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Assessment of soil fertility status in cotton-based cropping systems in Cote d'Ivoire

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Cotton is the main cash crop in northern Côte d'Ivoire, where intensive cultivation along with low external inputs has led to a decline in crop yields due to soil degradation. The present study aims to assess the evolution of soil fertility during the 2013 and 2021 periods in the cotton basin area of Côte d'Ivoire. More specifically, the study (i) identified the limiting physico-chemical parameters of soil fertility, and (ii) analysed the state of evolution of soil fertility in 2013 and 2021 in the cotton basin of Côte d'Ivoire. For this purpose, a total of 64 soil samples were taken in 2013 and in 2021 on the same cotton plots on the 0-20 cm horizon. Chemical analyses of the soil samples in the laboratory were carried out on the following parameters: particle size distribution, pH water, total nitrogen (N_T), Potassium (K^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^+) and Cation exchange capacity (CEC). The results of the soil analyses showed that the sandy-clay textured topsoils dominate the whole study area in both years. This leads to a low retention capacity of exchangeable bases. Determination of the soil pH showed that the pH varies from slightly acidic to neutral ($6.5<pH<7$). The most limiting chemical properties are Cation exchange capacity (CEC) and the sum of the exchangeable bases (SEB) in the department of Korogho, Boundiali, and Ferkessedougou and the most limiting chemical properties in the department of Mankono are CEC. However, during the period from 2013 to 2021 the content of exchangeable cations (Ca^{2+}, Mg^{2+} and K^+) and the base saturation (BS) increased significantly in all the departments, more precisely in the department of Mankono. Although we observed a slight increase in the chemical properties of the soils in 2021 compared to 2013, the values were still below the minimum required threshold. This result implies that the soils have poor physico-chemical properties and consequently a low level of fertility, which compromises the sustainability of the cotton production system. The application of organic and mineral amendments is therefore essential to increase the nutrient content of these soils.

KEYWORDS
cotton crop, soil fertility, productivity, physico-chemical properties, Cote d'Ivoire

Introduction

Soil fertility management issues are at the centre of debates on the sustainability of agricultural production systems in Africa, particularly in West Africa where farmers are concerned with"soil fatigue" (1). The decline in soil fertility markedly accounts for the low agricultural productivity and this is perceived to be widespread in the highland soils of the tropics, particularly in sub-Saharan Africa (2). One of the reasons for this low productivity is the extraction of nutrients by continuous cropping with low external nutrient supply, resulting in declining soil fertility (3). Soil fertility is a function of many soil properties, many of which are interrelated. In most cases, the term 'soil fertility' describes the current state of the soil, which means that soil fertility is a combination of the current soil quality (mineral composition, soil texture) and achieved qualities such as soil structure, soil organic matter (SOM) content and phosphorus concentration. Soil fertility is measured either by crop performance (yield) or by indicators such as SOM content, indicator plants, and water holding capacity (3). Thus, managing fertility means acting to maintain, sometimes improve, the organic, mineral, physical and biological status of soils to achieve a certain level of production in a sustainable manner (1). Soil fertility decline includes nutrient depletion (more nutrients removed than added), nutrient mining (high nutrient removal and no nutrient addition), acidification (lowering of pH), loss of organic matter, and an increase in toxic elements such as aluminum (4).

Like other countries in the Gulf of Guinea, Côte d'Ivoire is facing a continuous decline in soil fertility resulting in stagnant or declining cotton yields (5). Soil fertility degradation through nutrient depletion, mainly by erosion and/or crop removal, is one of the threats facing agricultural systems in Cote d'Ivoire. This affects a large part of the northern territory of Cote d'Ivoire, especially the fragile ecosystems of the northern cotton basin, and eventually leads to the reduction in soil fertility and, consequently a decline in the land productivity. The Global Assessment of Soil Degradation (6) showed that soil chemical degradation is more significant in many tropical regions.

Cotton is the main cash crop in northern Cote d'Ivoire. The continuous increase in cultivated areas has led to soil degradation and lower yields. Like other crops, cotton cultivation is subject to several constraints, notably increasingly irregular rainfall and declining yields (7). In the current cropping system, seed yields are still low, estimated at around Côte d'Ivoire with 452 kg/ha and Benin with 418 kg/ha (8). All other African countries harvested less than 350 kg/ha (8). Soil fertility decline can be assessed using a set of soil properties from different periods on the same site or from different land-use with the same soils. The former is easier to interpret, and the latter can be collected quickly, but the differences may be due to inherent differences and not the result of soil management.

