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IRON DYNAMICS AND RISK OF IRON TOXICITY IN SOILS OF THE FOREST ZONE OF SOUTH-EASTERN COTE D'IVOIRE

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ABSTRACT

In order to better understand the soils of the forest zone of the South-East of Côte d'Ivoire, four observation sites were identified at the Agropastorale B29 farm in the locality of Aboisso Comoé. These observations aimed in particular to quantify the different forms of iron in the soils, according to their depths and their topographical segments, in order to assess the risk of iron toxicity. For this purpose, soil pits were opened and described then soil samples were taken for laboratory analysis. The results obtained were compared to the reference values. They show that the soils are essentially Cambisols. They contain high levels of coarse manganiferric elements and clods, with polyhedral or particulate structures. They have a high concentration of free iron and total iron. Free iron is relatively more abundant in the surface horizons (0-20 cm) of the soil and in the topographic position of the lowlands. Thus, the free iron content is between 0.19% and 0.44%. A part of the free iron in the soil located on the surface of the soil where active surfaces such as clays and silts dominate, forms complexes with these particles and the other part is present in mobile forms in low topographical positions bottom. As for total iron, it is more concentrated at depth (60-120 cm), in the soils at the top and bottom of the slope with concentrations between 2.42% and 8.16%.

Keywords: Cambisol, Forest zone, Free iron, South-East of Côte d'Ivoire, Total iron.

1. INTRODUCTION

Since its independence, Côte d'Ivoire has based its economic and social development on agriculture. Thus, the agricultural sector of Côte d'Ivoire represents approximately 33 percent of

GDP, 70 percent of national export revenues and employs more than two-thirds of the country's active population [1,2]. In the 1960s, this agriculture was essentially based on the coffee-cocoa pairing which until recently constituted the pillars of the Ivorian economy. With an average annual production of 400,000 tonnes of marketable coffee, the country was ranked first in Africa and third in the world until the end of the 1980s. Since then, this production has seen a decline [3], putting the country in fourth place in Africa after Ethiopia, Uganda and Kenya, and in fifteenth place in the world [4]. Thus, coffee production, estimated at 250,000 T in 1990, was less than 120,000 T in 2015 [5]. Also, increasing cocoa production has become a necessity and a challenge for the main producing countries [6], in particular for Côte d'Ivoire, the world's leading producer [7]. Despite Côte d'Ivoire's position as the world's leading cocoa producer, Ivorian cocoa farming remains characterized by low yields.

Aboisso Comoé, a region in the southeast of Côte d'Ivoire and part of the forest ecozone, is an area of high agricultural production. In this region, perennial crops are grown (cocoa crops, rubber crops, coffee crops, oil palm crops, etc.), cash crops and vegetable crops. But it is clear that after several harvests, the yield remains low. However, this drop in production is due to the combined effects of several factors: the aging of the orchard, parasitic pressure, the substitution of the coffee-cocoa pair by more profitable crops, notably rubber, the low level of adoption of technical routes recommended by research, and above all, the problems of physical and chemical degradation of cultivated soils [8,9]. Indeed, the problems of physical and chemical degradation of cultivated soils are currently becoming a major concern throughout the world due to its unfavorable impacts on agricultural production, food security and the environment. Also, the modification of precipitation patterns due to climate change would increase the probability of poor harvests and a drop in production [10].

Zinc, manganese and iron are trace elements which intervene in small quantities to maintain the normal growth of the plant. But in high quantities, they become harmful to the plant [11]. So, the increase in iron availability in soils has also been identified as a threat to cultivated soils. While, since the 1960s, pedological studies carried out have highlighted the major presence of ferallitic and ferruginous soils which are characterized by high iron contents with the risk of iron toxicity in the soils, thus leading to a drop in the chemical fertility of agricultural land [12]. Iron toxicity is a nutritional (physiological) disorder which results from a high assimilation of reduced iron (Fe^{2+}) in plant tissues, following a high availability of reduced iron in the soil (> 0.003%). Iron toxicity is therefore a significant problem in West African soils, particularly in the lowlands where the topography is favorable. Therefore, devoting an entire study to soil iron would make it possible to determine the concentration of iron in soil samples in order to improve crop health for better yield and avoid iron toxicity in the environment, which generally forms under a form of hard water that can potentially destroy cultivated fields, due to salinity, or cause health problems in animals and humans.

Following the example of these facts, the present study therefore aims to evaluate the dynamics of the content of the different forms of iron in the Cambisols of the agropastoral farm B29, the conditions for the development of iron toxicity in the soil and establishes.

More specifically, this involves: (i) characterizing the physical and chemical properties of the soil, through openings of soil pits, and (ii) determining the relationships that exist between these forms of iron and their evolution and accumulation in function of soil distributions according to the topo sequences produced.

2. MATERIALS AND METHODS

2.1. Study environments

The research work was carried out in the locality of Aboisso comoé (dense humid forest zone), located in the south-east of Côte d'Ivoire. The locality of Aboisso Comoé bathes in the transitional equatorial climate of the Attien type, characterized by four (4) seasons including two (2) dry seasons and two (2) rainy seasons. The works were carried out at B29, located approximately 20 km from the town of Mamlanso. This village is located geographically by the coordinates 5° 45'49.6" North latitude and 3° 18'17.7“West longitude [13].

The soils of this area come from the alteration of materials from the volcano-sedimentary complex consisting essentially of microgabbro and amphibolo-pyroxenite. Most of the soils in this locality belong to the class of ferrallitic soils (Ferralsols), hydromorphic soils (Gleysols) and Cambisols (Fig. 1).

