$	0.85
13	$\hat{Y} = \bar{Y} = 46.9$	-	$\hat{Y} = \bar{Y} = 25.7$	-
14	$\hat{Y} = \bar{Y} = 80.4$	-	$\hat{Y} = \bar{Y} = 72.3$	-
15	$\hat{Y} = \bar{Y} = 51.2$	-	$\hat{Y} = \bar{Y} = 27.2$	-
16	$\hat{Y} = 85.1 - 0.166^{\circ}t$	0.60	$\hat{Y} = \bar{Y} = 58.2$	-
17	$\hat{Y} = \bar{Y} = 49.3$	-	$\hat{Y} = 13.4 + 0.915^{*}t - 0.01^{**}t^2$	0.52
18	$\hat{Y} = \bar{Y} = 56.6$	-	$\hat{Y} = \bar{Y} = 43.2$	-
19	$\hat{Y} = \bar{Y} = 53.3$	-	$\hat{Y} = \bar{Y} = 33.2$	-

1/ Base saturation (V) in %; time in months

**, *, °, significant at 001, 005, and 010, respectively, as per the F test

In turn, base saturation is a variable dependent on the sum of bases, as it also accounts for acidic cations ($H + Al^{3+}$), with its value expressed as a percentage. This helps in understanding why, in some cases at 0–20-cm layer, there was no correlation between the behaviors of sum of bases and base saturation. In turn, in the 20–40-cm layer, the behavior of both variables was the same across all 19 studied EAs, with 14 EAs exhibiting no significant variation over time in sum of bases and base saturation, and five EAs exhibiting significant quadratic models; the latter received gypsum.

Materials and methods

Data collection

Nineteen experimental areas (EAs) located in 15 municipalities across the humid and humid-to-sub-humid climate zones of southeastern Bahia, Brazil (SEI-BA, 2022), were sampled with 20 individual samples collected per composite sample (Figure 1). The initial analyses of the 0–20 cm and 20–40 cm layers were used to calculate the lime and gypsum rates (Table 1). The assessment time was 87 months, starting from month zero (T0), which was when lime and gypsum were applied, followed by subsequent sampling at the 40, 52, 72, and 87 months after inputs application. During these four periods, samples were collected from the 0–10 cm, 10–20cm, and 20–4 -cm layers, with the values for the 0–20-cm layer derived by averaging those from the 0–10 cm and 10–20 cm layers. In T40, two composite samples were collected by EA; in T52, T72, and T87, six composite samples were collected by EA.

Soil attributes analyzed

The following attributes were analyzed: pH in H_2O; Al^{3+}, Ca^{2+}, and Mg^{2+} extracted using 1.0 mol L^{-1} KCl; K^+ extracted using Mehlich^{-1}; potential acidity (H+Al) extracted using 0.5 mol L^{-1} Ca $(CH_3COO)_2$; organic matter determined using the Walkley-Black method; and remaining phosphorus (P-rem) obtained by shaking 60 mg L^{-1} of P in a 0.01 mol L^{-1} $CaCl_2$ solution (Teixeira et al., 2017). The sum of bases (SB) and base saturation (V%) was calculated according to basic cations levels. The sand, silt, and clay levels were determined following the methods described by Teixeira et al. (2017).

Lime and gypsum rates calculation

The lime rates were determined using the base saturation method – V% (Equation 1). The goal was to increase the V% to 75% in EA as it was below 65% in the 0–20-cm soil layer. For this purpose, we considered a reaction depth (p) of 5 cm and an RNV of the amendment of 90%.

$$LR = \frac{(V_2 - V_1) \times T}{10 \times RNV} \times \frac{p}{20} \quad \text{(Equation 1)}$$

In which:

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

V_2 = desired base saturation, 75%;

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

T = cation exchange capacity (CEC) at pH 7.0, in $mmol_c$ dm^{-3};

RNV = Relative Neutralizing Value, 90%;

p = lime reaction depth, 5 cm.

The gypsum doses were calculated based on the stoichiometric equation proposed by Souza Júnior et al.

