

Soil Acidification in Cocoa (*Theobroma cocoa*L.) Agrosystems in Côte d'Ivoire (I): Effect of carbonate based mineral amendments on soil chemical properties and growth of cocoa seedlings (*Theobroma cocoa* L.)

Abstract

Soil acidification is a major concern in Côte d'Ivoire. The present study examines the effect of an amendment based on crushed carbonate rock (dolomite and limestone) on soil chemistry and cocoa plant growth. To this end, cocoa seedlings were grown under controlled conditions under cover on soils taken from cocoa orchards in Aboisso (south-eastern Côte d'Ivoire). Soils were sampled at 0-20 cm, 20-40 cm and 40-60 cm. A representative composite sample of each horizon was then taken in a soil column. The experimental trial was conducted in total randomization with six repeated treatments (Dolomite 100%, Limestone 100%, Dolomite 50% + Limestone 50%) compared with the control, soil without amendment. After six months, the results showed that the application of carbonate did not induce a significant difference ($p > 0.05$) in cocoa seedlings growth. However, the amended soil showed improvement chemical properties compared to unamended soil. Soil treatments with limestone improved soil base cation content, CEC and pH, but all these parameters measured still lower to minimum threshold values for good cocoa tree growth. These results showed that the combination of dolomite and limestone appears to be the amendment with the greatest potential for improving the fertility of acid soils under cocoa. Field investigations should then be undertaken to assess the effect of this carbonate combination on soil acidity and fertility under natural conditions.

Key words: Soil acidification, Liming, Aboisso, Côte d'Ivoire

Introduction

Côte d'Ivoire is the world's largest cocoa producer since 1978[1], with about 42% of global production. Cocoa agrosystem expanded very rapidly in Côte d'Ivoire, especially after the Second World War[2]. However, the development of this crop was based on extensive cultivation practices combining cocoa with food crops. This agrosystem mode destroyed the primary forest, which have fallen from 16.5 million hectares in the 1960s to only 2 million hectares in 2020 [3]. This model is therefore no longer possible because of the scarcity of forest reserves. In addition to this deforestation, cocoa agrosystemsoils become more acidic[4]. Thus today, cocoa agrosystem in Côte d'Ivoire is faced with numerous constraints inducing itslow yield[5]and soil acidification[6]. Natural leaching of base cations and acidification are responsible for the loss of soil fertility[7]. Soil acidification leads to soil desaturation, especially of base cations (Ca^{2+} , Mg^{2+} , Na^+ and K^+). In this context, the former cocoa production areas,located in the south-east and east of Côte d'Ivoire, are converted to rubber and oil palm plantations[8]. This practice has gradually led to the migration of the cocoa production area from the south-east to the forested west regions of Côte d'Ivoire.

Alternative ways for sustainable soil fertility management in theseformer cocoa production areasin the south-east should be explored in order to limit further deforestation of remaining forest reserves. The application of powdered carbonate rocks in soil of cocoa plantationwould help to restore soil fertility[9]. Carbonates such as limestone (CaCO_3) and dolomite $\text{CaMg}(\text{CO}_3)_2$ are usually used for liming practices in agriculture. Carbonate application to soil (liming)are well known in temperate and boreal regions where these amendments have been used for soil liming during forest decline. It is recognised that the use of carbonate for soil amendment in these ecosystems leads to an improvement in tree mineral nutrition. This improvement iscoupled to a significant change in the floristic composition, with an enrichment of ruderal nitrophilous species and a regression of hyperacidophilous species, as well as in microbial diversity[10]. In the long term, the liming leads to an improvement of humus characteristics and chemical properties of the soil. It has favourable effects on the structure and decomposition of organic horizons[11, 12, 13]. Liming restores soil pH, calcium and magnesium reserves as well as CEC and saturation rate. The calcium and magnesium nutrient status in soils under the forest stand become better; however, liming has sometimes caused a decrease in tree potassium nutrition. Most studies additionally indicate biogeochemical cycles and biological activity improvement due to liming practices. In cocoa agrosystems,liming effect remains poorly investigated and documented. Thus, the objective of the present study was to evaluate the effect of a carbonate application on the chemical properties of acidic soil during cocoa growing.We hypothesised that mixing of carbonate (dolomite with slow dissolving rate and lime with fast dissolving rate) in equal proportions would be better for the long-term restoration of acid soils under cocoa farms. To this end, cocoa seedlings growth trials were carried out under controlled conditions on acid soil columns.

Material and method

Cocoa pod and soil sampling

The samples (cocoa seeds and soil) used in this study were obtained from cocoa plantations located in Aboisso (south-east of Côte d'Ivoire) (Figure 1). The cocoa seeds (*Theobroma cacao* L.) are the Forastero variety collected from plantations in Aboisso, where soils are ferralsol (FAO Soil classification). Soil pits were made in these plantations and a composite sample was taken from each soil horizon (0-20 cm (S-20), 20-40 cm (S-40) and 40-60 cm (S-60)). These different composite samples were then used to reconstitute a soil profile for cocoa seedling growth.

