

Soil acidification in cocoa (*Theobroma cacao*) agrosystems in Côte d'Ivoire: Insights into throughfall and soil solution chemistry responses to soil carbonate amendment

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Abstract

In former cocoa-producing regions of Côte d'Ivoire, Cocoa (*Theobroma cacao* L.) farming exacerbates soil acidification due to prolonged monoculture, nitrogen fertilization and leaching losses, posing a threat to long-term productivity and sustainability. This study evaluated the effectiveness of carbonate amendments (dolomite ($\text{CaMg}(\text{CO}_3)_2$) and quick lime (CaO)), in restoring soil chemical fertility across four cocoa plantations on Ferralsols ($\text{pH} < 5.0$).

Amendments were applied at rates of 3 t. ha^{-1} over three years. Solution collection devices were strategically installed using porous PTFE suction cups at -20 cm and -40 cm depths in pits for soil solution, and funnel collectors at 1 m above the soil surface for throughfall. Sampling occurred fortnightly during the rainy season and rainfall collected within 24 hours after each rainy event from the second-year post-amendment. Chemical analyses of these solutions included pH, cations (Ca, Mg, K, Na, Fe, Al), and dissolved phosphorus.

Results revealed marked soil solution alkalization (pH increase of 1 to 2 units at -20 cm), boosting exchangeable base cations up to 10-fold and phosphorus availability (total soluble P). Throughfall chemistry mirrored these improvements, with nutrient-enriched rainfall (e.g., K^+ concentrations doubled), highlighting the role of cocoa trees canopy in nutrient recycling and return to the soil. Additionally, dissolved phosphorus is strongly correlated with Al and Fe release in the soil solution, suggesting solubilization of Al-Fe oxide. This approach offers a cost-effective, scalable strategy for mitigating acidification in tropical agroecosystems, enhancing cocoa resilience amid climate variability.

INTRODUCTION

The degradation of agricultural land is a growing global concern, particularly in Africa. While two hectares of arable land per capita were available in 1900, this figure fell to just 0.50 hectares worldwide by 2010 (Zhao et al., 2025), primarily due to human activities (Clément, 2020). Agricultural intensification has intensified environmental issues, including deforestation, erosion, desertification, biodiversity loss, water contamination, and climate change (Pereira et al., 2025). Soils are increasingly affected by physical and chemical degradation, exacerbated by intensive fertilization, pesticide use, and toxic waste disposal.

Côte d'Ivoire is the world's leader in cocoa production, contributing 42% of global output. However, this success comes at an environmental cost. Since the 1960s, cocoa production has relied heavily on deforestation (Kalischek et al., 2023). Over the past two decades, more than 80% of the country's forest cover, approximately 10 million hectares, has been cleared for cocoa cultivation (Gbocho and Ourega, 2021). The political crisis of the 2000s further accelerated forest loss through illegal occupation of protected areas (Sidibé et al. 2020; Bavier et al. 2021). In the south-eastern region, the main cocoa-producing area, deforestation is accompanied by severe soil degradation, notably acidification, which threatens plantation sustainability.

In this country, cocoa plantations are often established on highly weathered soils that are naturally acidic and poor in exchangeable bases. Under long-term cocoa cultivation, acidification can be intensified by nutrient uptake, leaching under heavy rainfall, decomposition of organic residues, and the repeated use of acidifying fertilizers. Soil acidification, although less studied in tropical cocoa systems compared to temperate regions, is a key factor limiting soil fertility in tropical regions. In Côte d'Ivoire, agricultural practices are the main contributors (Bolou-Bi et al. 2023a; Kouassi et al. 2024). The removal of crop biomass disrupts the soil ionic balance, generating excess protons (H^+) that lower pH values. Additionally (Bolou-Bi et al. 2023a; Kouassi et al. 2024; Getachew et al. 2021), the application of acidifying mineral fertilizers, particularly nitrogen and phosphate fertilizers, exacerbates soil acidification (Wang et al., 2020).

Acidification significantly affects soil function. Protons bind to the clay-humus complex, displacing essential cations, which accumulate in the soil solution and are prone to leaching (Zhu et al., 2025). In tropical soils, acidic conditions mobilize aluminum-containing minerals, increasing Al^{3+} availability while immobilizing phosphorus, a critical nutrient. Elevated Al^{3+} concentrations can also be toxic to cocoa trees, limiting root growth and nutrient uptake (Pradhan et al., 2023).

Counteracting soil acidification is crucial for sustainable cocoa production. Thus, it has been demonstrated in some agrosystems that carbonate amendments such as lime or dolomite are considered an effective management option for correcting soil acidity and restoring chemical fertility. The main chemical effect of carbonate application is the neutralization of soil acidity through the consumption of hydrogen ions, which leads to an increase in soil pH (e.g. Antonangelo et al., 2022). In cocoa soils, this pH correction is important because it reduces aluminum toxicity, decreases the solubility of harmful acidic cations, and improves root development. A higher pH also enhances the availability of calcium and magnesium, two nutrients that are essential for cocoa growth, pod formation, and overall tree vigor.

Carbonate amendments also improve the balance of exchangeable cations in the soil (Lato et al., 2025). By supplying calcium and magnesium and replacing hydrogen and aluminum on the exchange complex, liming increases base saturation and improves the chemical environment of the rhizosphere. This is particularly important in cocoa agroecosystems, where nutrient depletion is common and fertilizer efficiency may be constrained by strong acidity. Under improved pH conditions, phosphorus availability may also increase because fixation by iron and aluminum oxides is reduced.

Although carbonate amendments have been widely studied in temperate and boreal forests (court et al., 2018), their effects on soil solution chemistry, throughfall, and cocoa nutrition remain poorly resolved in tropical agroecosystems. This limitation is important because soil and canopy processes are tightly coupled in unfertilized cocoa plantations, such that changes in soil chemistry may alter nutrient cycling across the whole system. Understanding these interactions is essential for developing more effective and sustainable fertility management strategies in cocoa-based systems.

Here, we assess how carbonate amendments affect soil acidification, nutrient dynamics, and cocoa tree nutrition, with particular attention to links between throughfall chemistry and soil fertility. We hypothesize that carbonate application increases soil solution pH, enhances nutrient availability, and alters the cycling of Ca^{2+} and Mg^{2+} within the cocoa system, partly through changes in Fe^{2+} and Al^{3+} availability. To test this hypothesis, we collected and analyzed soil solution and rainfall samples one year after carbonate amendment in cocoa plantations in south-eastern Côte d'Ivoire. This study provides new insight into the chemical and biological consequences of carbonate amendment in tropical perennial cropping systems.

MATERIALS AND METHODS

Site description

This study was conducted in cocoa plantations in the Aboisso area, located 116 km from Abidjan and 60 km from the Ghanaian border in southeastern Côte d'Ivoire, between longitudes 4°38' and 2°40'W and latitudes 5°05' and 5°48'N (Fig. 1). Soils in this region are ferralsol, typically acidic and nutrient-poor, with pH values ranging from 4 to 5.

This study was carried out in four plantations located in Béniankré, Eholié, N'zikro, and Yaou (Fig. 1). These sites were selected based on the results of an initial soil fertility assessment. The selected plantations are among the oldest, with an average age of 30 years and annual yields ranging between 260 and 600 kg/ha.

Solution collection, treatment and analysis

In each plantation, two contiguous 0.5-hectare plots were selected for the experiment. One plot was treated with a mixture of agricultural quicklime and dolomite (3 t ha^{-1} over three years), while the second plot remained untreated as a control.

Prior to the installation of the experimental plot, nine soil samples were obtained at different depths (0–20 cm, 20–40 cm, and 40–60 cm) in each site to assess the initial acidity levels of the soil. In the experimental plots, porous PTFE suction cups were installed only at -20 cm and -40 cm depths in three pits per plot to collect soil solutions. Rainfall was sampled under the cocoa canopy using funnel collectors positioned 1 m above the ground. Solution samples were collected from the second-year post-amendment, with soil solutions extracted fortnightly during the rainy season and rainfall collected within 24 hours after each rainy event. Samples were filtered in the laboratory and stored at 4°C until analysis.

Chemical analyses focused on pH and major element concentrations (Ca, Mg, K, Na, Fe, Al, and P). Major elements were quantified using inductively coupled plasma-atomic emission spectrometry (ICP-AES) at INRAE Nancy (France), with calibration tailored to environmental sample conditions and analytical validation using internal reference standards (1 per 20 samples).