(2018) (Equation 2). The goal was to reduce the Al^{3+} saturation (m%) to 20% in the EA, where it exceeded 20%. The layer thickness (LT) was considered to be 30 cm and the percentage of Ca^{2+} in the gypsum ($\%Ca_{gyp}$) was 16%.

$$GR = \left[Al^{3+} - \left(\frac{m_t \times t}{100}\right)\right] \times \frac{0.2 \times LT}{\%Ca_{gyp}} \quad \text{(Equation 2)}$$

In which:
GR = gypsum rate, in tons per hectare (t^{ha-1});
Al^{3+} = Al^{3+} level in the 20–40 cm layer, in $mmol_c\ dm^{-3}$;
m_t = saturation of Al^{3+} tolerable by the 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 the gypsum, 16%.

Lime and gypsum application method

The lime and gypsum doses (Table 1) were converted into grams per plant and manually applied by broadcasting, covering the entire soil surface. Lime and gypsum were not mixed into the soil. However, the organic mulch was tilled using a leaf blower to speed up the contact of the inputs with the soil surface.

Fertilization program for the EAs

The initial fertilization process involved applying 500 mg dm^{-3} of P (120 grams of single superphosphate), 130 mg dm^{-3} of K (5 g of potassium chloride), 40 g of dolomitic lime as a source of Ca and Mg, and 2 dm^3 of poultry litter. For the formative fertilization in the first and second years, 500 and 800 g of the NPK 16-16-16 fertilizer were applied to the soil surface, respectively, divided into four annual installments for all EAs. The canopy projection of the cacao trees was used as a reference for the application.

Production fertilization commenced in the third year and was tailored to each EA based on the respective soil analyses. For N, P, and K, the doses were based on the propositions by Souza Júnior et al. (2018). The doses were divided into four annual installments, using urea, monoammonium phosphate or triple superphosphate, and potassium chloride as sources.

Micronutrients were applied in a single annual dose based on the respective soil analyses of each EA, when needed. Doses used were: 1.0 kg ha^{-1} of B (for areas with a B content in the soil less than 0.7 mg dm^{-3}); 2.0 kg ha^{-1} of Cu (for areas with a Cu content in the soil less than 0.7 mg dm^{-3}) and 2.5 or 5.0 kg ha^{-1} of Zn (for areas with a Zn content in the soil between 3.5 and 5.0 mg dm^{-3} or less than 3.5 mg dm^{-3} of Zn, respectively). The sources used were boric acid and copper and zinc sulfates.

Statistical analysis

The results of the soil chemical attributes were submitted to analysis of variance (ANOVA), performed for each experimental area, given the non-homogeneity of the residual variance between the areas, evaluated based on the quotient of the largest by the smallest mean square of the residue being greater than 7.0, as recommended by Gomes and Garcia (2002) and Pimentel Gomes (2009), for agronomic experiments. This limit is a relaxation of Box's original proposal in relation to the value 4.0. Subsequently, a regression analysis of the soil chemical attributes was performed as a function of the time elapsed after the application of the inputs. The models tested were simple linear and quadratic, and the model that presented significant coefficients at up to 1%, 5% and 10% probability was accepted by the F test, using the mean square of the residue of each ANOVA, and the highest value of the coefficient of determination (R2).

Conclusions

In most EAs, the surface application of lime without soil mixing did not change the levels of Ca^{2+} and Mg^{2+} and, consequently, the base sum and saturation in the 0–20-cm soil layer. Nevertheless, in most EAs, the surface application of gypsum without soil mixing increased the Ca^{2+} levels in both soil layers. Additionally, it led to an increase in the Mg^{2+} and K^+ levels in the 20–40-cm layer. Variations in K^+ levels were primarily associated with potassium fertilization.

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Statement of contributions

All the authors contributed to the conception and design of the study. Conceptualization, statistical analysis, methodology, and writing original draft were performed by AO. Conceptualization, data acuration, methodology, supervisor, writing review were performed by JS and JN. JS was responsible for writing the review. DH was responsible for founding acquisition and writing review. All authors commented on the previous versions of the manuscript. All authors have read and approved the final manuscript.

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