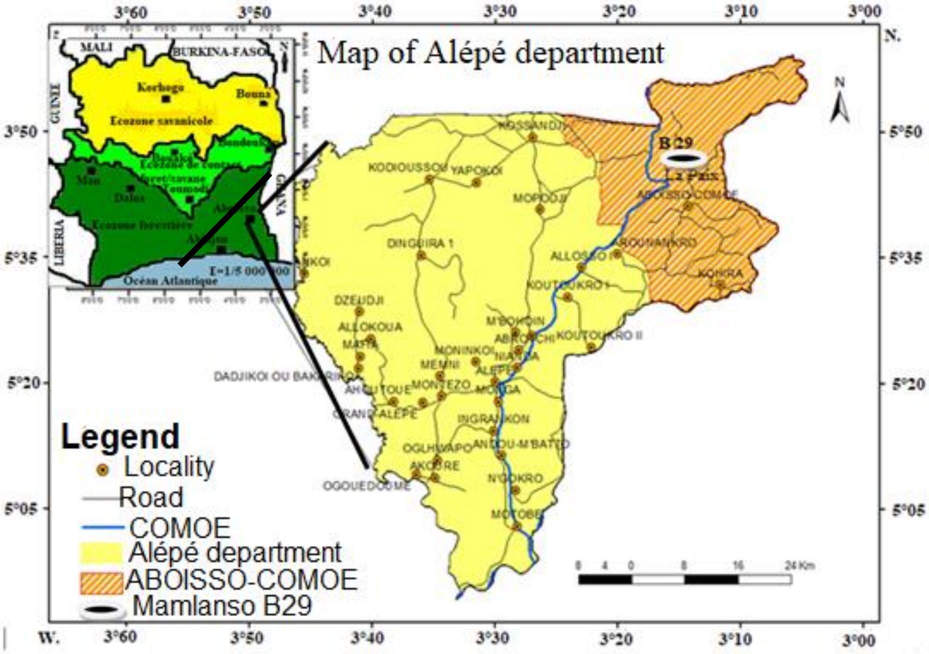


Fig. 1: Geographic map of the department of Alépé and the sub-prefecture of Aboisso-Comoé

2.2. Material and method

2.2.1. Technical field equipment

The technical equipment consists of a graduated tape measure, a GPS (Global Positioning System) of the Garmin type, a clinometer, spades, picks, scissors, indelible markers and a compass of the type TOPOCHAIX. The equipment for observing the environment and describing soil profiles consists of machetes, milestones, stakes, a geologist's hammer, a soil scientist's knife, plastic bags, a 50m tape measure, a 1m tailor's meter, a Munsell code, a 2mm diameter mesh sieve, soil description sheets from the IRD glossary (ex ORSTOM) and an Infinix Hot 4 mobile phone for sockets of photographs.

2.2.2. Choice of study plots

This phase was devoted to observation carried out in the field. It allowed us to constitute a database including the types of vegetation and the topographical segments which guided our choice and the selection of the places of description and sampling. The types of vegetation observed are primary forest, cocoa growing, rubber growing, coffee growing, rice growing and fallow. On the other hand, the topographic segments are the different altitude ranges, from the summit to the bottom, including the mid-slope. This is a method which was described by Ruhe and Walker [14], and which has the advantage of providing information for each unit.

2.2.3. Laboratory chemical analyzes

The soil samples were taken according to three depths 0-20 cm, 20-60 cm and 60-120 cm in order to better appreciate the dynamics of the iron forms. So, after sampling, the soil samples were first dried on newspaper at room temperature in the laboratory (25 to 30°C). The variables studied are the contents of free iron and total iron. These variables were obtained after soil analysis in the laboratories of the Yamoussoukro agronomy school (ESA) and SODEMI in Abidjan in Côte d'Ivoire. The dosage of reduced iron (Fe^{2+}) is carried out by spectrophotometry (Shimadzu ® UV -1205), with the Aquamerck Eisen-Test 8023 (Merck-1) method, based on the formation of a very stable pink – dark red complex between the Fe^{2+} and 2,2'-bipyridine. The solution is filtered at 0.22 µm and the optical densities (OD) are measured at 523 nm, then converted to mg. l^{-1} using a standard range. To determine total iron, the soil samples underwent crushing followed by grinding and pulverization to achieve a grain mesh size of 75 µm at 80%. The pulp was pelletized for the determination of chemical elements (major oxides) by X-ray Fluorescence (XRF).

2.2.4. Statistical analyzes of data

An analysis of variance (ANOVA) with a Games-Howell post hoc test was used to detect significant differences between land cover types, topographic positions and depths of soil horizons. The Howell test was chosen for the post-hoc comparison because it is robust for:

- Small, uneven samples and not all combinations of soil type and land cover type are there;
- Differences in variances between groups; which was the case with our dataset.

The statistical analysis was carried out on the differences in the contents of the explanatory factors for the upper layer (0-20 cm), the mid-depth layers (20-60 cm) and the layers of depth 60-120 cm, at l help of the R 4.2.3 software (R Core Team, 2023) and its working interface (RStudio, 2023). The data included the content of response or explanatory factors: total iron (Fet) and free iron (Fed).

The normality of the distribution was checked for each variable using the Shapiro-Wilk test. Non-parametric tests were applied where appropriate: the Mann-Whitney U test for comparison of element content between soil groups. The homogeneity of the data was also assessed by calculating the coefficient of variation (CV). CV values <15% were classified as less variable while those with a CV between 15 and 35% were moderately variable. A CV value > 35% indicated high variability [15].

3. RESULTS

3.1. Characteristics of the soil cover

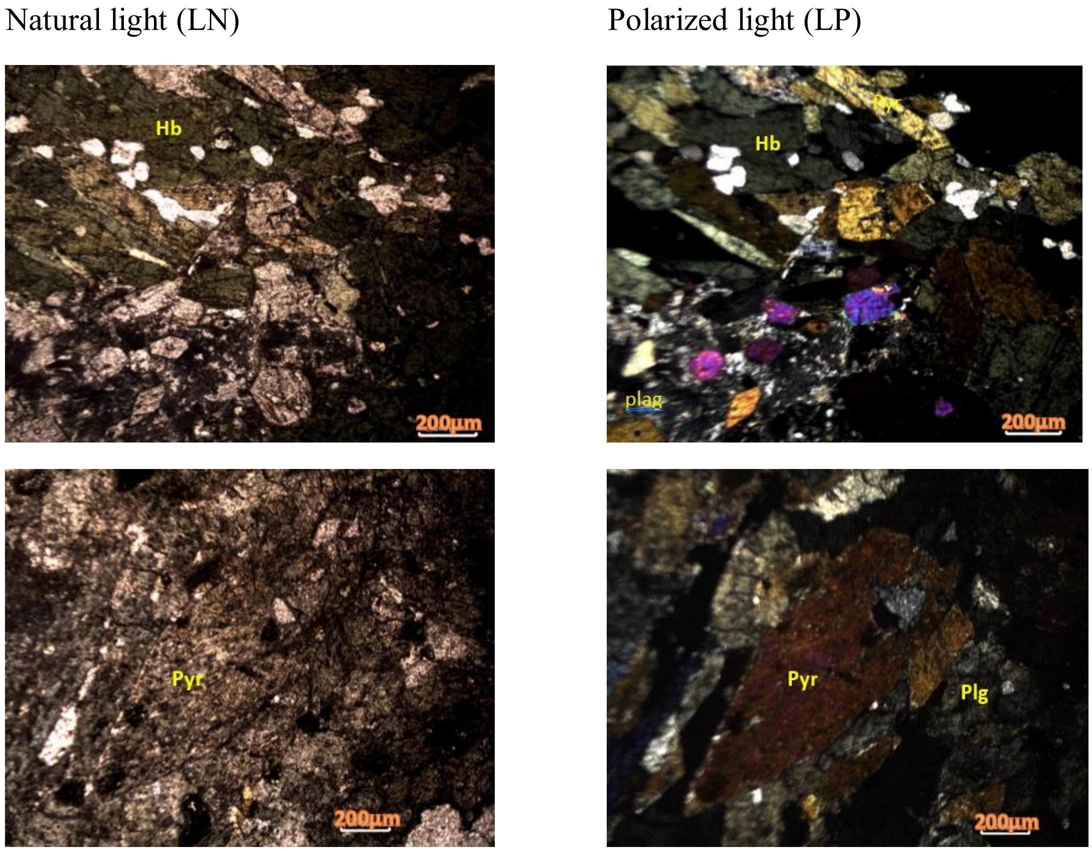
3.1.1. Macromorphology and micromorphology of rocks observed on the site