Statistical Analysis

Laboratory data were recorded, coded and statistically analyzed using JMP software. Data were analyzed using a factorial ANOVA with site included as a blocking factor. Significant effects were further explored using Tukey’s HSD post hoc test.

RESULTS

Overall initial soil acidity

At all depths, the initial soil pH showed little variation throughout the soil profile, with coefficients of variation less than 10% (Table 1).

Table 1
Descriptive statistics of soil pH across depth intervals, including modal frequency and distribution shape indicators from all soil samples collected at the four studied sites.

Depth (cm)	n	Mean pH	Median	Min	Max	SD	CV (%)	Modal class	Modal frequency (%)
0–20	36	5.07	4.99	4.62	5.69	0.34	6.80	4.5-5.0	47.20
20–40	36	4.88	4.85	4.53	5.37	0.25	5.09	4.5-5.0	69.40
40–60	36	4.92	4.86	4.02	5.62	0.38	7.77	4.5-5.0	41.70

Mean pH values indicated moderately acidic conditions (Fig. 1). Median values were close to the means, suggesting approximately symmetrical distributions. Slightly greater variability was observed in the deeper layer (40–60 cm) (Table 1). The dominant modal class (4.5-5.0) was consistent across all depths. This pattern confirms a unimodal distribution centered within a moderately acidic pH range, with a particularly high concentration of values in the intermediate depth.

Taking into account the sampling location, statistic data revealed significant effects of site ($F = 5.35, p < 0.01$) and depth ($F = 4.51, p < 0.05$) on soil pH values. A highly significant interaction between site and depth was observed ($F = 7.09, p < 0.001$), indicating that the variation of soil pH with depth differed among sites.

Effect of the carbonate amendment on soil acidity

Table 2 shows changes in soil pH three years after the application of the calcomagnesium amendment per site. Soil pH varied significantly between sites and years following amendment, with a clear temporal increase observed at all locations (Table 2). This increase, however, differed among sites, reflecting significant site × year interaction.

Table 2
Changes in soil pH across sites and years following amendment.

Sites	Year after amendment				Δ pH	Change (%)
	0	1	2	3		
Yaou	5,55 $\pm$ 0,17 ^d	5,90 $\pm$ 0,21 ^c	5,20 $\pm$ 0,07 ^a	6,42 $\pm$ 0,11 ^a	0.87 $\pm$ 0.20	+ 15.7%
Béniankré	4,18 $\pm$ 0,03 ^a	4,50 $\pm$ 0,19 ^a	6,35 $\pm$ 0,23 ^c	6,90 $\pm$ 0,13 ^b	2.72 $\pm$ 0.13	+ 65.1%
N'zikro	4,73 $\pm$ 0,06 ^b	5,03 $\pm$ 0,14 ^b	6,27 $\pm$ 0,14 ^c	6,58 $\pm$ 0,21 ^{ab}	1.85 $\pm$ 0.22	+ 39.1%
Eholié	5,18 $\pm$ 0,02 ^c	5,10 $\pm$ 0,06 ^b	5,69 $\pm$ 0,07 ^b	7,00 $\pm$ 0,09 ^b	1.82 $\pm$ 0.09	+ 35.1%
Mean $\pm$ SD	-	-	-	-	1.82 $\pm$ 0.76	-

Values are means $\pm$ standard deviation (SD) (n = 9). Different letters within the same row indicate significant differences among sites at $p < 0.05$ according to Tukey's HSD test. The data were analyzed using a factorial mixed-effects ANOVA with site, year, and their interaction as fixed effects and replicate as a random effect. The difference in pH (Δ pH) corresponds to the change between Year 3 and Year 0. Percentage change (%) represents the relative variation in pH over the same period.

At initial stage (year 0), soil pH differed significantly among all sites, ranging from strongly acidic conditions at Béniankré to moderately acidic conditions at Yaou. N'zikro and Eholié exhibited intermediate values, indicating substantial spatial heterogeneity in initial soil acidity. During the first year after amendment (year 1), pH increased slightly at most sites, although Béniankré remained significantly more acidic than the others. A partial convergence was observed, as N'zikro and Eholié no longer differed significantly. From Year 2 after amendment, an increase in soil pH was recorded across all sites. This increase was particularly pronounced at Béniankré and N'zikro, which reached similar pH and became significantly higher than Yaou. In contrast, Eholié showed a more moderate increase during this stage. By year 3, soil pH values approached near-neutral conditions at all sites. Eholié and Béniankré exhibited the highest values and did not differ significantly, whereas N'zikro showed intermediate values and Yaou remained significantly lower. These results indicate a progressive reduction in inter-site variability over time. The overall increase in soil pH between initial state and year 3 averaged 1.82 ± 0.76 across sites, with the largest change observed at Béniankré ($+ 2.72 \pm 0.13$), while Yaou showed a smaller increase ($+ 0.87 \pm 0.20$). This pattern suggests that initially more acidic soils exhibited a stronger response to amendment, contributing to the convergence of soil chemical conditions across sites.

Effect of the carbonate amendment on soil solutions

The average cation content of the solutions in untreated plots varied across sites (Table 3). Aluminum, calcium, potassium and magnesium exceeded $1 \mu\text{g.mL}^{-1}$, while sodium, phosphorus (P) and iron (Fe)

were generally below 1 $\mu\text{g.mL}^{-1}$. In general, cation and total dissolved phosphorus concentrations in soil solutions increased with depth, except for calcium at Eholié, where surface values were higher.

Table 3
Chemical composition of soil solution in untreated plots

	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	P_t	Fe^{2+}	Al^{3+}
($\mu\text{g.mL}^{-1}$)							
Eholié -20 cm	8.50	2.01	3.17	1.66	0.06	0.36	2.17
Eholié -40 cm	2.52	0.48	1.41	1.08	0.03	0.40	0.34
Yaou – 20 cm	1.02	0.43	2.15	0.62	0.09	0.45	7.10
Yaou – 40 cm	10.79	2.43	10.90	1.27	0.38	0.89	104.85
Béniankré -20 cm	2.96	0.45	0.54	1.41	0.02	0.24	0.16
Beniankré -40 cm	4.81	0.47	0.91	0.70	0.02	0.50	0.99
N'zikro – 20 cm	9.34	1.32	2.51	0.48	0.20	0.69	18.23
N'zikro – 40 cm	9.66	1.56	2.05	0.56	0.35	0.67	40.81
Min	1.02	0.43	0.54	0.48	0.02	0.24	0.16
Max	10.79	2.43	10.90	1.66	0.38	0.89	104.85
Average	6.20	1.14	2.95	0.97	0.14	0.52	21.83
Deviation	3.80	0.80	3.32	0.44	0.15	0.21	36.32

The levels of soluble bases in the soil solution, measured two and three years after the amendment, are presented in Figs. 3 and 4, respectively. The results show an increase in soluble base content in soil solutions following the amendment. Calcium is the predominant cation in soil solutions, followed by potassium (Fig. 3). Magnesium and sodium are the least abundant. In this first sampling campaign, the highest concentrations of base cations were observed in the surface horizons (-20 cm).

During the second sampling campaign, the data revealed a clear a migration of cations within the soil. As shown in Fig. 4, all cation levels in the soil solutions increased by 1 to 20-fold compared to the first campaign. In these solutions, calcium and potassium remain the dominant cations. Unlike the first campaign, cation concentrations are higher in the deeper horizons (-40 cm) (Fig. 4).

Effect of the carbonate amendment on rainfall composition

Throughfall is the portion rain that passes through the canopy before reaching the soil. Collecting throughfall provides valuable information on the recycling of cations by vegetation. The average base

cation content of the throughfall, measured two and three years after soil amendment, is presented in Fig. 5 and Fig. 6. Similar to soil solutions, Ca and K are the dominant cations. However, potassium is the most abundant cation in the throughfall. The data indicate that, from the first campaign onwards, base cation concentrations are 1 to 3 times higher in the throughfall of amended plots compared to unamended ones (Fig. 5).

In the second season, K and Ca were still the most abundant base cations in the throughfall. Throughfall from amended plots contained 1 to 4 times more soluble base cations than rainfall from unamended plots (Fig. 6). These results indicate the leaching of Ca, K and Mg via throughfall increased compared to the first campaign, while Na leaching remains similar.

