

Soil Acidification in Cocoa (*Theobroma cocoa* L.) Agrosystems in Côte d'Ivoire (I): Comparative effects of a carbonate (dolomite and limestone)-based mineral amendment on soil chemical properties and the growth of cocoa seedlings.

Abstract

Acidification of soils is a major concern in Côte d'Ivoire. The present study investigates the effect of a calco-magnesian (dolomite and limestone) amendment on soil chemistry and cocoa seedling growth. To this, cocoa seedlings were grown in a greenhouse using soils sampled from farms in Aboisso (south-east of Côte d'Ivoire). Soils were sampled at three different depths (0-20 cm; 20-40 cm and 40-60 cm). Then, a representative composite soil sample of each horizon was constituted in soil columns. The experimental trial was conducted in a total randomisation system with six repeated treatments (Dolomite 100%, Limestone 100%, Dolomite 50% + Limestone 50%) compared to control, soil without amendment. After six months, the results showed that carbonate application did not induce a significant difference ($p > 0.05$) in the growth of seedlings. However, the chemical properties of amended soil showed an improvement compared to the control. The treatments containing limestone improved the chemical properties of the soil (base cation, CEC, pH). However, all the parameters measured remain insufficient compared to the minimum threshold values for better cocoa tree growth. In addition, the combination of dolomite and limestone appears to be an amendment with a high potential for improving the fertility of acid soils under cocoa.

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. After some difficult during the starting of cocoa farming, cocoa agrosystem expanded very rapidly in the country, especially after the Second World War [2]. However, the development of this crop was based on extensive cultivation practices in shifting cultivation systems combining cocoa with food crops to the detriment of forest ecosystems. This cocoa agrosystem model is no longer possible because of the scarcity of forest reserves in Côte d'Ivoire, which have fallen from 16.5 million hectares in the 1960s to only 2 million hectares in 2020 [3]. In addition to this deforestation, cocoa agrosystem soils become more acidic [4]. Thus today, cocoa agrosystem in Côte d'Ivoire is faced with numerous constraints that threaten its sustainability with low yield [5], cocoa epidemics 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 saturation deficit, especially of alkaline earth cations (Ca^{2+} and Mg^{2+}) and alkaline cations (Na^+ and K^+). In this context, the former cocoa orchards, 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, with a drastic loss of about 80% of forest cover in Côte d'Ivoire.

Alternative ways for sustainable soil fertility management in the former cocoa plantation in 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 plantation would 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. Calcomagnesian amendments 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 calcomagnesian amendments in these ecosystems leads to an improvement in tree mineral nutrition condition, which is reflected in 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 calcomagnesian amendment leads to an improvement of humus and chemical characteristics of the soil. It has favourable effects on the structure and decomposition of organic horizons [11, 12, 13]. The application of amendments restores the chemical fertility of the soil. The pH, calcium and magnesium contents and reserves as well as the saturation rate of alkaline and alkaline earth cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+) are the most improved soil variables. The calcium and magnesium nutrient status in soils under the forest stand is 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, the effect of calcomagnesian amendments 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 of this study is 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 tree 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 the south-east of Côte d'Ivoire (Figure 1). The cocoa seeds (*Theobroma cacao* L.) are the Forastero variety collected from plantations in Aboisso cocoa-growing area (south-east of Côte d'Ivoire), where the plantations are developed on a ferralsol. 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 a shade house located at the University Félix Houphouët-Boigny, Abidjan (Côte d'Ivoire). The experimental device unit consisted of tube ($\varnothing \sim 20$ cm, L ~ 70 cm) nested in a wooden support. Each tube had a nylon filter (5 μ m mesh) at its base which served as a soil support. In these tubes, collected soil horizons from cocoa plantations were reconstituted according to the soil profile in field. Reconstituted soils were then watered for a fortnight before sowing of cocoa beans. One month after sowing, increasing doses of dolomite and lime was 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 plants 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 of cultivation, the device was dismantled in order to recover the soil at different depths (S-20, S-40, S-60) and plant biomass. For this purpose, a longitudinal section of the experimental unit was made, taking care to not mix soil horizons. Samples from each horizon in the experimental unit were taken 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. 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 sample is shaken with 50 ml of 1 M ammonium acetate solution (Reagent grade $\geq 98\%$, Sigma-Aldrich®) at pH 7 to

extract exchangeable bases (Ca^{2+} , Mg^{2+} , Na^+ and K^+). Three successive extractions were carried out on each batches of samples using the same solution of ammonium acetate. Then, the solutions resulting from these successive extractions were mixed for each soil batches, then filtered through a polytetrafluoroethylene (PTFE) filter. Exchangeable bases (Ca^{2+} , Mg^{2+} , Na^+ and K^+) were determined by Inductively Coupled Plasma Optical Emission Spectroscopy (Perkin Elmer®)