The characteristics observed above are quite clearly linked to the large rock mass made up of metamicrogabbros, metagranodiorites and amphibolo-pyroxenites (Fig. 2). The observation of thin sections clearly revealed crystalline elements of metamorphism. Their mineralogical composition is similar to that of green Hornblendes (Hb), Plagioclase (Plag) and Pyroxenes (Pyr). Hb dominates Pyr and Plag: Green Hornblende > Pyroxene > Plagioclase. Thus, very little quartz and opaque minerals are present among the rock samples observed (Fig. 3). All these rocks, poor in quartz, are clearly rich in ferro-magnesian elements. Also, the soils derived from it are characterized by a high percentage of clay and by their dark brown color (7.5YR 3/2). Internal drainage is relatively slow.

Considering the nature of the rocks present and their alteration, sodium feldspars ($NaSi_3AlO_8$) may be the dominant minerals of the site; their final evolution certainly led gradually to a mixture of clay which takes on an increasingly iron-bearing character, particularly in the deep horizons of the soils. The profiles below are characteristic of the open sequences and bring together the essential characteristics of the site's soils.

Metamicrogabbro **Metagranodiorites** **Amphibolo-pyroxénite**

Fig. 2: Rock outcrops observed on the study site


Natural light (LN)

Polarized light (LP)

Pyr : Pyroxène Plg : Plagioclase ; Hornblende verte ; LN : Lumière naturelle, LP : Lumière polarisée

Fig. 3: Observations in natural light and polorized light of the outcrops of the B29 agropastoral farm

3.1.2. Soil morphology

Fig. 4 illustrates three representative profiles at different topographic positions.

At the top, the soil is brownish, cambisolic and plinthitic, bright reddish-brown (2.5YR-3/-2) when fresh, sandy texture, polyhedral structure with fine lumpy sub-structure. Beyond 20 cm depth, the color becomes weak reddish-brown (10R-4/-3) in the fresh to dry state, the sandy-clayey texture and the massive structure with polyhedral substructure (Fig. 4C).

At the bottom of the slope, the soil is light yellow under the black surface layer, suggesting a weak eluvial and illuvial process. Temporary hydromorphism beyond 50 cm depth is observed, with the presence of pseudogley. In addition, the temporary water table when it disappears can cause the formation of spots (presence of pseudogley, noted “g”) and iron-manganiferous concretions at depth (Fig. 4A).

At the bottom, the thickness of the upper horizon reaches 20 cm. Its color becomes greyish-brown with orange spots (5YR-4/-6) and gley1 5/N in the fresh dry state (Fig. 4). The texture and structure are respectively sandy-clayey (even clayey-loamy) and massive with polyhedral substructure. Additionally, the permanent water table causes the formation of marked spots (Gley1 4/5G_/1, greenish brown, 10Y-5/-2) and reductive horizons (G) (Fig. 4B).

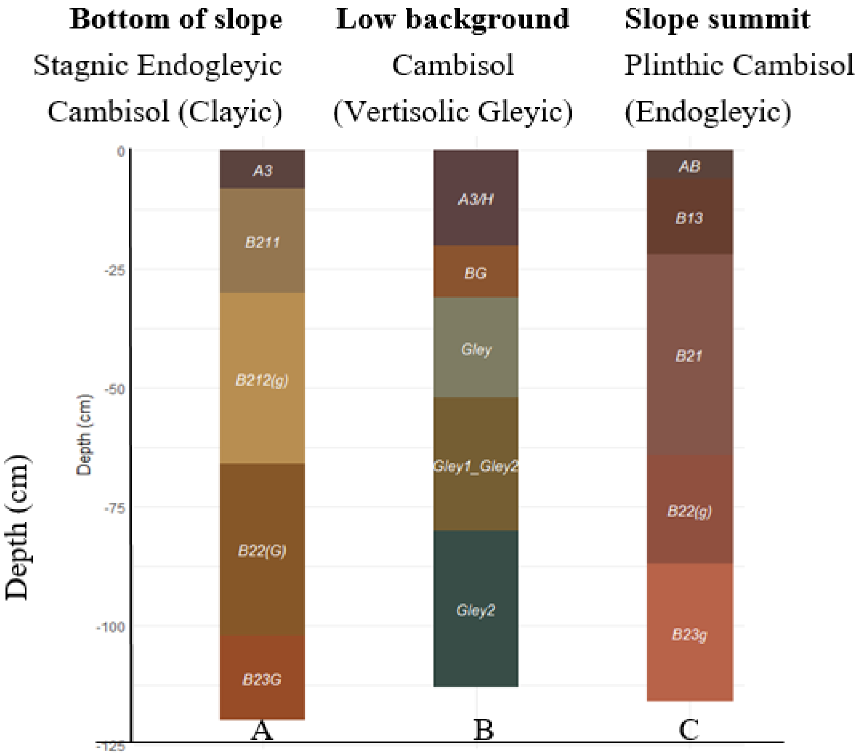


Fig. 4: Soil sequences of the B29 agropastoral farm

Fig. 5S, 5BV and 5BF summarize the common morphological characters of the pits described at the summit, at the bottom of the slope and at the bottom. The “A” horizon appears as the surface layer, while the next “B” horizon is a more or less yellowed illuvial horizon. The AB or A3 transition horizon is becoming more frequent on the site. The “C” horizon has not been reached. The passage to the slope is made by simple change of slope; there is no recess highlighted by a cornice. The soils are deeply disturbed and leached. The surface humus horizon is relatively thin. In total: poor drainage (drainage class > 2) was an important feature in the deep horizons and at the shallow position. Local oxidations giving rusty, bright brown-brown stains (2.5Y4/3).