To improve degraded soils and restore their productivity, it is necessary to determine the current state of soil properties and to understand the limiting factors for cotton production and their spatial distribution at the regional scale. The objectives of this study are: (i) to identify the limiting physico-chemical parameters of soil fertility for cotton production; (ii) to analyse the state of evolution of soil fertility from the periods 2013 to 2021 in the cotton basin of Côte d'Ivoire.

Material and methods

Study area

The study was conducted in the four main cotton production departments of Côte d'Ivoire. These are: Korhogo, Boundiali, and Ferkessédougou departments in the Northern part of the cotton basin and the Mankono department in the central part of the cotton basin (Figure 1). The Northern and Central cotton basins are the two most important cotton production areas out of the five cotton basins of Côte d'Ivoire. The study area is located between longitudes 2- ° 30'_ and 8- ° 30'_ West and latitudes 6- ° 50'_ and 10- ° 30'_ North and covers an area of approximately 201.69 km^2 out of the country's 322.462 km^2 (9). Two rainfall regimes characterize these zones namely: the tropical transition regime and the equatorial attenuated transition regime. The three classes of soils distinguished in this zone are the: tropical ferruginous soils, hydromorphic soils and, soils on basic rocks (10). The vegetation of the study area is subdivided into three main types namely, the forest zone corresponding to the Center-West, the Guinean Savanna zone located in the East, and the northern part of the cotton zone which belongs to the Sudanian savanna zone.

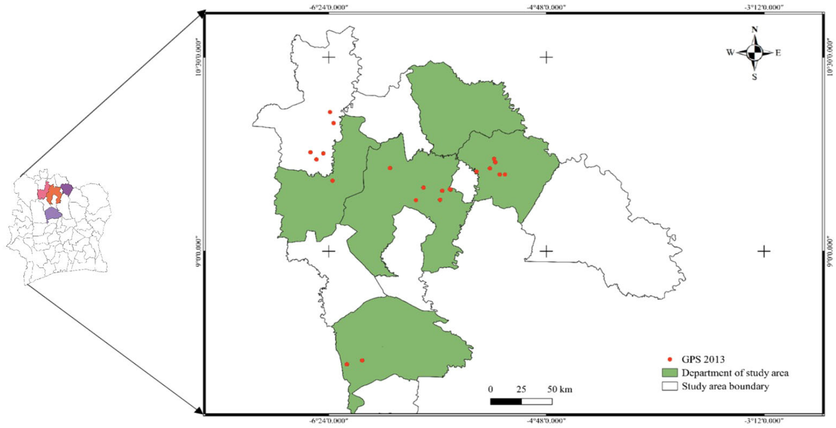

FIGURE 1
Location of villages where samples were taken from cotton plots in 2013 at Korogho, Ferkessedougou, Boundiali and Mankono.

Three of the country's four main rivers: Sassandra, Bandama, and Comoé flow through the Ivorian cotton basin. The four cotton production departments were intentionally chosen for the study because they are subject to strong climatic variations and declining soil fertility, and have been identified as the most vulnerable agro-ecological zones (5, 11)

Soil sampling and analysis

Soil sampling was carried out at each site in the study area during two periods, the first being in 2013 during which topsoil samples from different farmers' fields were taken to a depth of 0-20 cm and characterised. Soil sampling in 2021 consisted of systematically taking samples from each plot at 0-20 cm topsoil depth using the soil auger. The samples were taken with 17 repetitions on each sampling point within a plot. Depending on the size of the plot, samples were taken from maximum 5 sampling points. The 17 equiponderate elementary samples per sampling point were taken to constitute one composite sample. In total, 64 composite soil samples were taken into account for the database in 2013 across the study area. The locations of the sampling points in the 2013 period were recorded with a GPS (eTrex 22x). Soil sampling in the 2021 period was carried out by: (i) using the GPS coordinates of the sites sampled in 2013 and (ii) with confirmation of the exact location of the soil sampling site by the cotton plot owner. In each department of the 2021 sampling period, 20 composite samples were taken in Korogho, 12 composite samples in Ferkessedougou, 22 composite samples in Boundiali and 10 composite samples in Mankono, giving a total of 64 composite soil samples in the whole study area. The soil samples were stored in plastic bags to avoid contamination and sent to the ENVAL (Laboratoire de l'Environnement et de l'Alimentation de Cote d'Ivoire) laboratory for analysis of the physico-chemical parameters (pH, total N, exchangeable Ca, K, Mg and Na, CEC, Base satiurarion, Sand, Silt and Clay content). The laboratory analytical techniques used for the evaluation of the physico-chemical parameters of soil samples in 2021 were almost the same as the methods carried out in 2013.