Effect of the carbonate amendment on total dissolved phosphorus

Phosphorus is a critical nutrient for cocoa production. However, in acid soils, it is strongly adsorbed by Al, Fe, and Mn oxides and hydroxides. Figure 7 shows the relationship between phosphorus (P), aluminum (Al), and iron (Fe) in soil solutions. Results of the first campaign, conducted two years after amendment, reveal a correlation between the amounts Al and Fe released into the soil solutions and the total dissolved phosphorus, with correlation coefficients estimated at 0.88 and 0.85 for P-Al and P-Fe, respectively.

During the second campaign, three years after soil amendment, statistical analysis revealed no significant correlation between Al, Fe, and P three years post-amendment ($p > 0.05$). In fact, the data indicate that the highest total P concentrations correspond to the lowest Al and Fe levels (Fig. 8).

DISCUSSION

Soil amendment and acidity

Soils at the experimental sites are acidic, with pH values < 5.50 (Table 1), a major limitation to crop production worldwide (Du et al., 2024). Soil acidity develops when hydrogen ions (H^+) are produced in large quantities in the soil complex and interact with clay particles, releasing aluminum. This process naturally results from CO_2 -water reactions, plant uptake of excess cations relative to anions, and organic matter decomposition. Adsorption of H^+ and Al^{3+} by clay minerals displaces base cations (Ca^{2+} , Mg^{2+} , and K^+) which can be leached, causing nutrient deficiencies (Yerima et al., 2020).

Liming is a widely used strategy to correct soil acidity (Enesi et al., 2023). In this study, quicklime associated to dolomite (calcium and magnesium carbonate) were applied to soil. After carbonate application to soil, carbonate dissociates into cations (Ca^{2+} and Mg^{2+}) and carbonate ions. The carbonate ions react with H^+ to form bicarbonate, which further reacts to produce CO_2 and water. This

sequence increases Ca^{2+} and Mg^{2+} on soil exchange sites and raises soil pH, as observed in this study (Table 2) and reported in previous research (Enesi et al. 2023; Abdi, 2024).

Soil amendment and soil solution chemistry

This increase in soil pH resulting from carbonates application reduces aluminum toxicity while enhance phosphorus availability and the supply of Ca^{2+} and/or Mg^{2+} (Borgmann et al., 2021). The addition of the soil amendment significantly raised the Ca^{2+} and Mg^{2+} concentration in the soil solution, as these elements are intrinsic components of the liming materials used (Lato et al., 2025). These materials are typically applied in excess to saturate the soil exchange complex, with surplus cations subsequently leached from soil profile. The predominance of Ca^{2+} as the major exchangeable cation is attributable to its presence in both amendments and, more importantly, to the faster dissolution rate of quicklime compared to dolomite (Ivanishin and Nasr-El-Din, 2021). The efficiency of limestone depends primarily on its neutralizing value and particle size. Fine-ground limestone with a neutralizing value of 98% (lime) has a great capacity to neutralize soil acidity by rapidly releasing calcium into the soil solution.

Quickliming stimulates the mineral nutrition of cocoa trees and promotes K^+ uptake. According to Dos Santos et al. (2025), applying a higher dose of dolomite (3 ton/ha) decreases soil K^+ concentrations, primarily due to enhancing leaching in soil profile, as indicated through high observed levels of K in soil solutions. Similarly, the high concentration of P in soil solutions may be attributed to a reduction in soil acidity, with dissolves Al^{3+} and Fe^{2+} oxides and hydroxides. Under these conditions, the dynamics of these three elements appear closely interrelated, in agreement with Borgmann et al. (2021). The initial increase in Al^{3+} concentration in the soil solution shortly after liming likely reflects a cation exchange process without immediate neutralization of Al^{3+} (Anderson et al., 2021). However, this phenomenon may be also amplified by intensive organic matter mineralization following soil amendment.

The concentration of these elements in the soil solutions demonstrates the dynamics behavior of the amendment products within the soil profile. During the first season, chemical elements are more concentrated in the surface horizons, whereas in the second season, their abundance increase in deeper horizons (Lato et al., 2025). According to these authors, the effects of liming are significantly confined to the soil surface. Moreover, Doulgieris et al. (2023) reported that Ca^{2+} restoration of is more restricted to superficial soil horizons than Mg^{2+} . Thus, the observed decline in surface horizons concentrations during the second season can be attributed to intense leaching of nutrients, particularly Ca^{2+} and K^+ , into deeper horizons following heavy rainfall. This phenomenon may be also linked to high nutrient uptake by cocoa trees, reducing their availability in the surface soil horizons. In addition, better results were obtained in the second year of lime application compared to the first year (Argüello et al., 2023). This trend suggests the slow reaction of lime in the soil and its gradual downward movement over time, combined with more uniformly distributed rainfall throughout the growing season during the second year. The results of this study are consistent with previous research conducted in tropical regions. For example, Han et al. (2023) reported that high liming rates in cocoa plantations induced the vertical displacement of K^+ , leading to reduced concentrations in deeper soil horizons. Similarly, Van et al. (2025) demonstrated that liming

enhances phosphorus (P) solubilization in surface horizons by dissolving aluminium (Al) and iron (Fe) oxides and hydroxides, thereby improving P availability in previously acidic soils. Regasa and Worku, (2025) also observed a transient increase in Al^{3+} concentrations following dolomitic amendment, reflecting cation-exchange processes prior to complete acid neutralization. In addition, Zahoor and Shah, (2025) documented a rapid increase in exchangeable and soil-solution K^+ in Brazilian ferrallitic soils following dolomitic lime application, which was then followed by a gradual decline due to leaching losses under high rainfall regimes.

Effect of carbonate application on the composition of rainwater

As highlighted in the previous paragraphs, calcomagnesium lime is an effective amendment for correcting soil acidity due to its very strong acid-neutralizing capacity (Yang et al. 2025; Mahmud and Chong, 2022). It neutralizes existing acidity, enhances biological activity, and reduces heavy metal toxicity. Upon application, Ca^{2+} and Mg^{2+} ions displace H^+ , Fe^{2+} , Al^{3+} , Mn^{4+} , and Cu^{2+} ions from soil exchange sites, thereby increasing soil pH. Beyond pH correction, lime also supplies significant amounts of Ca^{2+} and Mg^{2+} , depending on the liming material used. Indirectly, liming improves the availability of nutrients such as P, Mo, and B, creates favorable conditions for microbial processes (e.g., nitrogen fixation and nitrification), and, in some cases, enhances soil structure (Mitsuta et al. 2025; Zhang et al. 2025).. Through its multiple positive effects on soil physical, chemical, and biological properties, lime helps to improve crop productivity and quality (Enesi et al., 2023). Long-term field trials have shown that liming stabilizes seasonal fluctuations in nutrient availability (Yang et al., 2025). This stabilization is partly achieved through improved nutrient cycling within plan-soil rainfall system. Rainwater that reaches the soil after flowing over leaves, branches and trunks can account for up to 90% of the nutrients leaching from canopy (Bessaad and Korboulewsky, 2020). Thus, throughfall is typically more enriched in cations than incident rain (Yang et al., 2024). The elevated concentration of Ca^{2+} , Mg^{2+} , K^+ , and P observed in throughfall in amended plots (Figs. 5 and 6) indicate that calcomagnesium amendment enhanced the availability and uptake of these nutrients by the cocoa trees, as demonstrated by (Mahmud and Chong, 2022). These authors reported improved Ca^{2+} and Mg^{2+} nutrition and increased bioavailability of other nutrients in acid forest soils. Variations in throughfall composition reflect good plant nutritional status and are mainly driven by evaporation, ion exchange, canopy leaching, and water mixing (Haas et al., 2024), while canopy water recycling processes (evapotranspiration and condensation) may also play a role (Yang et al., 2024). The downward flux of cations from throughfall to the soil contributes further to soil fertility and, consequently, to cocoa tree nutrition.

CONCLUSION

Cocoa cultivation in Côte d'Ivoire has contributed significantly to the national economy but has also led to soil acidification and environmental degradation. This study demonstrates that calcomagnesium lime effectively restores acidified cocoa soils in the Aboisso region. Application of the amendment increased soil pH by 1–2 units, enhanced the availability and uptake of essential nutrients (Ca^{2+} , Mg^{2+} , K^+ , P, Na^+),

and enriched throughfall with dissolved cations, improving nutrient cycling. Soluble base cation concentrations were up to ten times higher in amended soils compared to unamended soils, while transient Al^{3+} fluxes and increased phosphorus availability indicate improved soil chemical conditions.