Experimental growth of cocoa seedling

The experimental growth of plant was conducted under rain-shelters located at the University Félix Houphouët-Boigny, Abidjan (Côte d'Ivoire). The experimental device unit consisted of tube (\varnothing ~20 cm, L~70 cm) nested in woodtrays with metal stands. At the base of each tube, a nylon filter (5 μ m mesh) was placed to hold the soil column and filter the soil solution. In each experimental tube, field soil profile was reconstructed with each composite sample of various soil horizons collected cocoa plantations. Reconstituted soils were then watered for a fortnight before sowing of cocoa beans. One month after sowing of cocoa beans, increasing doses of dolomite and lime were applied three times every two weeks to reach 3 t ha⁻¹. The treatments, with six replications are defined as: control treatment without carbonate (T0), treatment with dolomite (100%)(T1), treatment with limestone (100%) (T2) and treatment with dolomite (50%) + limestone (50%) (T3). Cocoa seedlings were watered with 20 ml of distilled water every two days. Growth parameters (plant height and number of leaves) were measured and data were collected every fortnight before and after soil amendment. After 6 months, the device was dismantled to recover the soil samples (S-20, S-40, S-60) and plant biomasses. For this purpose, experimental tube units were cut following the longitudinal section. Then, various soil horizons were carefully removed and then air-dried. These samples were sieved to 2 mm and stored for laboratory analysis.

Soil chemical analyses

Soil acidity was determined by measuring pH in soil/water ratio of 1/5 (m/V) with five replicates per treatment[14]. Ten grams of air-dried soil were mixed with 50 ml of distilled water. This mixture was stirred for one hour, centrifuged at 3000 rpm and pH was then determined in the supernatant solution using an Analab[®] pH meter. In addition, three batches per treatment of 5 g of air-dried soil samples shaken with 50 ml of 1 M ammonium acetate solution (Reagent grade \geq 98%, Sigma-Aldrich[®]) at pH 7 to extract exchangeable bases (Ca²⁺, Mg²⁺, Na⁺ and K⁺). Three successive extractions were carried out on each batch of samples using 1 M ammonium acetate solution[15]. Then, the solutions resulting from these successive extractions were mixed for each soil batches, then filtered through a polytetrafluoroethylene (PTFE) filter. Exchangeable bases (Ca²⁺, Mg²⁺,

Na⁺ and K⁺) were determined by Inductively Coupled Plasma Optical Emission Spectroscopy (Perkin Elmer[®])

Soil CEC was determined by the cobaltihexamine chloride method [16]. About 2.5 g of dried sample, sieved to 2 mm, was shaken with 50 ml of 50 mmol⁺.L⁻¹ of cobaltihexamine solution (Reagent grade ≥98%, Sigma-Aldrich[®]). After centrifuging and filtering the solution, concentration of cobaltihexamine ions remaining in solution after exchange with the soil was determined at 475 nm using HACH DR/2000[®] colorimeter to deduce the CEC value.

Total carbon and nitrogen were determined after 2 mg of soil sample pyrolysis (three replicates per sample) using Flashsmart Elemental analyser, ThermoFischer[®]. The total soil organic matter (SOM) content is obtained by multiplying carbon content using a factor of 1.72.

Available phosphorus was determined by the Truog method [17]. The phosphorus in the soil (three replicates per sample) was extracted in the presence of 200 ml sulphuric acid (0.002 M) buffered by a solution of ammonium sulphate at pH = 3.5, shaken for 30 minutes with 1 g of air-dried soil sieved to 2 mm. Then, extracted phosphorus was then measured by spectrophotometry.

Statistical analysis

All univariate analyses were performed using by SAS version 9 software. A repeated measures ANOVA was applied to identify the effect of treatments (limed or not). A one-way ANOVA followed by a comparison of Student-Newman-Keuls (SNK) test was used to identify significant differences between treatments for sites, with a significance level of 5%. We used ANOVA because data were sufficiently homogeneous within groups and with sufficient normality.

Results and Discussion

Soil selected initial characteristics

Table 1 presents the selected properties of the initial composite soil samples. These results indicate that soils are dominated by sandy soils at the surface (S-20 and S-40) while the deep horizon (S-60) has a grain size dominated by clay (>40% of clay). Soils are acidic with pH values < 5.5, below the average threshold value defined in the literature at 6.05 for cocoa growth [15]. Soil fertility indicators (CEC, exchangeable bases, SOM) showed low level of fertility in these soils. All soil fertility indicators were below the threshold values defined for cocoa production [18]. However, the data for some chemical balance characteristics of these samples were contrasted with the minimum threshold values (Table 1). Indeed, the Ca/Mg, Mg/K and (Ca+Mg)/K ratios in the deep horizons are higher than the minimum limit, while the surface horizon is lower than these values.