- Temporary or permanent hydromorphism occurs at less than 50 cm depth, with the formation of pseudogleys or hydromorphic gley soils (Gleysols); hence the vertisolic character at the shallow position.
- Ferruginous concretions and nodules are abundant.
- Fairly gradual variations in clay levels in the profile.

3.2. Distribution of soil iron

3.2.1. Distribution of free iron content according to soil depth

Fig. 6 illustrates the variations in average free iron contents at depth and at different topographic positions (n = 70). The free iron (Fed) contents varied between 0.17±0.04 and 0.4±0.41% in the horizons, while they were 0.20±0.7% and 0.37±0 .44%. According to the Games Howell test, there were statistically significant differences between Fed content and the horizon variable, F(2, 40) = 7.3, p = 0.002 (Fig. 7). The difference is due to a statistically decreasing Fed content from surface to depth.

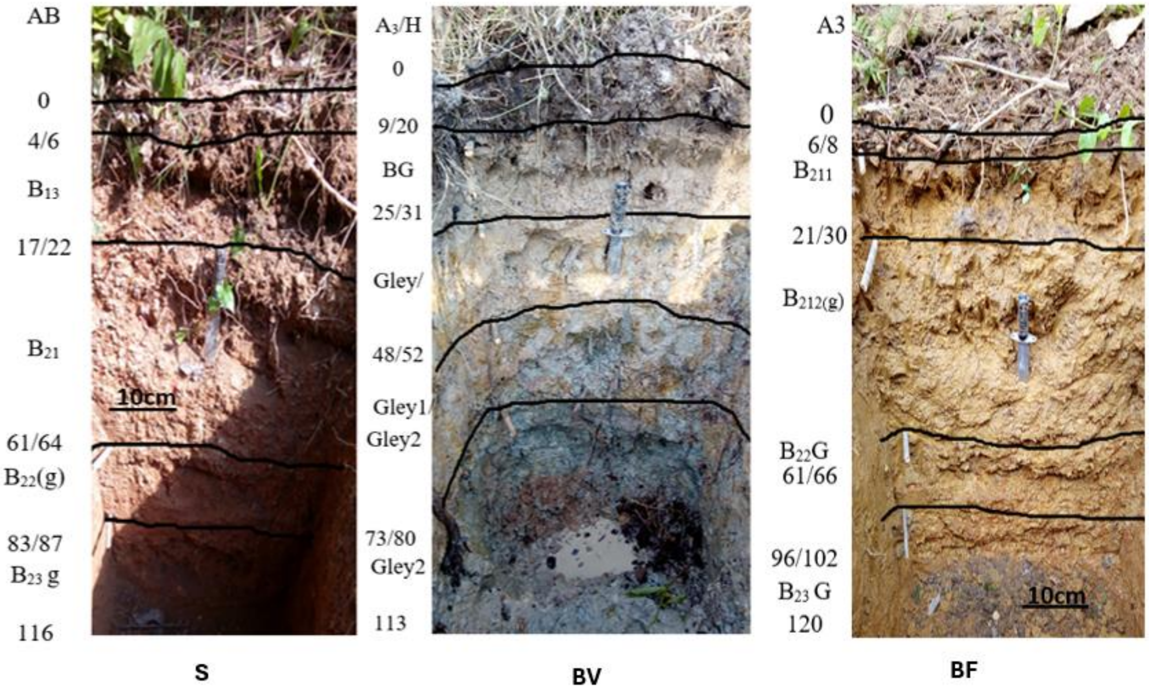
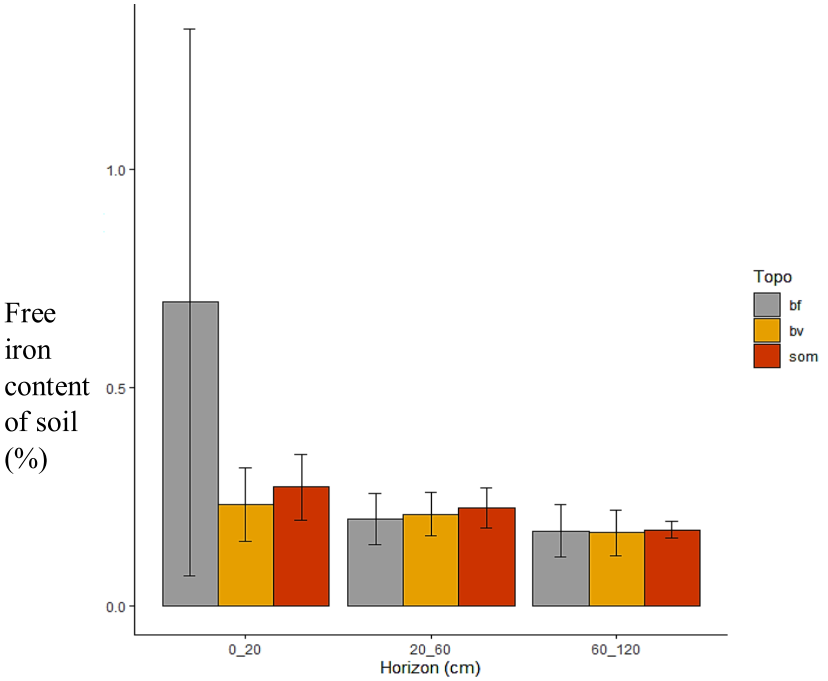
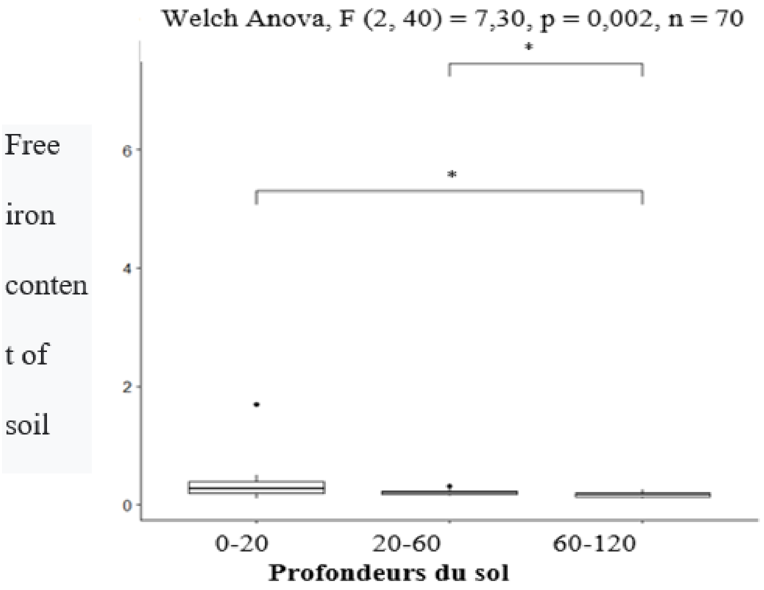