These findings highlight calcomagnesium amendment as a low-cost, practical strategy for rehabilitating degraded soils, with potential to enhance cocoa productivity and sustain farmer adoption. Long-term monitoring of soil chemistry, nutrient flows, and biological activity is recommended. Widespread application could support agroecological management, reconciling crop productivity with forest conservation in Côte d'Ivoire.

DECLARATIONS

ETHICS DECLARATIONS

Ethics approval

Not applicable.

Consent to participate

All authors are consent to publish this manuscript.

Consent for publication

All authors consent to publish this manuscript

COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

Authorship provides credit for a researcher's contributions to a study and carries accountability. The following authors contributed to this manuscript as follows: - Emile B. Bolou-Bi: Conceptualization, Formal analysis, Investigation, Data curation, Writing - original draft, Supervision; - Edwige-Gwladys

Gnimassoun: Investigation, Methodology, Formal analysis, Writing - review & editing. All authors read and approved the final manuscript.

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Data Availability

The datasets generated and/or analyzed during the current study are not publicly available because they are part of an ongoing research project but are available from the corresponding author on reasonable request.

REFERENCES

1. Abdi BT. Studies on the effects of liming acidic soil on improving soil physicochemical properties and yield of crops: a review. *Middle East Res J Agric Food Sci.* 2024;4(3):95–103. <https://doi.org/10.36348/merjafs.2024.v04i03.001>.
2. Anderson GC, Pathan S, Hall DJM, Sharma R, Easton J. Short- and long-term effects of lime and gypsum applications on acid soils in a water-limited environment: 3. Soil solution chemistry. *Agron.* 2021;11:1–19. <https://doi.org/10.3390/agronomy11050826>.
3. Antonangelo JA, Neto JF, Crusciol CAC, Zhang H, Alleoni LRF. Lime and calcium-magnesium silicate cause chemical attributes stratification in no-till fields. *Soil Tillage Res.* 2022;224:105522. <https://doi.org/10.1016/j.still.2022.105522>.
4. Argüello D, Chavez E, Gutierrez E, Pittomvils M, Dekeyrel J, Blommaert H, Smolders E. Soil amendments to reduce cadmium in cacao (*Theobroma cacao* L.): a comprehensive field study in Ecuador. *Chemosphere.* 2023;324(5):138318. <https://doi.org/10.1016/j.chemosphere.2023.138318>.
5. Bavier J, Angel M, Aboa A. 2021. Insight: In Ivory Coast, a battle to save cocoa-ravaged forests. Reuters. <https://www.reuters.com/business/environment/ivory-coast-battle-save-cocoa-ravaged-forests-2021-1117/>
6. Bessaad A, Korboulewsky N. How much does leaf leaching matter during the pre-drying period in a whole-tree harvesting system? *For. Ecol Manage.* 2020;477:118492. <https://doi.org/10.1016/j.foreco.2020.118492>.
7. Bolou-Bi EB, Ettien JBD, Konan AK. Soil acidification in cocoa (*Theobroma cacao*) agrosystems in Côte d'Ivoire (I): effect of carbonate-based mineral amendments on soil chemical properties and growth of cocoa seedlings. *Int J Plant Soil Sci.* 2023a;35(22):398–409. <https://doi.org/10.9734/ijpss/2023/v35i224148>.

8. Borgmann C, Secco D, Marins A, Zanao LAJ, Bassegio D, De Souza SNM, Zang FN, Benetoli TR. Commun Soil Sci Plant Anal. 2021;52(12):1–14. <https://doi.org/10.1080/00103624.2021.1885688>. Effect of soil compaction and application of lime and gypsum on soil properties and yield of soybean.
9. Clément M. 2020. La dégradation des sols en France et dans le monde, une catastrophe écologique ignorée. Planet Vie. <https://planet-vie.ens.fr/thematiques/ecologie/gestion-de-l-environnement-pollution/la-degradation-des-sols-en-france-et-dans> (accessed 9.8.23).
10. Court M, Heijden GVD, Didier S, Nys C, Richter C, Pousse N, Saint-André L&, Legout A. Long-term effects of forest liming on mineral soil, organic layer and foliage chemistry: Insights from multiple beech experimental sites in Northern France. Ecol Manag. 2018;409:872–89. <https://doi.org/10.1016/j.foreco.2017.12.007>.
11. Dos Santos AO, De Souza OJJ, Neves JCL, Ahnert D. Temporal changes in basic cations in soils under cocoa cultivation in the Brazilian Atlantic Forest. Aust J Crop Sci. 2025;19(3):274–83. <https://doi.org/10.21475/ajcs.25.19.03.p281>.
12. Doulgeris C, Kypritidou Z, Kinigopoulou V, Hatzigiannakis E. Simulation of potassium availability in the application of biochar in agricultural soil. Agron. 2023;13(3):1–15. <https://doi.org/10.3390/agronomy13030784>.
13. Du L, Zhang Z, Chen Y, Wang Y, Zhou C, Yang H, Zhang W. Heterogeneous impact of soil acidification on crop yield reduction and its regulatory variables: a global meta-analysis. Field Crops Res. 2024;319:109643. <https://doi.org/10.1016/j.fcr.2024.109643>.
14. Enesi RO, Dyck M, Chang S, Thilakarathna MS, Fan X, Strelkov S, Gorim LY. Liming remediates soil acidity and improves crop yield and profitability—a meta-analysis. Front Agron. 2023;5:1194896. <https://doi.org/10.3389/fagro.2023.1194896>.
15. Gbocho DO, Ourega DD. 2021. Degradation of the forest heritage of the Department of Aboisso: a consequence of the massive intrusion of urban elites into the rural environment. pp. 129–43.
16. Getachew A, Tilahun A, Teklu E, Chilot Y, Carol H, Robert T, Nosworthy MG, Sheleme B, Sileshi GW. Extent and management of acid soils for sustainable crop production system in tropical agroecosystems: a review. Acta Agric Scand B Soil Plant Sci. 2021;71(9):852–69. <https://doi.org/10.1080/09064710.2021.1954239>.
17. Haas H, Kalin L, Yen H. Improved forest canopy evaporation leads to better predictions of ecohydrological processes. Ecol Model. 2024;489:110620. <https://doi.org/10.1016/j.ecolmodel.2024.110620>.
18. Han T, Li D, Liu K, Huang J, Zhang L, Liu S, Shah A, Liu L, Feng G, Zhang H. Soil potassium regulation by initial K level and acidification degree when subjected to liming: a meta-analysis and long-term field experiment. Earth Sci Rev. 2023;103912. <https://doi.org/10.1016/j.earscirev.2023.103912>.
19. Ivanishin IB, Nasr-El-Din HA. Effect of calcium content on the dissolution rate of dolomites in HCl acid. J Pet Sci Eng. 2021;202:108463. <https://doi.org/10.1016/j.petrol.2021.108463>.