The physical characteristics of the soils revealed that cocoa agrosystems soils in Aboisso are acidic and dominated by a sandy texture, which induces high base leaching in these soils under abundant rainfall, with an annual average of 1500 mm. The low pH values are included in the range of pH values varying from 4.0 to 6.6 defined for soils in the region [19]. At these low pH values, many

unfavourable phenomena for plant growth such as phosphorus deficiency, Al^{3+} and Mn^{2+} toxicity [20, 21] occur in the soil. Thus, these results indicate that these soils have a low level of fertility, related to a low level of exchangeable bases and a rather poorly developed organic horizon [22]. The causes of this poverty in exchangeable bases would be linked to the phenomenon of acidification and losses by leaching [23]. The studied soils are depleted in major cations (Ca^{2+} , Mg^{2+} and K^+) with values below the respective fertility thresholds [18], requiring an external input to compensate for the deficit and at the same time to correct the acidity, which correction is essential for the release of other important elements such as phosphorus for better nutrition of the cocoa tree.

Effects of soil amendments on soil chemical properties

Figure 2 shows the evolution of pH in soil horizons after the Ca-Mg amendment. In general, results indicated that, regardless of the treatment, the pH values remained below the minimum threshold pH value (6.05) required for cocoa cultivation. In detail, pH values increased in S-20, for all treatments compared to the control. The pH of treatments T2 and T3 increased by 1.2 pH units while that of treatment T1 increased by only 0.5 pH unit. However, statistical analyses showed that there is no significant difference between the pH of treatments T2 and T3; but a significant difference existed between these treatments and treatments T1 and T0. In S-40 horizon, pH values of all treatments remained similar to that of the T0 control with non-significant differences. In S-60 horizon, pH values displayed similar values, statistically insignificant difference, for all treatments compared to the control. Table 2 shows the selected chemical parameters of soil after Ca-Mg amendment. Results showed a clear evolution of organic matter (OM), organic carbon and total nitrogen in all horizons. In the S-20 horizon, treatment T2 recorded the highest organic matter and organic carbon content with a higher C/N ratio compared to the T0 control. In the S-40 horizon, the organic matter content remained constant for all treatments, whereas the T2 treatment displayed higher organic carbon and total nitrogen content with a higher C/N ratio. Finally, in the S-60 horizon, change in organic matter, organic carbon and total nitrogen are null for all treatments compared to the T0 control, although T3 treatment induced slight increase. Compared to the control, treatments T1, T2 and T3 induced an increase in exchangeable Ca^{2+} of 11.1%, 11.0% and 20.0% respectively in S-20. With regard to exchangeable Mg^{2+} , the increase determined was 33%, 2% and 19% for treatments T1, T2 and T3 respectively. Treatments T3 and T1 induced an increase in exchangeable K^+ content of 29.0% and 14.0% respectively, whereas for T2, there was no change. In the S-40 horizon, exchangeable Ca^{2+} was not improved for all treatments. Exchangeable Mg^{2+} for treatment T3 was improved by 40.0% while the increase in Mg^{2+} for treatments T1 and T2 was almost nil (less than 1%). As for exchangeable K^+ , treatments T3 and T1 induced an improvement of 41% and 1.5% respectively, whereas treatment T2 had no effect. Finally, in the S-60 horizon, all treatments improved the content of exchangeable Ca^{2+} cations compared to the T0 control, but this is not statically significant with 4.30%, 7.88% and 5.32% for T1, T2, and T3 respectively. As for

exchangeable Mg^{2+} , only treatments T1 and T2 induced not statically significant increase of 2.55% and 1.80% respectively. Exchangeable K^+ cations increased only for treatment T2 with a high rate of 45.92%. Although this data indicates increases in base cation levels, these levels remain below the minimum limit for good cocoa tree growth (11 $cmol_c kg^{-1}$, 2.45 $cmol_c kg^{-1}$ and 0.7 $cmol_c kg^{-1}$ respectively for exchangeable Ca^{2+} , Mg^{2+} and K^+). Similarly, the CEC was not significantly improved under the experimental conditions. In the same way, amendment treatments did not induce significant shifts in the ionic balances in the soils with the Ca/Mg ratio in all horizons and for all treatments remaining below the minimum value of 2.80 for cocoa production. The Mg/K and (Ca+Mg)/K ratios appeared above the minimal limit. Available phosphorus in all soil horizons showed higher values compared to the minimum threshold limit of 11.5 ppm. Thus, in comparison with the control, P content improvement in soil varied between 60% and 90% for the surface horizons (S-20 and S-40) and from 8% to 14% for the deep horizons (S-60).