Fig. 5: Representative soil types observed at each topographical position of the agropastoral farm B29



som: summit, bv : bottom of slope; bf : low background; Topo : topographic position

Fig. 6: Average free iron contents in the soil depending on the horizon and topography



– Games Howel reviewl *'***', '*' significant at p<0.001, 0.05, respectively*

Fig. 7: Multiple comparison of average free iron contents in soil depending on depth

3.2.2. Distribution of free iron content according to topographical position

There were no statistically significant differences between the topographic position and Fed variables at the 5% threshold (p =0.057). However, in a natural environment like that of the site studied, a threshold of 10% would be statistically possible. In other words, the differences obtained between this predictive variable and the explanatory variable Fed would not be entirely due to chance. Indeed; along the toposequences, the lateral variation of the fed content at the bottom of the slope the fed content showed a statistically significantly different negative correlation between the bottom of the slope and the lowland (p = 0.027), and between the summit and the lowland at the bottom of the slope. Threshold of 10% (p = 0.052), on the other hand. The presence of a negative regression coefficient produced at the top and bottom of the slope reflects a significant effect; hence the existence of potentially significant differences at the 10% threshold between the positions of upper slopes and the lowlands (Table 1).

Table 1: Summary of the relationships developed between free iron and topographical positions

Regressor	Estimée	σ	t value	Pr(>|t|)	Pr(>|t|) globale
Slope	0,372	0,054	6,893	$2{,}36^{*}10^{-9***}$	0,057.
Topobv	-0,168	0,075	-2,256	$0{,}027^{*}$	
Toposom	-0,148	0,075	-1,983	0,052.	

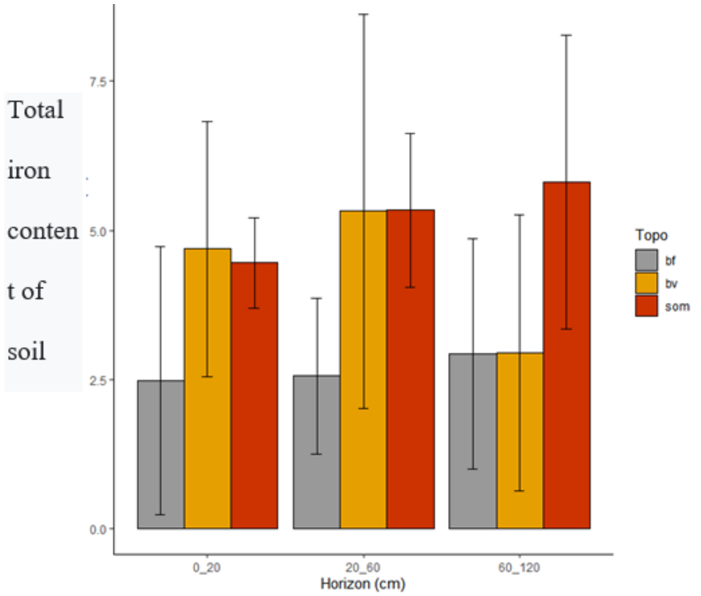
‘***’, ‘*’ and ‘.’ significant at p<0.001, 0.05, 0.1, respectively; ns: not significant

som: summit, bv: bottom of slope; Topo: topographic position

3.2.3. Distribution of total iron content according to soil depth and topographic position

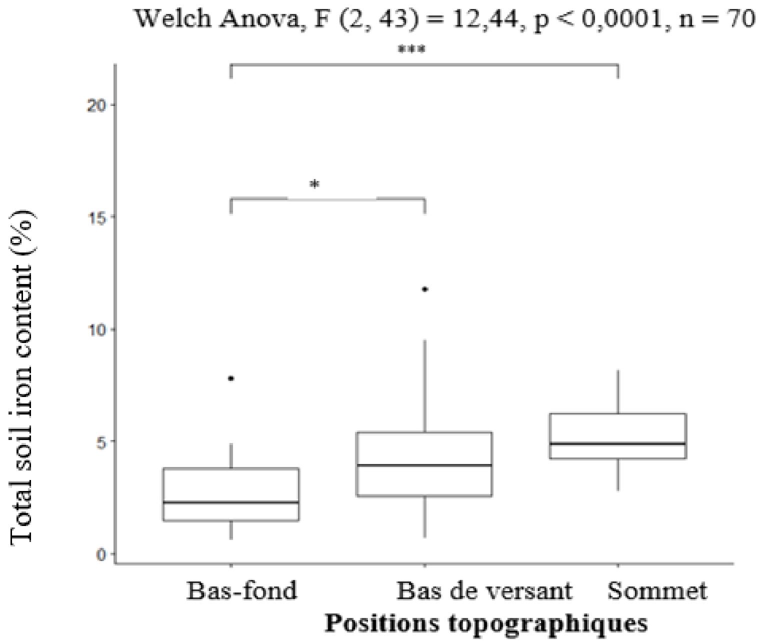
Fig. 8 shows the average total iron contents at depth and at different topographic positions (n = 70). Total iron (Fet) contents varied between 3.87±2.04% and 4.41±2.47% in the horizons, while they were 2.63±1.78% and 5.2± 1.69%. According to the Games Howell test, there were statistically significant differences between the variable’s topographic positions and total iron. They are due to the higher averages at the top and bottom positions of the slope, F (2, 43) = 12.44, p < 0.0001 (Fig. 9).