Soil CEC was determined by the cobaltihexamine chloride method. About 2.5 g of dried sample, sieved to 2 mm, was shaken with 50 ml of 50 $\text{mmol}^+\cdot\text{L}^{-1}$ of cobaltihexammine solution (Reagent grade $\geq 98\%$, Sigma-Aldrich®). After centrifuging and filtering the solution, concentration of cobaltihexammine 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, Thermo Fischer®. 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 [14]. 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 [15]. 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 [16]. At these low pH values, many unfavourable phenomena for plant growth such as phosphorus deficiency, Al^{3+} and Mn^{2+} toxicity [17, 18] 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 [19]. The causes of this poverty in exchangeable bases would be linked to the phenomenon of acidification and losses by leaching [20]. The studied soils are depleted in major cations (Ca^{2+} ; Mg^{2+} and K^+) with values below the respective fertility thresholds [15], 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 ($11 \text{ cmol}_+ \text{ kg}^{-1}$, $2.45 \text{ cmol}_+ \text{ kg}^{-1}$ and $0.7 \text{ cmol}_+ \text{ kg}^{-1}$ 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 [21], 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 [22], 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 applied products of amendment did not migrate into the soil's deep horizon in our experimental conditions. Bolou-Bi et al [23] 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+} [24]. Under these conditions, the exchange complex of the surface horizons would not have been completely saturated for possible migration to the deep horizons. One of the hypotheses in the literature to explain this low migration of powered carbonate in soil would be a too high content of Al^{3+} in the soil horizons, especially from 30 cm, which plays a role of buffer [25]. 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. [26], 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. [27]. 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 [28]. According to Djongo [29] and Rahajaharitombo [30], 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 [31]. 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 [32]. 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. [33] 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. [34], 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) [35], 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 [36, 37]. Rosas et al. [38] 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 lime 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 a deficiency in major cations, lower than the minimum threshold values, and a high acidity rate. The addition of the soil improver led to an improvement in the chemical properties of the soil

compared to the control. This improvement was more important with the addition of dolomite combined with lime. 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. However, the growth of cocoa seedlings in our experimental conditions was positively impacted by the addition of amendment products with the best biomass production for the combination of dolomite and lime. this treatment also allowed a good efficiency of phosphorus use in the soil. Thus, the combination of dolomite and lime may therefore constitute an alternative to the use of fertiliser use in cocoa agrosystem. This practice of lime application to soil is 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 yield and sustainability, it would be advisable to carry out a more in-depth study on the nutrient cycles after the application of lime and dolomite, as well as after the application of other types of crushed rock, abundant in Côte d'Ivoire. Finally, long-term *in situ* studies to assess, using environmental tracers, the dynamics of the amendment products in the soil-plant system for better soil restoration and cocoa nutrition.

Data availability

The data is available on request to the author.

References

[1] ICCO, 2015. Quarterly Bulletin of Cocoa Statistics, XLI (2), Cocoa year 2014/2015.