In this greenhouse experiment, the application of dolomite and limestone slightly improved the chemical properties of the soil (Table 2). This improvement is strongly dependent on type of applied product to the soil. Indeed, the results showed that the improvement of the chemical properties is better under treatments T2 and T3, namely limestone and limestone + dolomite mixture. The first parameter impacted by these treatments is soil acidity. The increase in soil pH could be explained by the release of basic cations (Ca^{2+} and Mg^{2+}) into the soil solution. Indeed, it is now recognised that calcium and magnesium carbonates neutralise acidic soils. This neutralisation of soil acidity takes place firstly, by Ca-Mg carbonate ionisation into Ca^{2+} , Mg^{2+} and carbonate ions in soil solution. Then, ionized Ca^{2+} and or Mg^{2+} ions bind to soil constituents and excess protons react in the soil solution with carbonate to form carbon dioxide and water. This process depends to the Ca-Mg carbonate dissolution rate. The dissolution rate of limestone compared to dolomite would therefore underlie this improvement in the lime containing treatments (T2 and T3). Driscoll [24], working on the dissolution of calcitic and dolomitic limestones in soil columns under controlled conditions, proved that with the same rainfall intensity, the dolomitic material takes about twice as long to dissolve as calcitic lime. According to Wijanarko and Taufiq[25], studied the effect of lime on soil properties and soybean yield, when lime is incorporated into the soil to a depth of 20 cm, it reacts rapidly with the soil and at the same time improves these chemical properties. This improvement in the acid-base status of the soil is only detectable in the surface horizons, suggesting that liming products did not migrate into the soil's deep horizon in our experimental conditions. Bolou-Bi et al [26] showed that dolomite would take about two years to reach a depth of 20 to 40 cm in soil profile. In the case of lime, this could be explained by an insufficient amount of lime applied with an undersaturation of the soil exchange complex by Ca^{2+} and Mg^{2+} [27]. Under these conditions, the exchange complex of the surface horizons would not have been completely saturated for possible migration to the deep horizons. This low migration of powdered carbonate in soil would be due to high content of Al^{3+} in the soil horizons, especially from 30 cm, which plays a buffer role in soil[28]. It

is practically impossible to modify the acidity of this horizon and therefore to decrease the Al^{3+} content.

In the case of exchangeable bases, the T3 treatment induced a greater increase in the quantity of exchangeable Ca^{2+} cations and the treatment with dolomite recorded a greater increase in exchangeable Mg^{2+} in S-20 (Table 2). The release of base cations in the soil is linked to the nature of the amendment product used. Thus, the combination of dolomite + limestone releases a greater quantity of Ca^{2+} cations into the soil. Similarly, the treatment with dolomite releases more Mg^{2+} cations. The results are consistent with Katherine et al. [29], who showed after 70 days of testing on an acid soil that the addition of a dolomitic limestone amendment is very effective in increasing the amount of exchangeable Mg^{2+} and Ca^{2+} cations and especially in correcting soils deficient in exchangeable Mg^{2+} . The exchangeable Ca^{2+} content of all treatments remained lower than that of the T0 control in the S-40. However, Mg^{2+} cations were highest in treatment T3. This finding is due to higher mobility of these cations due to their lower binding energies to functional groups, compared to Ca^{2+} cations as mentioned by de Vargas et al. [30]. These authors observed in acid soils, a better distribution of Mg^{2+} cations than Ca^{2+} cations in the soil profiles following the application of dolomite and quicklime. The almost zero increase in CEC for all treatments compared to the T0 control may be due to the low levels of cation exchange of the adsorbent complex by the base cations of the amendments. This observation of the effect of Ca-Mg amendment on a ferrallitic soil was early mentioned in the tropics [31]. According to Djongo[32]and Rahajaharitombo[33], the slight CEC value would be linked to the NH_4^+ ions brought by the ammonium acetate during the determination of the CEC, which could not extract the acid cations (Al^{3+} , Fe^{3+} and H^+) that are strongly linked to the colloidal complex of the soil. Thus, only a threshold level of base cations, provided by soil amendments, must be reached in order to promote an exchange of acid cations at the level of the soil adsorbent complex [34]. Nevertheless, the increase in pH could induce a release of these acidic elements that potentially bind phosphorus in the soil. For example, increasing the soil pH with lime to at least 6.2 (for most crops) would result in higher phosphorus availability [35].Indeed, the increase in soil pH creates geochemical conditions to release of assimilable phosphorus which is complexed at low pH by Fe^{2+} and Al^{3+} . Rastija et al. [36] showed that a gradual increase in pH induces an increase in bioavailable phosphorus in the soil by reducing exchangeable Al and the acid saturation rate.

Although the effect of liming on soil organic carbon stocks is poorly known, in this study all treatments induced an increase in SOC (Table 2). This is more important for the T2 treatment in S-20 and S-40 reflects the rapidity of the lime on the mineralisation of the soil organic matter compared to the other treatments. According to Paradelo et al. [37], the net effect in liming on SOC will be the result of a number of processes that take place simultaneously. These processes are (i) the increased plant productivity resulting in larger OM inputs which in the context of this study would have a limited impact, (ii) the amelioration of soil structure, that will reduce mineralization by means

of better physical protection of SOC. This process is a long-term process that would also have a fairly limited impact in the time frame of this study. The last process is an increased OM mineralization due to a more favorable pH. This mineralisation of organic matter induced by lime leads to at the same time an increase in the C/N ratio in the soil. In our case, C/N ratio falls in the cultivated aerobic soils C/N range (8 to 15) [38], reflecting the dynamic equilibrium that results from the dominating presence of a microbial population, the ratio being similar to the average chemical composition of microbial cells.