- Topographic positions very significantly explain the evolution of total iron in the soil studied (Table 2). There were no significant differences between depth and variations in average soil total iron contents (p = 0.72). The différences observe are due to chance.



som: summit, bv: bottom of slope; bf: lowland; Topo: topographic position

Fig. 8: Average total iron contents of the soil according to horizon and topography



'***', '*' significant at $p<0.001$, 0.05, respectively

Fig. 9: Multiple comparison of average total iron contents in soil according to topographic position – Games Howel review

Table 2: Summary of the relationships developed between total iron and topographic positions

Régressor	Estimée	σ	t value	Pr(>|t|)	Pr(>|t|) globale
Slope	2,631	0,453	5,804	$1{,}94\text{x}10^{-7***}$	$0{,}0005^{***}$
Topobv	1,685	0,628	2,684	$0{,}0092^{***}$	
Toposom	2,570	0,628	4,096	$0{,}0001^{***}$	

‘***'significant to p<0,001

3.3. Analytical characteristics of soil iron forms

3.3.1. Characteristics of soil iron forms according to depth and topography

Fig. 10 compares the two forms of iron analyzed. It shows non-parallel evolutions of total iron (Fet) and free iron (Fed) contents in the soil studied. The Fed content decreases from surface horizons (0-20 cm) towards depth (20-60 cm and 60-120 cm). Conversely, Fet, more concentrated at depth, gradually decreases towards the surface.

- One point seems clear in lowland soils: at around 30 cm depth, the Fet content drops suddenly from 60% to less than 5% before rising again and remaining there; reflecting the potential presence of horizons and very probably of original material more or less deferrified by the water table. See fig. 10 below.

3.3.2. Characteristics of some equilibria linked to the forms of iron in the soil

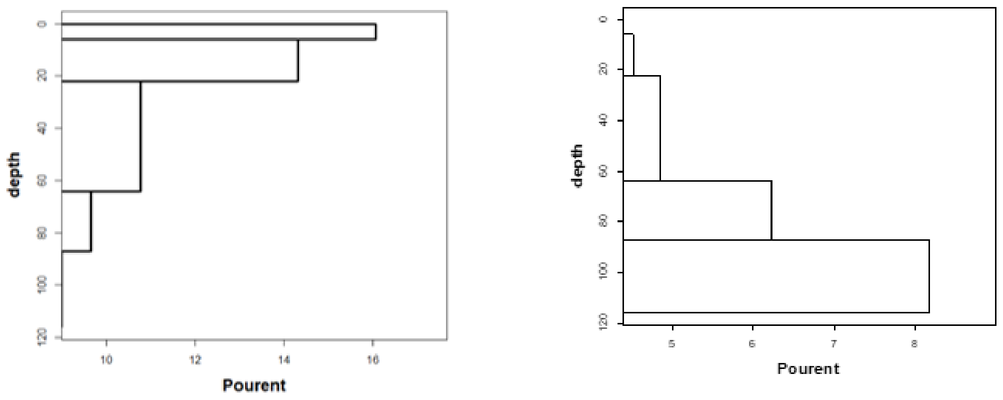
Fig. 11 illustrates the evolution of the Fed/Fet ratio according to depth and topographic position (topography). Vertical variations indicated mean values between 0.08±0.07 and 0.17±0.26. Values varied laterally between 0.05±0.02 and 0.21±0.27. It emerges from this analysis that the ratios are very low.

The values of the Fed/Fet ratio are low (Table 3). The highest are found on the surface of the summit, bottom of the slope and shallow positions, 5%, 8% and 17% of the Fet, respectively.

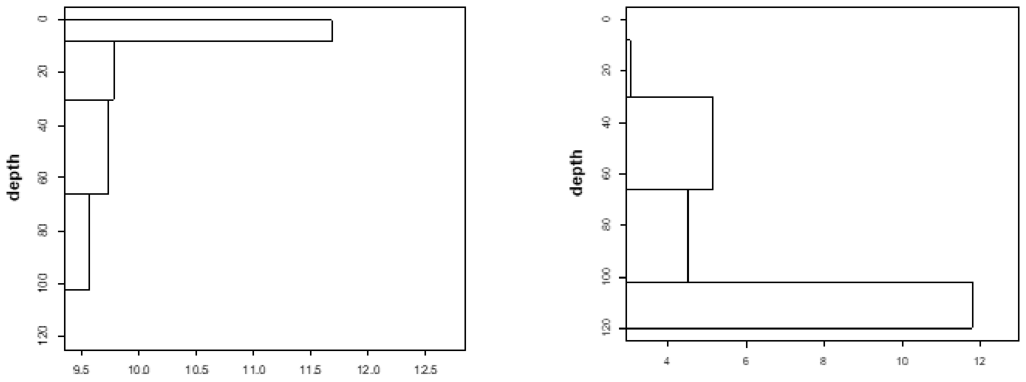
SUMMIT

Free iron

Total iron



BOTTOM OF SIDE



LOW BACKGROUND

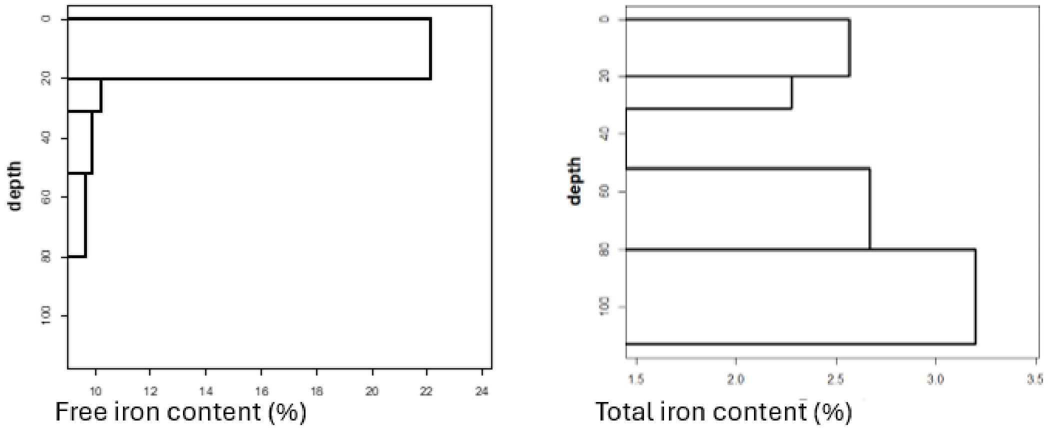
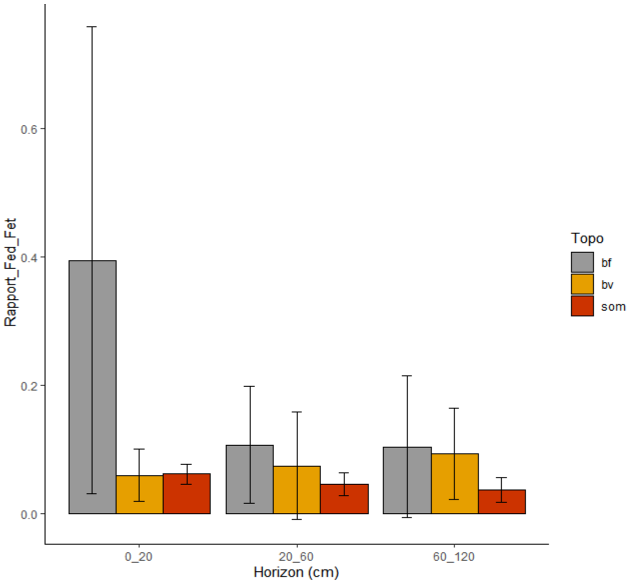