- [2] Youan LG, Gnamba-Yao JB and Aloko NJ, 2020. The impact of the dynamics of cocoa farming on the rural development of the sub-prefecture of KOUIBLY in the west of Côte d'Ivoire. *Revue Esp. Geo. & Soc. Mar.*, 33-34:165-190.
- [3] FAO 2018. Climate-Smart Agriculture in Côte d'Ivoire. CSA Country Profiles for Africa Series. Available on <https://www.fao.org/3/ca1322en/CA1322EN.pdf>
- [4] Baligar VC and Fageria K, 2005. Soil aluminum effects on growth and nutrition of cacao. *J. Soil Sci. Plant Nutr.* 51:709-713. <https://doi.org/10.1111/j.1747-0765.2005.tb00097.x>.
- [5] Kassin KE, 2009. Studies of pedoclimatic conditions for cocoa replanting in the Center-West of Côte d'Ivoire: case of the departments of Divo and Gagnoa. Doctoral thesis, University of Cocody-Abidjan, Abidjan, Ivory Coast.
- [6] Stemler C, 2012. Analysis of variation in responses to fertilizer and dynamics of intensification in the cocoa sector in Côte d'Ivoire. CIRAD, Montpellier, France.
- [7] Uwiragiye Y, Ngaba MJY, Yang M, Elrys AS, Chen Z and Zhou J. Spatially explicit soil acidification under optimized fertilizer use in sub-saharan Africa. *Agronomy*. 2023; 13(3):632. <https://doi.org/10.3390/agronomy13030632>.
- [8] Assiri AA, Konan A, N'Guessan KF, Kebe BI, Kassin KE, Couloud JY, Yoro GR and Yao Kouamé A, 2015. Comparison of two cocoa replanting techniques on non-forestry antecedents in Ivory Coast. *J. Anim. Plant Sci.* 23:365-378. doi:10.4314/acsj.v23i4.6.
- [9] Fabre B and Kockmann F, 2002. The practice of liming: from the construction of the Regional benchmark to the operational advice approach. *And you. Gest. Ground.* 9:213-224.
- [10] Wei X, Hao M, Shao M and Gale WJ, 2006. Change in soil properties and availability of soil Micronutrients after 18 years of cropping and fertilization. *Soil Tillage Res.* 91:120-130. <https://doi.org/10.1016/j.still.2005.11.009>.
- [11] Mattieu L, 2017. Study of the impact of liming on the physicochemical properties of the soil and biogeochemical cycles in forest ecosystems. End of study dissertations in Bioengineering, Gembloux Agro-Bio Tech, Gembloux, Belgium.
- [12] Chimdi A, Gebrekidan H, Kibret K and Tadesse A, 2012. Effect of liming on acidity Related chemical properties of soils of different land use system in western Oromia, Ethiopia. *World J. Agric. Sci.* 8 : 560-567. Available online <http://www.idosi.org/.../2.pdf>.
- [13] Castro GSA and Crusciol CAC, 2015. Effects of surface application of dolomitic limestone and calcium-magnesium silicate on soybean and maize in rotation with green manure in a tropical region. *J. Plant Nutr. Bragantia* 74:311-321. <https://doi.org/10.1590/1678-4499.0346>.
- [14] Philippe M, 1995. Choice of a method for measuring phosphorus. Martinique analysis laboratory. CIRAD-FLHOR, Montpellier 15 p.
- [15] Snoeck D, Koko L, Joffre J, Bastide P and Jagoret P, 2015. Cacao Nutrition and Fertilization. In: Lighthouse E. (Ed.), *Sustainable Agriculture Reviews*. Cham, Springer International Publishing 19 :155-202. doi: [10.1007/978-3-319-26777-7_4](https://doi.org/10.1007/978-3-319-26777-7_4).