Effects of soil amendments on cocoa plant growth

The results indicated a progressive growth of shoots from treatments T1 to T3 with an increase varying from 23% to 90% while the production of root biomass increased from 17% in treatment 1 to 60% in treatment 3. Thus, the plants in treatment T3 had the highest total dry biomass with a total dry mass of 8.90 g plant⁻¹ and the control with the lowest total dry biomass (4.87 g plant⁻¹). The mass ratios between root and shoot showed values from 0.32 for the plants of treatment T0 to 0.27 for the plants of treatment T3. Plants from treatments T1 and T2 have ratios of 0.30 and 0.28 respectively. The plants from treatment T3 appeared to be the most efficient in assimilating nutrients with low biomass (g)/nutrient (mg) ratios (Figure 4). These increases in plant growth result from the improvements soil chemistry. The treatment T3 showed the best biomass production. This could be explained by the fact that treatment T3, by increasing the pH in S-20, released a greater quantity of assimilable phosphorus and major basic cations (Ca²⁺, Mg²⁺ and K⁺) (Figure 4), which are indispensable for the nutrition and growth of cocoa plants. This observation is in agreement with literature data. Baligar and Fageria[4] showed that liming improves the availability and absorption of nutrients in cacao seedlings, indicating that it not only regulates phytotoxicity but also the efficient use of nutrients. On the other hand, some studies noted that the application of lime raises the pH, improves the absorption and redistribution of N in the plant and releases the phosphorus retained in the soil [39, 40]. Rosas et al. [41] found that the increase in pH improves the availability of P in cacao soils.

Conclusion

The aim of this work was to highlight the effect of dolomite and limestone on the chemical properties of an acid soil and cocoa seedling growth. The characterisation of the studied soil revealed that the fertility is low with base cation (Mg²⁺, Ca²⁺, Na⁺ and K⁺) deficiencies, lower than the minimum threshold values, and a high acidity rate. Liming improves soil chemical properties compared to initial soil status. This improvement was better with treatment using dolomite combined with limestone. However, the pH in the S-20 horizon, exchangeable bases and assimilable soil P, although improved, did not all reach the minimum threshold values recommended for cocoa production. The growth of cocoa seedlings in our experimental conditions was positively impacted

by liming with the best biomass production for treatment combined dolomite and limestone. This treatment also allowed a good efficiency of phosphorus use in the soil. Thus, the combination of dolomite and limestone may therefore constitute an alternative to the use of fertilizer use in cocoa agrosystem. Liming practice is and economic and environmental importance for cocoa production in south-eastern Côte d'Ivoire because, compared with fertilizers, these crushed rocks remain accessible to farmers. However, to better constrain this additional impact on cocoa agrosystem, it would be advisable to carry out a more field study on the nutrient cycles after liming with limestone and dolomite mixture, as well as after the application of other types of powdered basaltic rock, abundant in Côte d'Ivoire. Finally, long-term *in situ* studies to assess, using environmental tracers, the dynamics of liming products in the soil-plant system for better soil restoration and cocoa nutrition.

Data availability

The data is available on request to the author.

Conflict of Interest

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.

Disclosure statement

Author contribution statement (CRediT): Emile B. Bolou-Bi (<https://orcid.org/0000-0001-7803-3214>) - Conceptualization, methodology, visualization and writing - original draft, Jean Baptiste D. Ettien - Funding acquisition and supervision, Annicet Konan - Methodology, Investigation, formal analysis and visualization.

Acknowledgements

This study was funded by the DemoPlot program of the Cargill. The authors would like to thank the ANADER agent in Aboisso for their help during the field campaigns, and Wognin Rosalie and Kouassi Gisèle for their assistance during the laboratory analyses. We would like to thank the two anonymous reviewers for their comments and suggestions to improve the quality of the manuscript.

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Table 1: Selected initial characteristics of soil

| | | S-20 | S-40 | S-60 |
|------------------|------------------------------------|-------------|-------------|-------------|
| Clay | ----- | 14.30 | 18.80 | 49.60 |
| Silt | (%) | 4.40 | 7.90 | 24.30 |
| Sand | ----- | 81.20 | 74.20 | 26.10 |
| OM | | 3.06 | 1.69 | 1.66 |
| pH | - | 4.40 | 5.10 | 5.30 |
| Ca ²⁺ | --- | 0.09 | 0.33 | 1.75 |
| Mg ²⁺ | cmol _c kg ⁻¹ | 0.04 | 0.07 | 0.16 |
| K ⁺ | ----- | 0.02 | 0.02 | 0.06 |
| CEC | | 5.00 | 5.42 | 9.10 |
| Ca/Mg | - | 2.02 | 4.45 | 10.71 |
| Mg/K | - | 2.32 | 4.05 | 2.52 |
| Ca+Mg/K | - | 7.01 | 22.05 | 29.46 |

Table2: Selected chemical parameters of soil after Ca-Mg amendment. In the same column, the same letters indicate that the difference is not statistically significant with $p>0.05$. *Snoeck et al. 2005.