Fig. 10: Variations in average free iron and total iron contents in soil sequences



som: summit, bv: bottom of slope; bf: lowland; Topo: topographic position; Fed: free iron; Fet: total iron

Fig. 11: Characteristics of the free iron/total iron ratio according to depths and topographic positions

Table 3: Balance between free iron and total iron in the soil studied

Samples		Summit			Bottom of slope			Low background		
		Area	Depth		Area	Depth		Area	Depth	
Depth (cm)		[0-20]	[20-60]	[60-120]	[0-20]	[20-60]	[60-120]	[0-20]	[20-60]	[60-120]
Shapes iron (% dry weight)	Fe_d	0,32	0,25	0,19	0,23	0,20	0,19	0,44	0,20	0,19
	Fe_t	4,40	4,69	7,20	2,94	4,11	8,16	2,57	2,42	2,94
	Fe_d/ Fe_t	0,07	0,05	0,03	0,08	0,05	0,02	0,17	0,08	0,06
	Fe_t-Fe_d	4,08	4,44	7,00	2,71	1,17	8,00	2,13	2,21	2,75

4. DISCUSSION

According to [16], trace elements are mineral elements necessary in small quantities for plant nutrition.

In the soils of the study site, there was a very marked distribution of iron along the toposequences.

This characteristic is explained by more or less restrictive conditions existing in the environment. Total iron was significantly more concentrated at the topographic positions of the top and bottom of the slope, but its content was reduced in the lowlands. These characteristics observed on the redistribution of free iron and total iron along the toposequences give the iron element a role as an indicator of the importance of pedogenesis processes. These processes are linked to the saturation of the soil by water, or more simply a role as an indicator of hydromorphy as reported by [17]. [18] reported that the redistribution of soil iron can affect some of its properties. This is what motivated this research into the dynamics of iron using the physicochemical approach.

Two lessons can be drawn from these results:

4.1 Influence of the depth of the horizons at the lowland topographic position on the dynamics of the free iron content (Fe_2O_3) in the B29 soil.

The statistical processing of data on the ferrous iron content of the soil reveals that there is a strong effect of depth on the accumulation of free iron in the lowland soil. The difference is due to a higher Fed content found on the surface.

[11] reported similar results in surface and depth horizons, at the shallow position. These authors explained these variations in free iron by the existence in a natural environment such as that of the Awokpa lowlands (Benin), of the bacterial reduction of ferric iron, the process of which constitutes the main factor in the dissolution of oxides [19]. Bacterial reduction influences the biogeochemical cycles of iron through its solubilization and its mobility in Fe^{2+}. The noted presence of brownish films on the surface of the water, an indicator of iron toxicity in the shallows. The absence of tillering, formation of empty paddy grains and the browning of the leaves of the rice plants in the places where the presence of films is noted speak in favor of this thesis. At the lowland position, there was a fairly high quantity of iron (Fe^{2+}) mobilized and accumulated in the soil solution. This observation is supported by the lateral variations obtained along the toposequences. At the top and bottom positions of the slope the Fed content is leached (statistically significantly negative regression coefficient), while it is positive at the bottom; which reflects an accumulation in this position. In the Awokpa lowland, this iron can come from in situ solution, in the lowland, or from the transfer of solubilized iron from the adjacent slopes of the lowland in this case from the laterite hills which adjoin the lowland. -bottom. From these hills come springs of water loaded with iron which flow permanently into the shallows. However, work has highlighted the influence that plant cover can have on iron migration processes [20].

The humid lowland constitutes a good condition for the development of weeds which form litter which can also release, directly or by biodegradation, organic acids capable of forming organometallic complexes which precipitate in the form of hydroxide. Numerous studies have shown that in anaerobic environments such as very hydromorphic soils, ferri-reducing bacteria play an important role in the decomposition of natural organic matter [21,22].

The samples analyzed have a high total iron content. This appears to be due not only to primary minerals likely to contain iron (magnetite), but also to the presence of concretions. The presence in quality and quantity of minerals whose alterability is known to be high (pyroxenes and amphiboles) argues in favor of the thesis of total iron enrichment of the soil. The observation of biotite altering to give iron-bearing chlorites and the presence, on the surface of the ground, of manganese gravels and pebbles strongly argue in favor of such a thesis.

4.2 The fixing power with regard to iron. Role of clays

The iron attaches to the finest elements of the ground. Similar results were found for luvisols (alfisols). We therefore tried to correlate the iron-fixing power of the soil with the physico-chemical characteristics of the soil in order to assess those which prevent the “mobility” of iron. For all soils, we observed the strongest correlations with fine texture (clay, coarse silt and fine sand). These results can be explained by the fixing power linked to the specific surface area of the clays.

Regarding the feature selection of Boruta, in fact, as a rule, whenever to reduce the dimensionality, methods such as principal component analysis (PCA) are usually used. So it’s natural to ask why, where the need for other feature selection methods comes from. The problem with these techniques is that they are unsupervised methods of feature selection. For example, PCA uses the variance of the data to find the components. But these techniques do not take into account the information between the entity values and the target value(s). Furthermore, there are certain assumptions, such as normality, associated with such methods that require some sort of transformations before you start applying them. These constraints do not apply to all data types.

The Boruta package overcame all these constraints by calculating the score for each variable. Next, the maximum score among the shadow entities is identified and a hit is assigned to each entity that scores higher than the maximum score. This is what motivated the choice of this method for the selection of characteristics whose importance is confirmed. Features that have an importance significantly higher than the maximum score are treated as relevant (confirmed) features. Other characteristics are treated as provisional or rejected.

However, in order to conclude iron toxicity in the B29 soils, the analysis of soil samples from the experimental site gave concentrations of free iron between 0.44 and 0.14% and those of iron total is between 22.14% and 5.15%, particularly very strong compared to the field observations of [23] and [24] who set the iron toxicity threshold at 0 .03%.