20. Kalischek N, Lang N, Renier C, Daudt RC, Addoah T, Thompson W, Blaser-Hart WJ, Garrett R, Schindler K, Wegner JD. Cocoa plantations are associated with deforestation in Côte d'Ivoire and Ghana. *Nat Food*. 2023;4:384–93. <https://doi.org/10.1038/s43016-023-00751-8>.
21. Kouassi AG, Koné B, Bolou Bi E, Yao-Kouamé A. Distribution de l'aluminium échangeable et total dans les sols des agrosystèmes à base de cacaoyer (*Theobroma cacao* L.) dans les régions du centre-ouest de la Côte d'Ivoire. *Rev Afr Environ Agric*. 2024;6(4):54–61. <https://doi.org/10.4314/rafea.v6i4.6>.
22. Laço A, Berbecea A, Laço I, Crista F, Crista L, Sala F, Radulov I. 2025. Mitigating soil acidity: impact of aglime (CaCO₃) Particle size and application rate on exchangeable aluminium and base cations dynamics. *Sustainability*: 17(18):8135. <https://doi.org/10.3390/su17188135>
23. Mahmud MS, Chong KP. Effects of liming on soil properties and its roles in increasing the productivity and profitability of the oil palm industry in Malaysia. *Agric*. 2022;12:1–14. <https://doi.org/10.3390/agriculture12030322>.
24. Mitsuta A, Lourenço KS, Chang J, Ros M, Schils R, Uchida Y, Kuramae EE. Liming enhances the abundance and stability of nitrogen-cycling microbes: the buffering effect of long-term lime application. *Biol Fertil Soils*. 2025;61:761–72. <https://doi.org/10.1007/s00374-025-01889-2>.
25. Pereira P, Inacio M, Barcelo D, Zhao W. Impacts of agriculture intensification on biodiversity loss, climate change and ecosystem services. *Curr Opin Environ Sci Health*. 2025;46:100637. <https://doi.org/10.1016/j.coesh.2025.100637>.
26. Pradhan AK, Shandilya ZM, Sarma P, Bora RK, Regnon P, Lakshmi Narayana RV, Vemireddy T, Tanti B. Concurrent effect of aluminum toxicity and phosphorus deficiency on the root growth of aluminum-tolerant and sensitive rice cultivars. *Acta Physiol Plant*. 2023;45(33):1–13.
27. Regasa A, Worku A. 2025. Effects of lime and vermicompost application on soil physicochemical properties and phosphorus availability in tropical acidic soils. *Sci. Rep.* 15: 2096. <https://doi.org/10.1038/s41598-025-02053-4>
28. Sidibé O, Kouadio HK, Bamba I, Konan EK. Political-military crisis and forest fragmentation in the Mont Péko National Park in Côte d'Ivoire. *Cybergeog: Eur J Geogr Environ Nat Landsc Doc*. 2020;945. <https://doi.org/10.4000/cybergeog.34842>.
29. Van LN, Hermann L, Dinh TL, Van CN, Enez A, Brau L, Lesueur D. Liming effect on soil chemical and biological properties, pests and diseases, and crop yields in robusta coffee and black pepper in Vietnam. *Soil Res*. 2025;63(3):24143. <https://doi.org/10.1071/SR24143>.
30. Wang J, Tu X, Zhang H, Cui J, Ni K, Chen J, Cheng Y, Zhang J, Chang SX. Effects of ammonium-based nitrogen addition on soil nitrification and nitrogen gas emissions depend on fertilizer-induced changes in pH in a tea plantation soil. *Sci Total Environ*. 2020;747:141340. <https://doi.org/10.1016/j.scitotenv.2020.141340>.
31. Yang J, Wang A, Shen L, Dai G, Liu Y, Zhang Y, Fei W, Wu J. The impact of canopy on nutrient fluxes through rainfall partitioning in a mixed broadleaf and coniferous forest. *For*. 2024;15:1–16. <https://doi.org/10.3390/f15040623>.

32. Yang T, Sun G, Sun M, Du H, Luo Z, Feng Q, Zheng Y, Zhou J, Long Z. Effects of lime, magnesia and silicon on soil acid-neutralizing capacity and rice yield in acidic paddy fields. *Agric.* 2025;15:1–13. <https://doi.org/10.3390/agriculture15101042>.
33. Yerima BPK, Enang RK, Kome GK, Ranst EV. Exchangeable aluminium and acidity in Acrisols and Ferralsols of the north-west highlands of Cameroon. *Geoderma Reg.* 2020;23:e00343. <https://doi.org/10.1016/j.geodrs.2020.e00343>.
34. Zahoor A, Shah GM. Effects of liming on the chemical properties of tropical peat soils. *Commun Soil Sci Plant Anal.* 2025. <https://doi.org/10.1080/03650340.2025.2527094>.
35. Zhang B, Tang L, Chen Z, Chen X, You L, Pan R, Chen T, Liu Y, Lin W, Huang J. Comparative and synergistic impacts of lime and biochar on soil properties, nitrogen transformation, and microbial function in acidic soils under tobacco cropping. *Front Plant Sci.* 2025;1–15. <https://doi.org/10.3389/fpls.2025.1530128>.
36. Zhao T, Zhang X, Liu W, Wang J, Li Z, Liu L. Increase in global per capita cropland imbalance across countries from 1985 to 2022: a threat to achieving Sustainable Development Goals. *Geogr Sustain.* 2025;6:1–12. <https://doi.org/10.1016/j.geosus.2024.09.005>.
37. Zhu X, Zhao S, Lin S, Wang J, Leng S. The impact of soil acidification on cementing substances and aggregate stability. *PLoS ONE.* 2025;20(4):1–17. <https://doi.org/10.1371/journal.pone.0318417>.

Figures

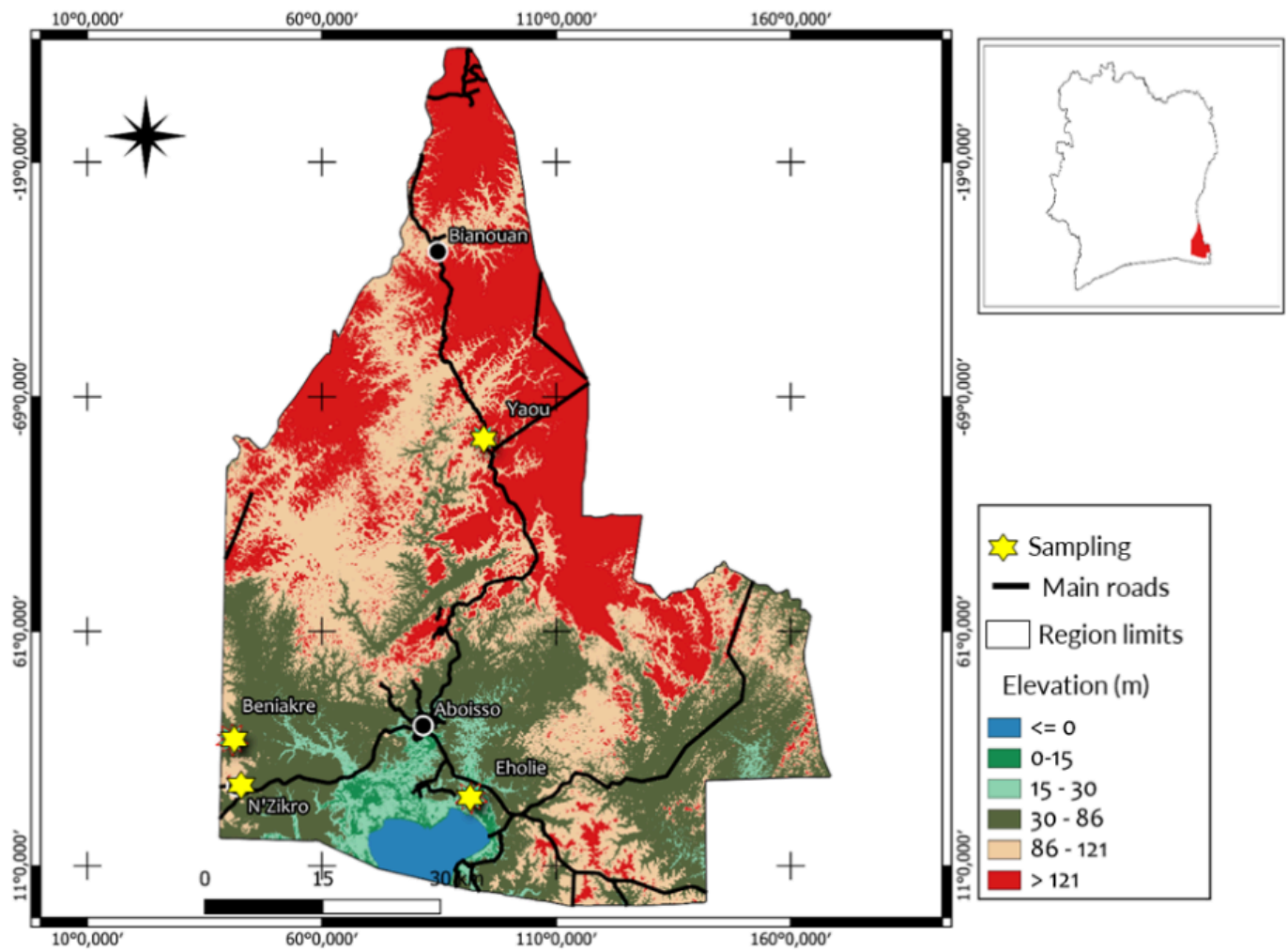


Figure 1

Location of the study area (data extracted from the 1:500,000 South-East soil map of Côte d'Ivoire).