| | | C | N | OM | Ca²⁺ | Mg²⁺ | K⁺ | CEC | P_{available} | C/N | Ca/Mg | Mg/K | Ca+Mg/K |
|----------------|----|-----------------|-------------|-------------|--|------------------------|----------------------|-------------|------------------------------|------------|--------------|-------------|----------------|
| | | ----- (%) ----- | | | ----- cmol _c kg ⁻¹ ----- | | | | mg kg ⁻¹ | - | - | - | - |
| S-20 | T0 | 0.90±0.04d | 0.08±0.01b | 1.54±0.24b | 0.88±0.06c | 0.48±0.09c | 0.07±0.00b | 5.60±0.12ab | 45.66±2.31c | 11.21 | 1.83 | 6.86 | 19.43 |
| | T1 | 1.04±0.09b | 0.10±0.01a | 1.78±0.15b | 0.98±0.04b | 0.64±0.07a | 0.08±0.01a | 5.44±0.24b | 51.04±3.46b | 10.40 | 1.53 | 9.14 | 23.14 |
| | T2 | 1.18±0.01a | 0.10±0.01a | 2.02±0.19a | 0.98±0.05b | 0.49±0.06c | 0.07±0.01b | 5.68±0.04a | 85.90±0.71a | 11.80 | 2.00 | 7.00 | 21.00 |
| | T3 | 1.02±0.01c | 0.09±0.01a | 1.75±0.17b | 1.06±0.10a | 0.57±0.07b | 0.09±0.00a | 5.20±0.11b | 86.10±1.41a | 11.33 | 1.84 | 6.33 | 18.00 |
| S-40 | T0 | 0.76±0.06c | 0.07±0.01c | 1.30±0.11b | 1.31±0.29a | 0.48±0.00b | 0.07±0.00b | 6.24±2.64b | 74.12±6.66b | 10.86 | 2.72 | 7.29 | 27.12 |
| | T1 | 0.88±0.01b | 0.08±0.00b | 1.51±0.02a | 0.81±0.12b | 0.49±0.10b | 0.07±0.02b | 7.80±0.09a | 89.08±9.64ab | 11.00 | 1.69 | 7.24 | 19.31 |
| | T2 | 1.18±0.01a | 0.10±0.00a | 1.47±0.03a | 0.81±0.17b | 0.48±0.13b | 0.07±0.02b | 3.84±1.07c | 107.80±13.44a | 11.80 | 1.67 | 7.45 | 19.86 |
| | T3 | 0.88±0.11b | 0.08±0.01b | 1.51±0.18a | 1.19±0.11ab | 0.67±0.02a | 0.10±0.01a | 5.36±0.05b | 88.98±2.83ab | 11.00 | 1.79 | 7.16 | 20.00 |
| S-60 | T0 | 0.80±0.06a | 0.07±0.01ab | 1.37±0.11b | 0.98±0.04a | 0.67±0.01a | 0.10±0.03b | 5.60±0.35a | 85.48±15.31c | 11.43 | 1.47 | 6.78 | 16.75 |
| | T1 | 0.70±0.09b | 0.07±0.01ab | 1.20±0.05c | 1.02±0.02a | 0.71±0.01a | 0.10 ±0.01b | 5.04±0.21a | 144.07±11.24b | 10.00 | 1.50 | 7.55 | 18.90 |
| | T2 | 0.68±0.11b | 0.06±0.01b | 1.17±0.19bc | 1.05±0.02a | 0.68±0.01a | 0.14±0.03a | 4.96±0.28a | 188.09±4.24a | 11.33 | 1.54 | 4.86 | 12.36 |
| | T3 | 0.84±0.09a | 0.08±0.01a | 1.44±0.02a | 1.03±0.02a | 0.66±0.01a | 0.09±0.01a | 5.36±0.21a | 92.18±3.06c | 10.50 | 1.56 | 6.95 | 17.78 |
| Minimal Limit* | | 2.60 | 0.03 | 2.88 | 11.00 | 2.45 | 0.70 | 21.00 | 11.00 | 12.50 | 2.80 | 3.00 | 11.50 |

Figure captions

Figure 1: Study area in the Aboisso region.

Figure 2: Evolution of the pH of the soil horizons of the different treatments after the cocoa seedling growth. The same letters indicate that the difference is not statistically significant with $p > 0.05$.

Figure 3: Biomass (Shoot (green) and root (brown)) of cocoa seedling after of six months of growth. The same letters or symbol in each type of biomass indicate that the difference is not statistically significant with $p > 0.05$.

Figure 4: Relation between total biomass produced and the sum of bases in soil after Ca-Mg amendment.