One would be tempted, given these results, to assert that the toxicity observed in the present study would be due to the iron level in the soil.

It should also be noted with [10] that the iron concentration levels in the soil solution from which iron toxicity was observed are different depending on the authors, the soils studied and the experiments carried out. Thus, in hydroponic culture, symptoms attributed to iron toxicity appear when the ferrous iron concentration is greater than 0.005% [25]. In rice field soils, symptoms appear for iron concentrations in the solution, from 0.01 to 0.05% [24], 0.055% [26] and 0.003 to 0.03% [23]. In cocoa-cultivated soils, [27] set the threshold value at 0.0027% while the contents of the different forms of iron obtained in B29 soils are much higher than this threshold value in cocoa-cultivated and non-cocoa-cultivated environments. One would be tempted, given these results, to assert that the soils of the agropastoral farm would be very affected by iron toxicity.

As [28], it has been observed that the high absorption of iron is accompanied by a deficiency of certain major nutrients such as potassium and phosphorus, which are very essential for soil fertility.

Indeed, iron toxicity appears most often in soils with deficiencies in P, K, Ca, Na and Mg. [29] thus assert that excess absorption of iron, toxic for the plant, is as much linked to a nutritional imbalance due to a low availability of P, K, Ca, Na and Mg in the soil, as to a high concentration in reduced, soluble iron. It should be noted that the iron concentration levels in the soil solution from which iron toxicity has been observed are different depending on the authors, the soils studied and the experiments carried out.

Our analysis results show values that are very much higher than the different threshold values given by the authors cited above, this allows us to affirm that our soils have very pronounced iron toxicity.

It is known that the presence of high levels of aluminum and free iron (trace elements) in soils considerably reduces crop productivity by inhibiting growth, absorption and use of nutrients [30]. Based on such an assertion, we can emphasize that the soils of Mamlanso B29 have an average level of fertility, given that the content of iron and aluminum in the soils is very high.

The total iron content decreases from the top to the bottom in the soil. On the other hand, the soils of the site have total iron contents which decrease from depth towards the surface. This could be explained by the fact that the alteration of the parent rock takes place at depth. So according to [31], the parent rock remains the original supplier of major cations and trace elements in the soil. The soils are very concentrated in total iron with maximum values between 9.49% and 11.79% and minimum values between 0.59% and 0.71%. Unlike the total iron values, those of free iron are between 0.103% and 0.44% in the soils of the site. The free iron to total iron ratios are very low, even negligible, showing that ferromagnesian minerals weather very slowly. This alteration is even slower in the soils at the top than those at the bottom.

We also noticed during the in-situ characterization that the deeper we go in the profiles, the soil horizons have more reddish hues.

So, according to [12] and [11], oil stains and brownish films are the expression of iron toxicity. At ground level, reddish spots observed in the soil horizons and spots that resemble hydrocarbon or oil spots on the surface of the water indicate the iron richness of the environment.

We could thus conclude that the study of the distribution of the different forms of iron compounds in soils comprising, among other things, the profiles of Cambisols makes it possible to deduce that the red hues observed indicate a high proportion of iron-hydroxide compounds. hydrated, which are associated with high total iron contents.

The observation presented above leads us to extrapolate that during the alteration of the rock, it is the hydrated hydroxides which are formed, in the very first stage, with the appearance of a high concentration of hydrated hydroxides in the horizons, rich in elevated Fe^{2+} and Fe^{3+} ions. [31] reported that this formation process takes place when the pH is between 5 and 10, matching the pH observed in the study area. The similarity in the behavior of these elements leads us to affirm that the dynamics and availability of free iron and many other trace elements are linked to that of total iron. The depletion of total iron observed at the surface indicates that the nutrient contents of the bedrock are not reflected up to the surface of the soils studied, because of the rain, which is essentially abundant in the study area [32].

The total iron contents being at least more than 59 times higher than the threshold value set at 0.001% allows us to deduce that B29 soils present iron toxicity which could in the long run inhibit the bioavailability of nutrients in the soils. To remedy this iron toxicity, one of the solutions proposed by [10] is the addition of 1465 kg ha^{-1} of kaolin in place of drainage, already known.

4.3 Free iron/total iron ratios

It was noted after the various analyzes that in the horizons (0-20 cm), the free iron/total iron ratio increases from the top (0.07) to the bottom (0.17), passing to 0.08 at mid-slope. In the intermediate horizons (20-60 cm), the free iron/total iron ratio remains constant at the value 0.05 at the top and mid-slope but increases to 0.08 at the bottom. On the other hand, the soils have a very low free iron/total iron ratio in the depth horizons (60-120 cm) which is 0.03 and 0.02 respectively at the summit and at the mid-slope. As for the lowland soil, at a depth of 60-120 cm, the free iron/total iron ratio is relatively high (0.06) compared to the other topographic segments. However, free iron/total iron ratios are very low overall; which is an indicator of poorly evolved soil or rich in magnetite or micro-concretions. Ferromagnesian minerals still contain iron. Magnetite can exist in great abundance, such as in basalt-derived soil. The variety of these residues makes the calculation of the free iron/total iron ratio somewhat illusory, which will be much more influenced by the minerals of the parent rock than by the nature of the soil. The free iron/total iron ratio being between 2% and 17% shows that the rock outcrops of the study site are poorly rich in iron. Furthermore, the existence of indices of iron toxicity observed in the shallows suggested a wind origin linked to residues from mining activities in the study area.

5. CONCLUSION

The results of the study established the dynamics between free iron and total iron in the distribution of toposequence soils and highlight the presence of iron toxicity in the 0-20, 20-60 and 60-120 cm horizons. This study made it possible to interpret the relationship between free iron and total iron. Thus, the soils are more concentrated in total iron in the 60-120 cm layer while free iron is more concentrated in the 0-20 cm layer.

The free iron content is very high and above the threshold value 0.001%, thus inducing iron toxicity in B29 soils. So, even if the toxicity threshold is between 0.001% and 0.055%, it is good to know that the phenomenon of iron toxicity is present in B29 Cambisols. However, the application of composts as a natural amendment, the use of legumes in combination or in crop rotation and the incorporation of crop residues constitute possible solutions for maintaining the fertility of tropical soils.

Despite the interesting results obtained after investigation, the present study does not claim to have identified all aspects of the problems raised. Nevertheless, additional studies prove important to clearly identify the necessary production environment, for sustainable production and high crop yield, and to improve the income of producer farmers by considering carrying out an experimental study on the potential for iron toxicity and the yield of rice cultivation on lowland soils.

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