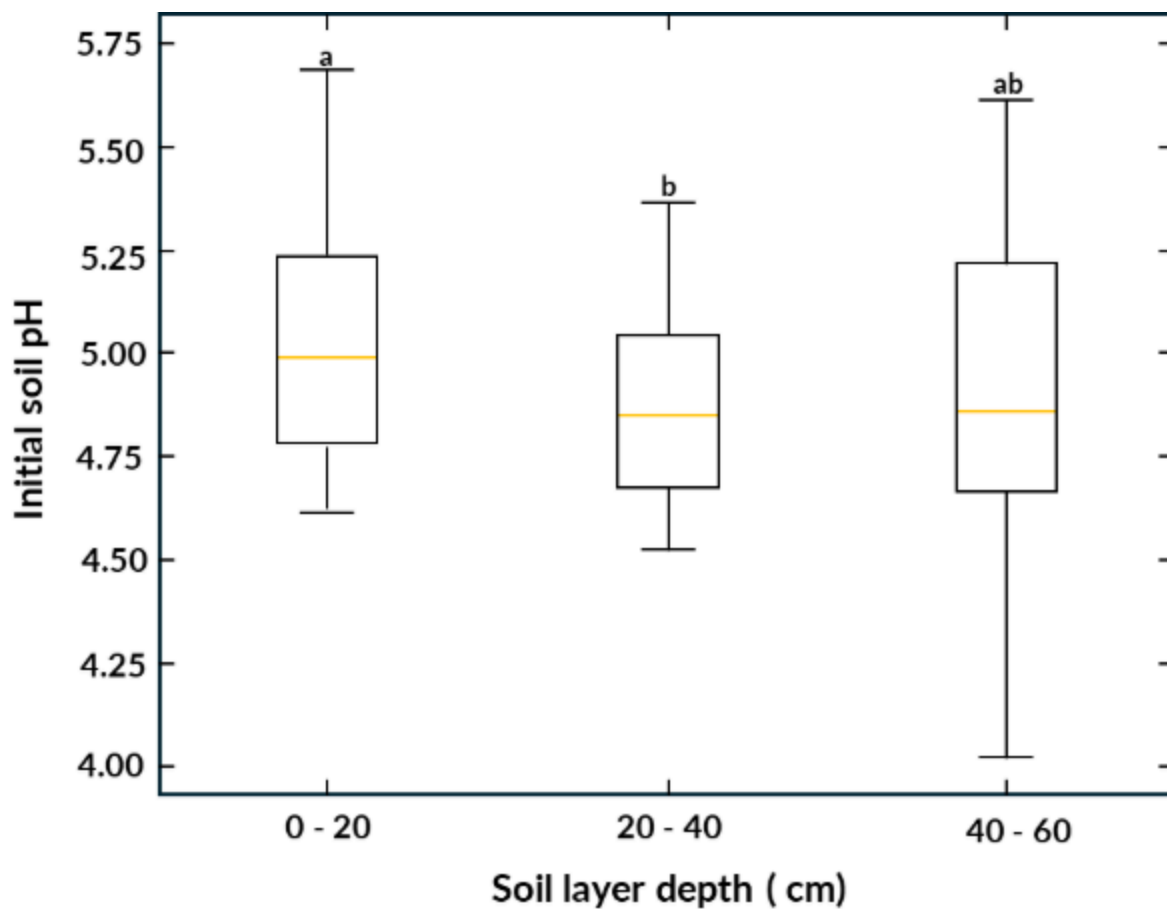


Figure 2

Soil pH boxplots at depth intervals of 0-20, 20-40, and 40-60 cm. Different letters indicate significant statistical differences ($p < 0.05$) between depths. The 0-20 cm layer differed significantly from the 20-40 cm layer, while the 40-60 cm layer showed intermediate values.

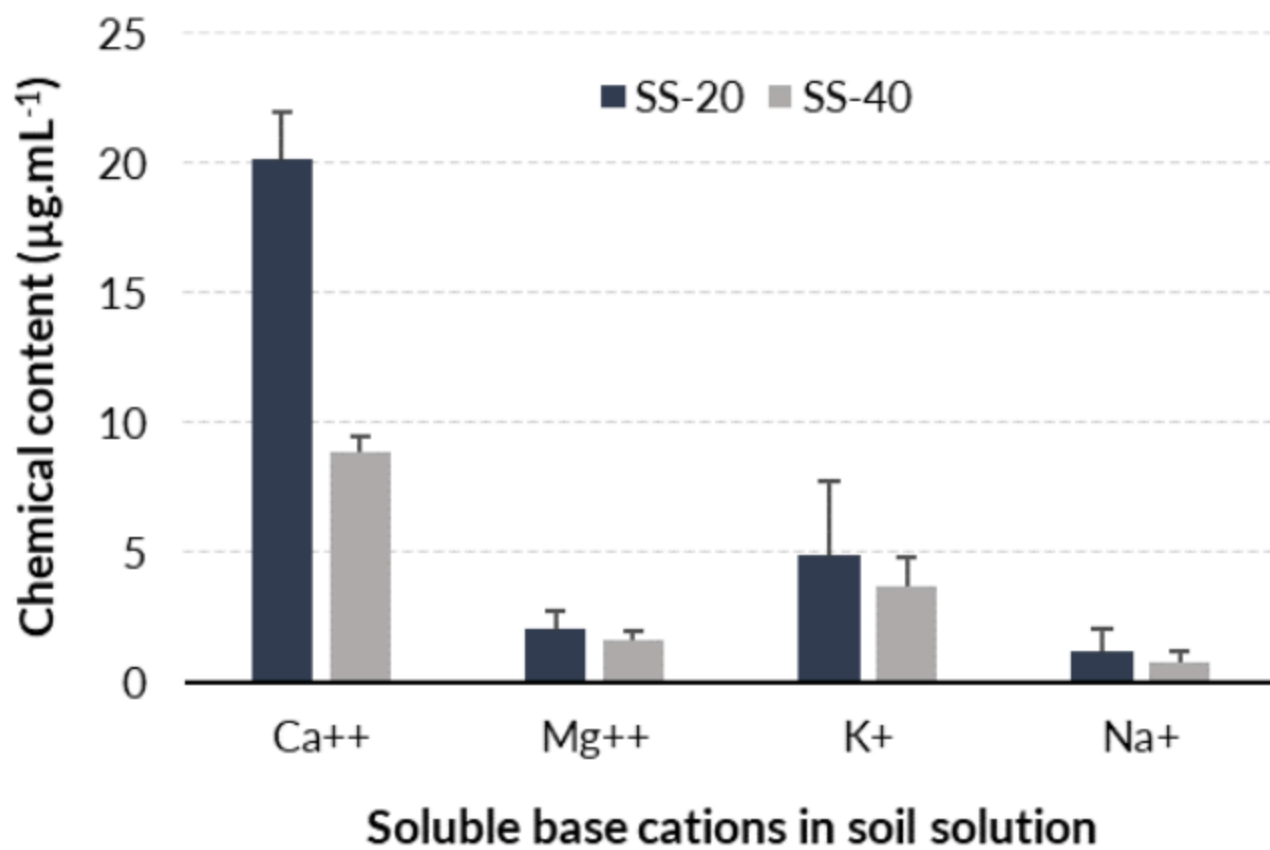


Figure 3

Average concentration of soluble bases in soil solution from cocoa plantations two years after amendment.