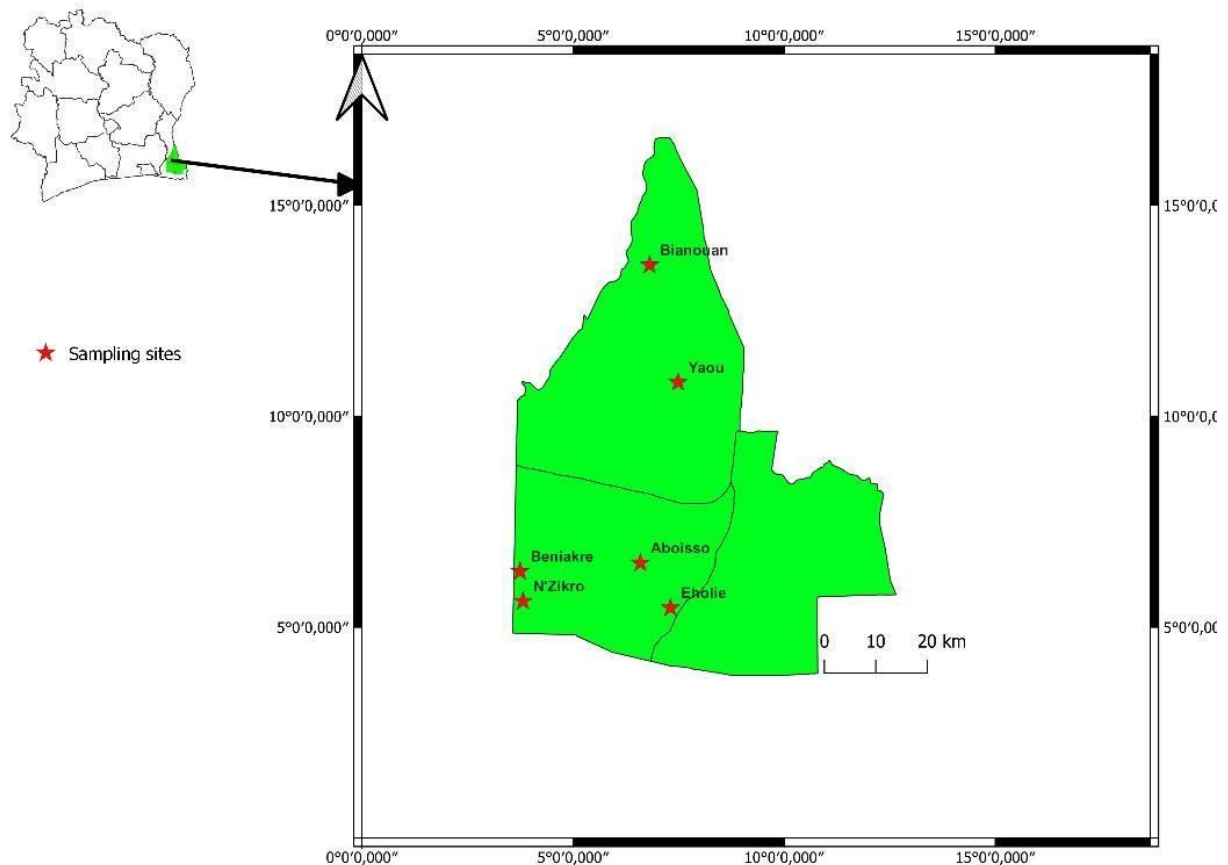


Figure 1

Figure 2

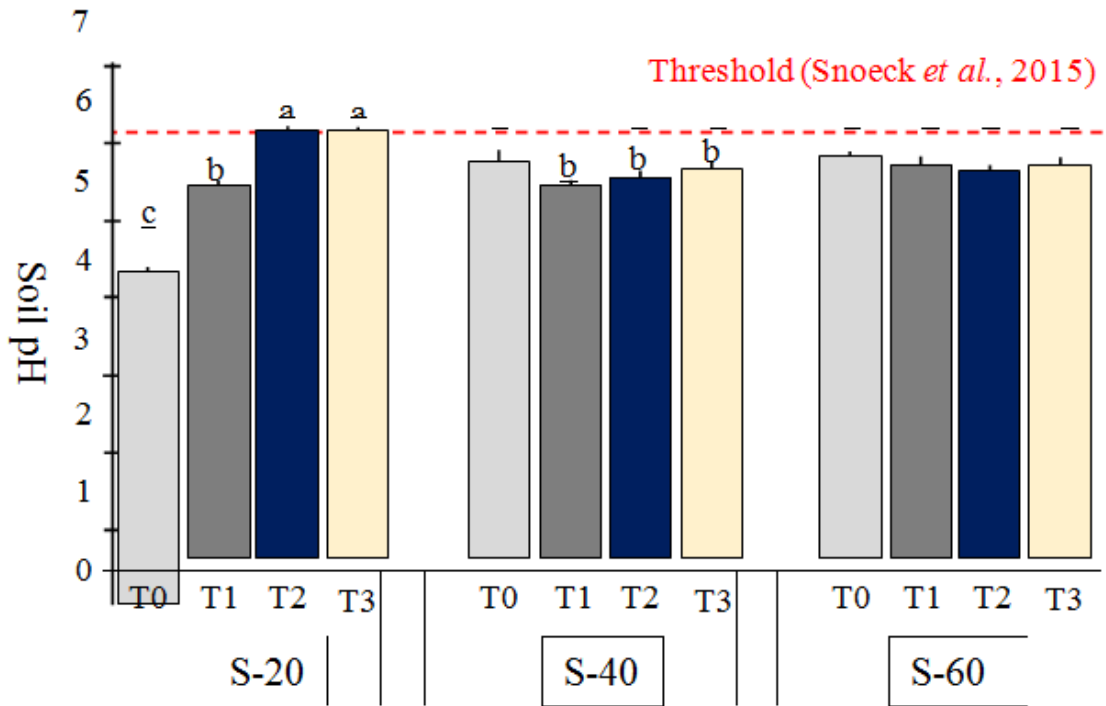
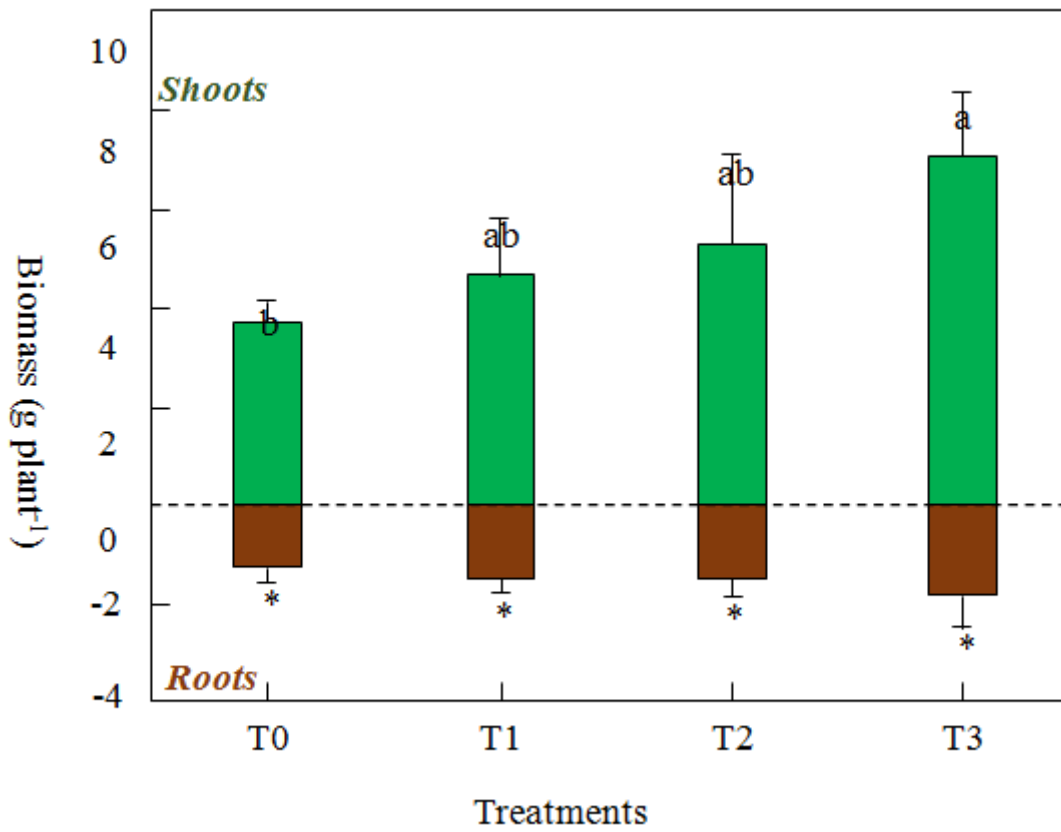