- [16] Adéchina O, Ouattara A, Alla KS, Nassa E and Yao-Kouamé A, 2018. Chemical characterization and physico-chemical soils from Mamlanso to Aboisso Comoé in the South-East of Ivory Coast. Mission report, Abidjan, Ivory Coast. 15p.
- [17] Rahman MA, Lee SH, Ji HC, Kabir AH, Jones CS and Lee KW, 2018. Importance of mineral nutrition for mitigating aluminum toxicity in plants on acidic soils: current status and opportunities. *Int. J. Mol. Sci.* 19:3073. doi: [10.3390/ijms19103073](https://doi.org/10.3390/ijms19103073).
- [18] Arias M, García-Río L, Mejuto J, Núñez-Delgado A and Silva-Carvalho J, 2006. Retention of phosphorus by iron and aluminum-oxides-coated quartz particles. *J. Colloid Interface Sci.* 295:65-70. <https://doi.org/10.1016/j.jcis.2005.08.001>.
- [19] N'Guessan K, Akotto OF, Snoeck D, Camara M and Yao-Kouamé A, 2016. Potentiel de fertilité chimique des vergers de cacaoyer (*Theobroma cacao* L., Malvaceae) en Côte-d'Ivoire. *Int. J. Innov. Appl. Stud.* 18:868- 879.
- [20] Goulding KW, 2016. Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. *Soil Use Manag.* 32 : 390-399. <https://doi.org/10.1111/sum.12270>
- [21] Driscoll K, 2014. Fate of limestone dissolution products in acidic metalcontaminated soil mesocosms. Master's Theses, Laurentian University of Sudbury, Canada. 441 p.
- [22] Wijanarko A and Taufiq A, 2016. Effect of lime application on soil properties and Soybean yield on tidal land. *J. Agric. Sci* 38:14-23. <https://doi.org/10.17503/agrivita.v38i1.683>
- [23] Bolou-Bi EB, Dambrine E, Angeli N, Pollier B, Nys C, Guerold F and Legout A. 2016. Magnesium isotope variations to Trace Liming input to Terrestrial Ecosystems: A case study in the Vosges Mountains. *J. Environ. Qual.* 45:276-284. <https://doi.org/10.2134/jeq2015.02.0096>.
- [24] Chaganti V and Culman S, 2017. Historical perspective of soil balancing theory and identifying knowledge gaps: A Review. *Crop. Forage Turfgrass Manag.* 3:1-7. <https://doi.org/10.2134/cftm.2016.10.0072>.
- [25] Godefroy J, Lassoudiere A, Lossois P and Penel JP, 1978. Action du chaulage sur les Caractéristiques physico-chimiques et la productivité d'un sol tourbeux en culture bananière. *Fruits* 33:77-90.
- [26] Katherine SR, David LR and Keith SJ, 1995. Effect of liming on the chemical composition of soils. *J. Sci. Food Agri.* 199:159-167. <https://doi.org/10.1002/jsfa.2740690205>.
- [27] de Vargas JPR, Santos DR, Bastos M, Schaefer G and Parisi PB, 2019. Application forms and types of soil acidity corrective: Changes in depth Chemical attributes in long-term period experiment. *Soil Tillage Res.* 185 :47-60. <https://doi.org/10.1016/j.still.2018.08.014>.
- [28] Angui P, Gone D and Djebre L, 2009. Comparative effects of lime and dolomite induction on [some chemical parameters of a ferrallitic soil and an organic soil in the south of Ivory Coast.](https://doi.org/10.4314/aga.v21i2.49805) *Agron. Afri.* 21:155-163. doi:10.4314/aga.v21i2.49805
- [29] Djongo MY, 1995. Ion exchange properties of clayey ferrallitic soils of the valley

Nairi and sandy plateau of Mbe-Bateké in Congo. Application to the correction of their acidity, Doctoral Thesis, Soil Science, University of Paris 12-Val de Marne, Paris, France.

- [30] Rahajaharitompo RL, 2004. Management of fertility and phosphate fertilization of ferrallitic soils in the highlands of Madagascar. Doctoral thesis, University of Antananarivo, Madagascar.
- [31] Bycé B, Moreau R and Feller C, 1998. Decomposition of a crumb of manure in a sandy slope soil and a clay-luminous lowland soil in the Sudano-Sahelian environment (Burkina-Faso). *And you. Gest. Ground.* 5:83-92.
- [32] Mkhonza NP, Buthelezi-Dube NN and Muchaonyerwa P, 2020. Effects of lime application on nitrogen and phosphorus availability in humic soils. *Sci. Rep.*10:8634. <https://doi.org/10.1038/s41598-020-65501-3>.
- [33] Rastija D, Loncaric Z, Karalic K and Bensa A, 2008. Liming and fertilisation impact on nutrient statut in acid soil. *Cereal Res. Commun.* 36:339-342. <http://www.jstor.org/stable/90002710>.
- [34] Paradelo R, Virto I and Chenu C, 2015. Net effect of liming on soil organic carbon stocks: A review. *Agric. Ecosyst. Environ.* 202 :98-107. <https://doi.org/10.1016/j.agee.2015.01.005>.
- [35] Boyd C.E, 2009. Carbon-nitrogen ratio management: C:N influences rate at which residue decomposes. Available on <https://www.globalseafood.org/advocate/carbon-nitrogen-ratio-management/>.
- [36] Zhu J, Li M and Whelan M, 2018. Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review. *Sci Total Environ.* 612: 522537. <https://doi.org/10.1016/j.scitotenv.2017.08.095>.
- [37] Lavres JJ, Reis AR, Rossi ML, Cabral CP, Nogueira NL and Malavolta E, 2010. Changes in the ultrastructure of soybean cultivars in response to manganese supply in solution culture. *Sci. Agric.* 67 :287-294. <https://doi.org/10.1590/S0103-90162010000300006>.
- [38] Rosas-Patiño G, Puentes-Páramo YJ and Menjivar-Flores JC, 2019. Liming effect on macronutrient intake for cacao (*Theobroma cacao* L.) in the Colombian Amazon. *Cien. Tecnol. Agropecuaria* 20:17-28. https://doi.org/10.21930/rcta.vol20_num1_art:1247.