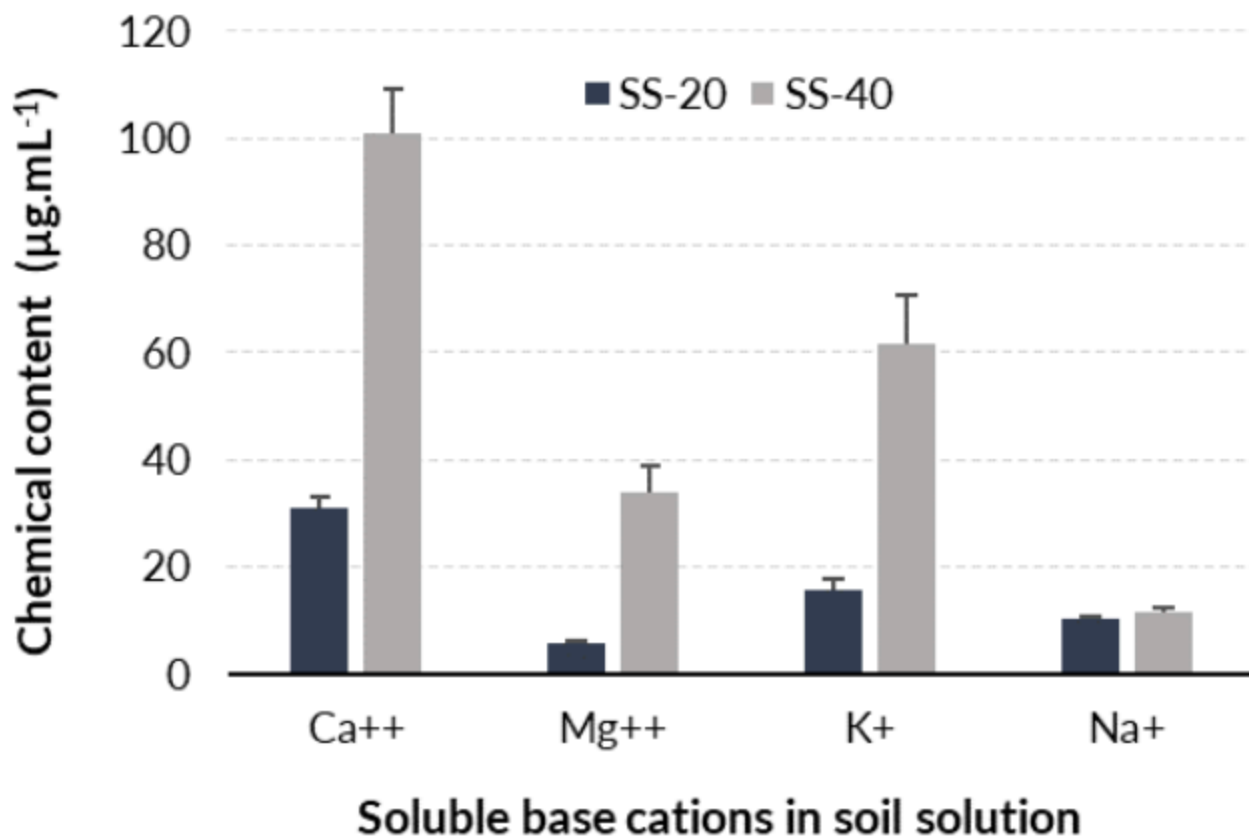


Figure 4

Average concentration of soluble bases in soil solution from cocoa plantations three years after amendment.

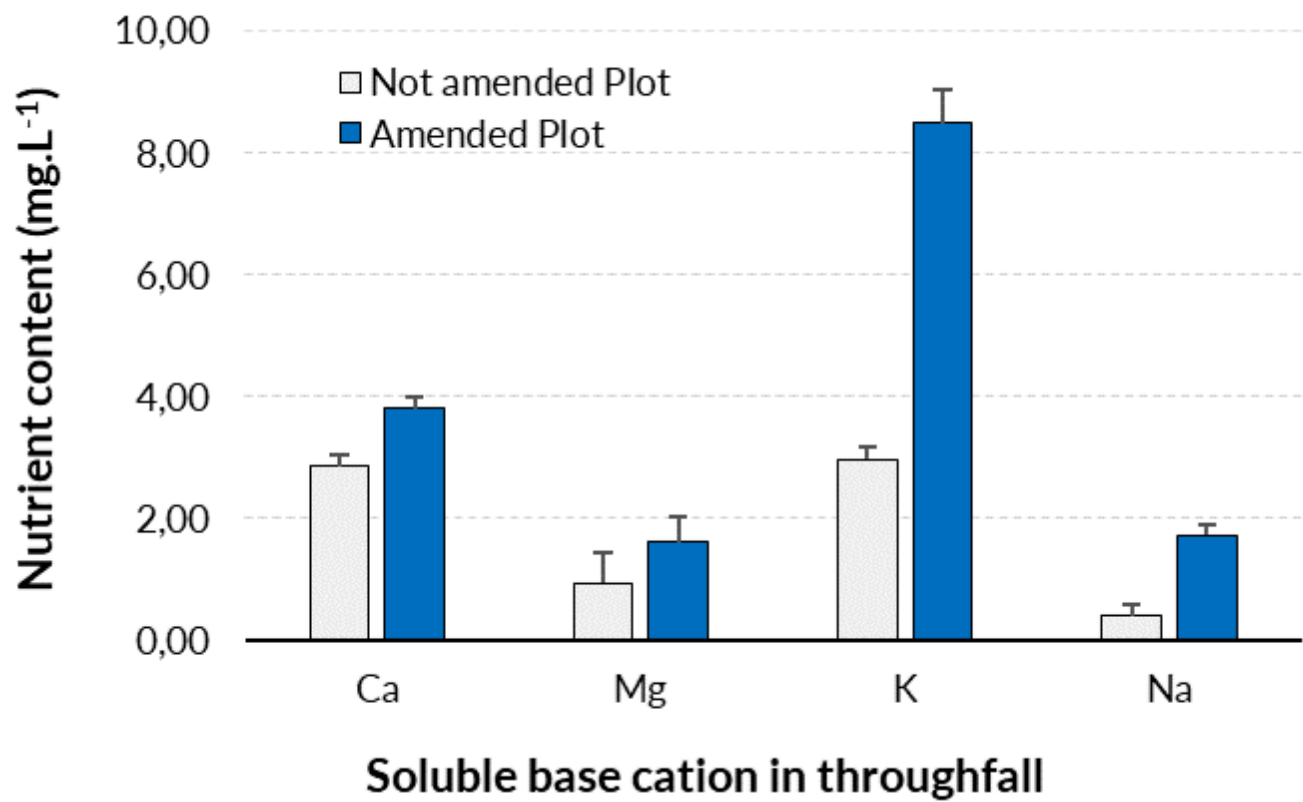


Figure 5

Soluble base content in throughfall collected under cocoa plantations (NA: unamended, A-CaMg: amended) two years after amendment.

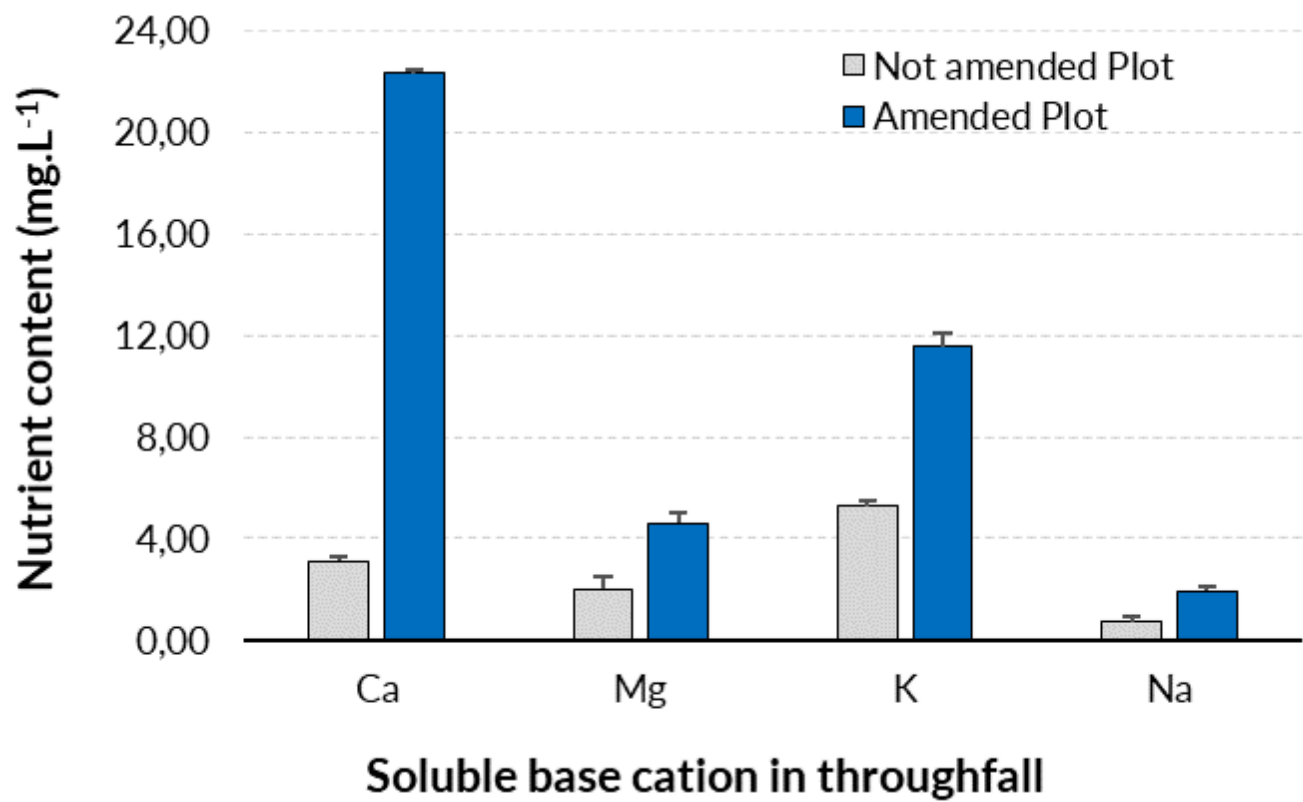


Figure 6

Soluble base content in throughfall collected under cocoa plantations (NA: unamended, A-CaMg: amended) three years after amendment.