Figure 3



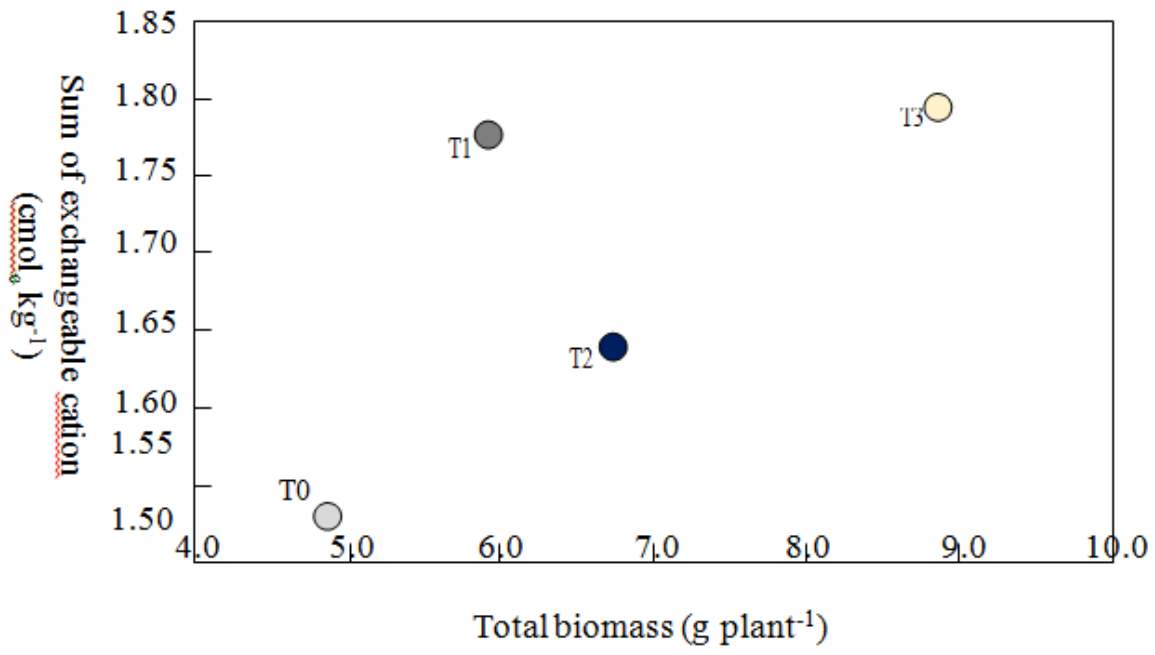


Figure 4