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

Table 2: 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

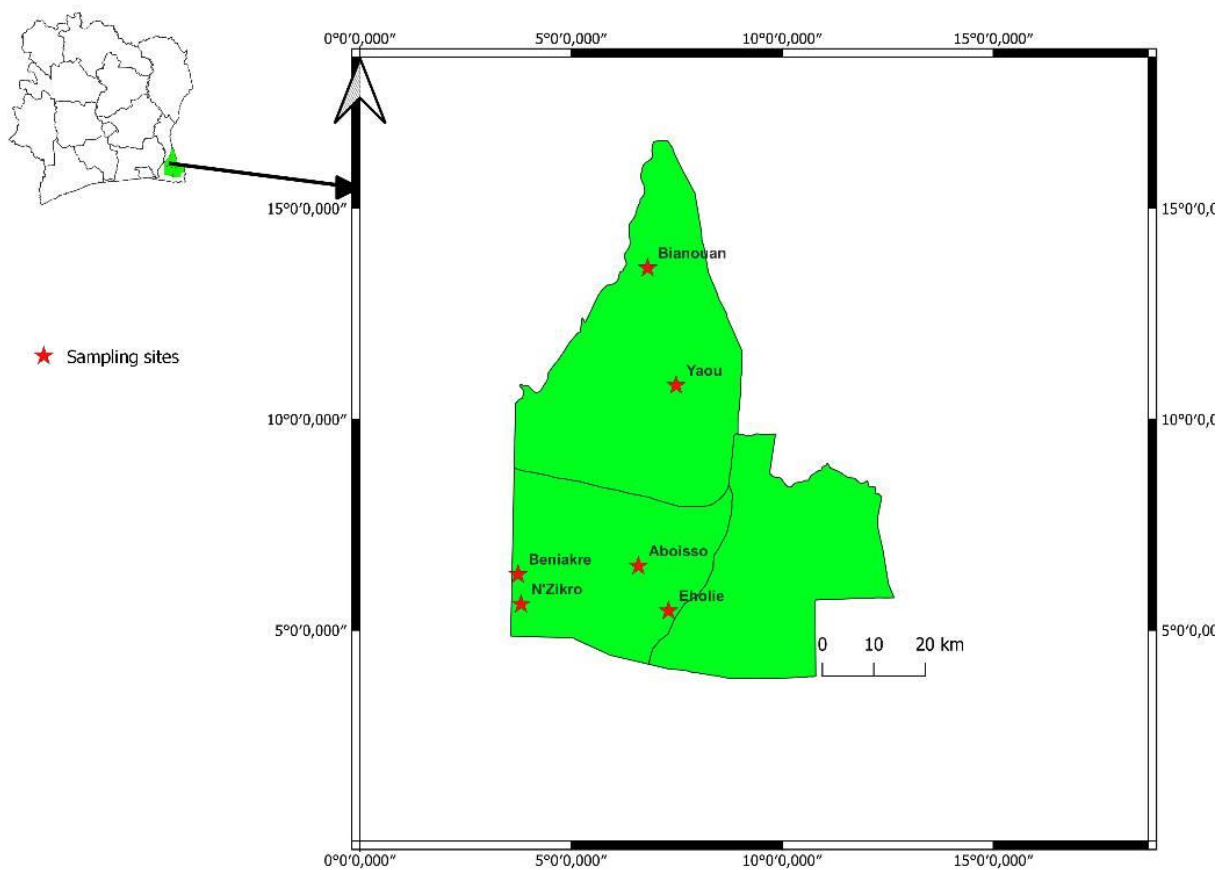


Figure 2

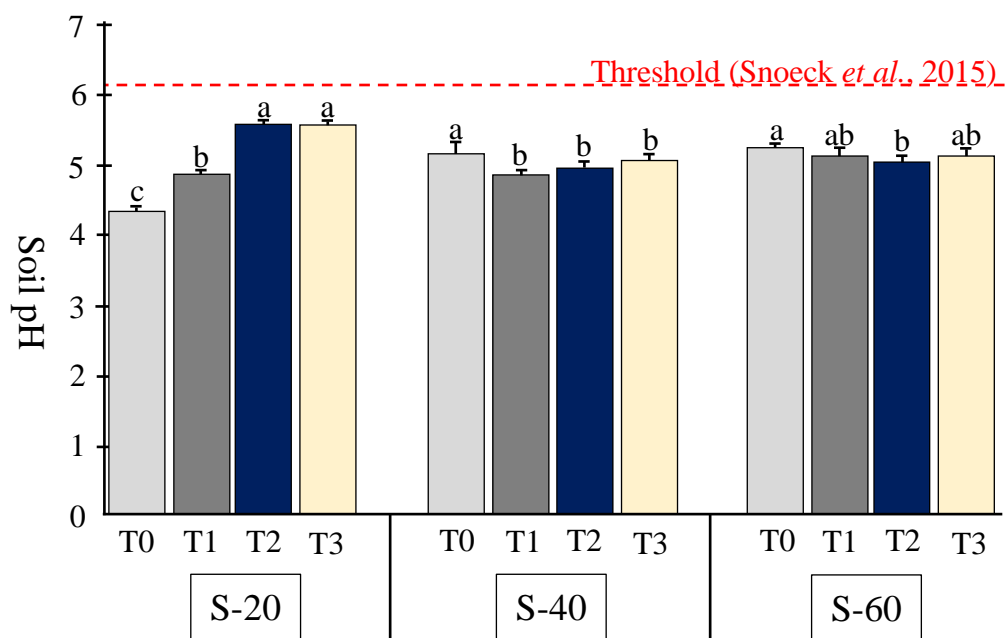


Figure 3

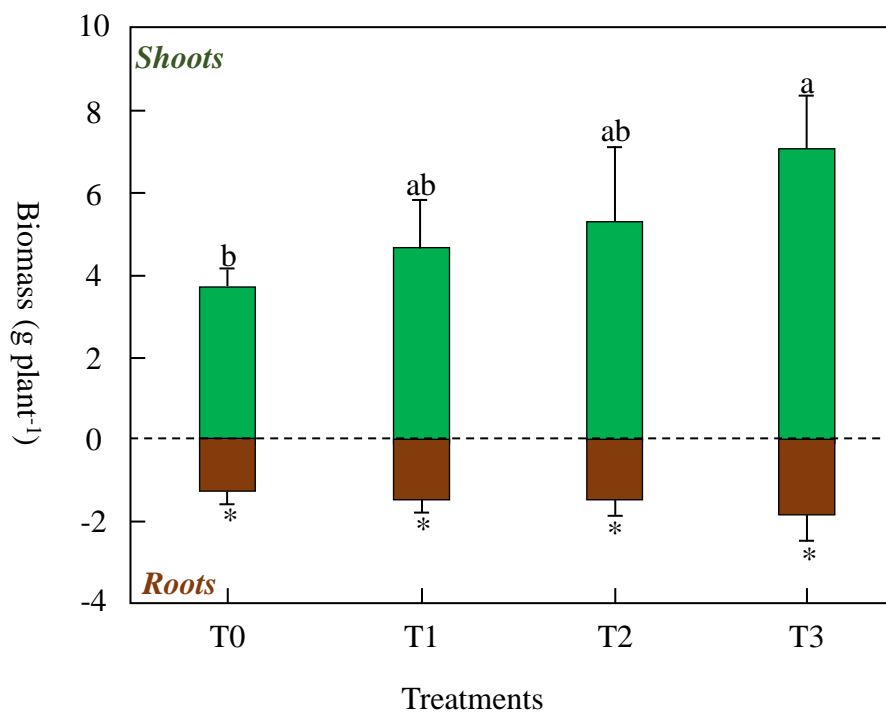


Figure 4