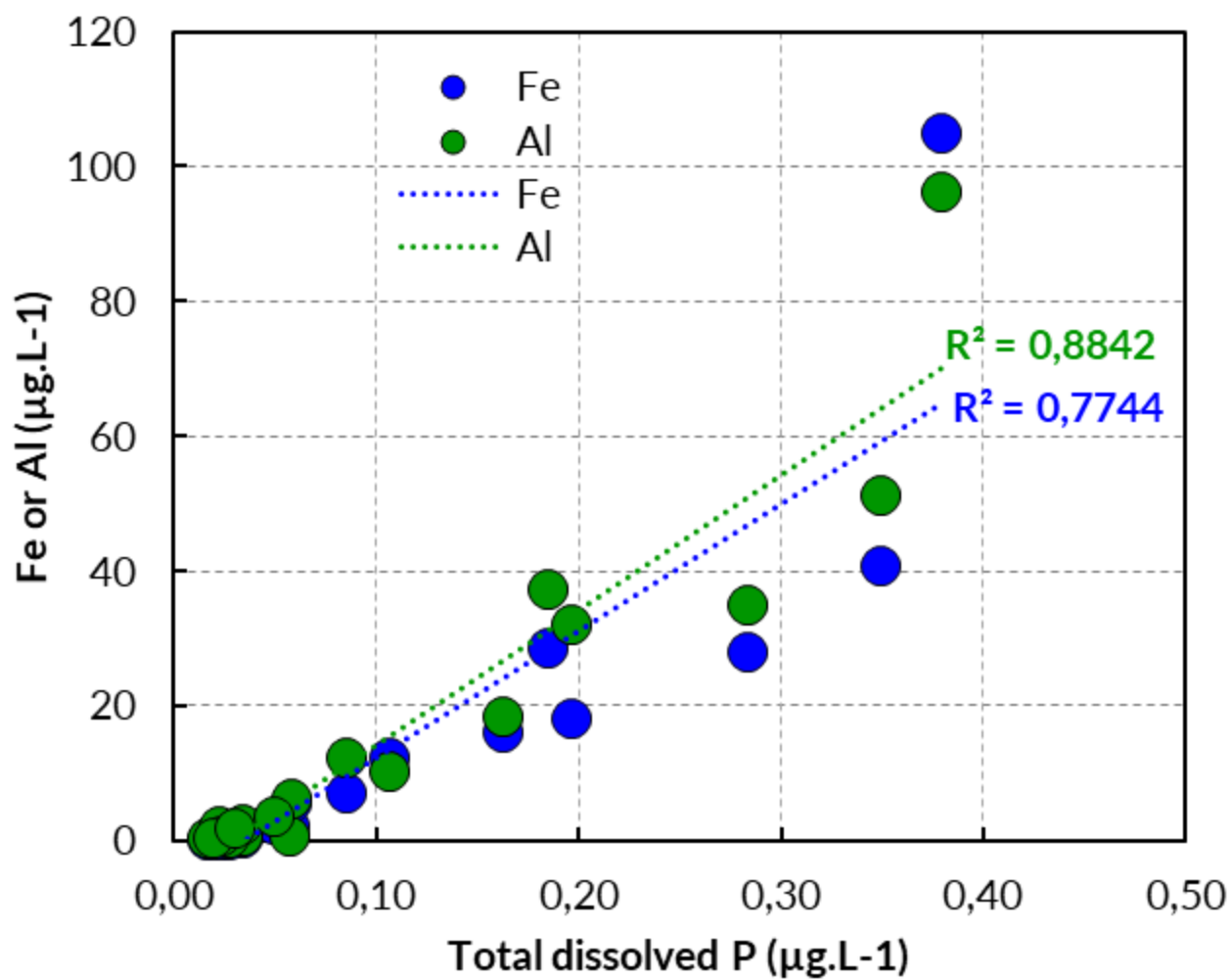


Figure 7

Correlation between Fe, Al, and total dissolved phosphorus in soil solution two years after amendment.

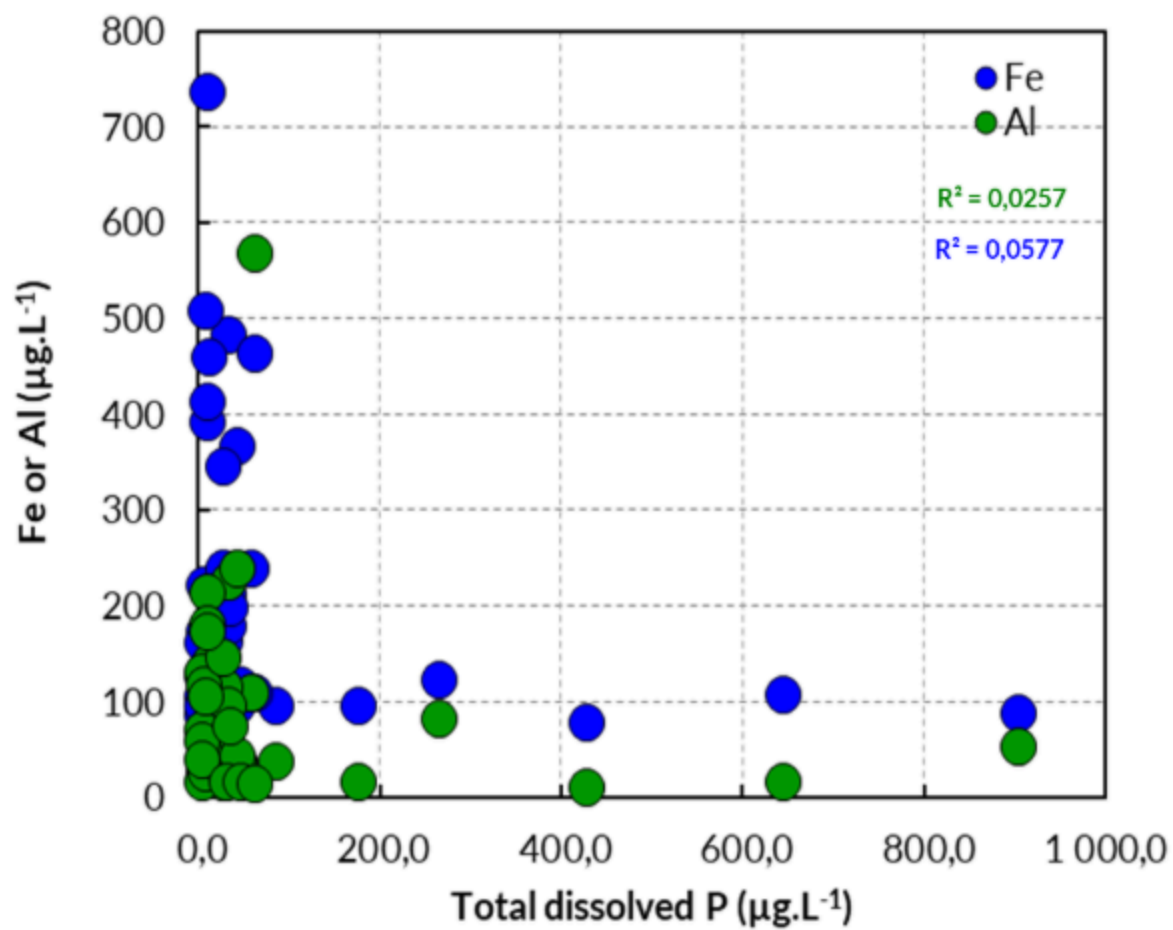


Figure 8

Correlation between Fe, Al, and total phosphorus in soil solution three years after amendment.