The determination of the physicochemical characteristics followed the methods described by Tran and Boko (12). The analyses consisted of the determination of particle size distribution, carried out by sieving and by the use of Robinson's pipette; Total nitrogen was determined by the method of Kjeldahl. The pH-water was determined by using a soil-water suspension with the ratio (1/2.5). The cation exchange capacity (CEC) was determined according to the NFX 31-130 standard (13). This method aims to displace all the cations adsorbed on the exchange sites of the CEC, and then saturate these sites with a single cation ($NH4^+$) while the exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were, determined by Atomic Absorption Spectrophotometry (Optima 2100 DV) including exchangeable aluminum.

Statistical analysis

The data obtained were subjected to various statistical tests: ANOVA, descriptive statistics, and homogeneity test with the Statistical Package for the Social Sciences (SPSS) (version 26.0) at 95% level of significance ($\alpha = 0.05$).

Method of assessing soil fertility levels

Soil fertility status assessment was based on analysis and interpretation of data such as total nitrogen content (N_T), Cation Exchange Capacity (CEC), pH_{water}, base saturation (BS), Sum of

10.3389/fsoil.2022.959325

Exchangeable Bases (SEB). Soil fertility levels were identified by the method of maximum limitations according to the criteria defined in Table 1.

Class 0, optimal fertility level: no limitation, the soil characteristic is optimal;

Class, I, high fertility level: soils are in this class when the characteristics have no or only four slight limitations. This class refers to situations that could slightly reduce yields without requiring special cultivation techniques;

Class II, medium fertility level: soils are in this class when the characteristics do not present more than 3 moderate limitations possibly combined with low limitations. This class refers to situations that cause a greater decrease in yields or the use of special cultivation techniques. These limitations do not affect profitability;

Class III, low fertility level: soils are in this class when their characteristics show more than 3 moderate limitations associated with one severe limitation. This class refers to situations that cause a decrease in yields or the implementation of cultivation techniques that could jeopardize profitability;

Class IV, very low fertility level: soils are in this class when their characteristics present more than one severe limitation.

Results

Soil fertility status in the northern (Korhogo, Ferkessédougou, Boundiali) and central (Mankono) cotton zones in 2013

Particle size distribution

The topsoils in the north and centre of the cotton basin are sandy-loam. In the northern part of the cotton basin, the average silt content varies from 31.91 to 14.77%. The average clay content varies from 11.87 to 7.67%. The sand content is between 77.54 and 56.42%. The proportions of clay are globally low and lower in the three northern departments of the cotton basin (Korhogo, Ferkessédougou, and Boundiali) (5). The topsoils in the central part of the cotton basin have on average 10.40% clay, 17.94% silt, and 71.64% sand.

Average total nitrogen

The average total nitrogen (N_T) concentration in the topsoils of the north of the cotton basin varies from 0.06 to 0.054% against the norm of 0.1 to 0.15%. The centre of the cotton basin (Mankono) has an average total nitrogen content of 0.08%. Overall, the topsoils in the north and centre of the cotton basin are largely poor in total nitrogen (Table 2).

Magnesium

The average concentration of exchangeable magnesium (Mg^{2+}) varies from 0.6 to 0.5 $cmol^+/kg$ against the norm of 1 to 1.5 $cmol^+/kg$ in the north of the cotton basin. The department of Mankono in the centre of the cotton basin has a moderate magnesium concentrations (average of 0.7 $cmol^+/kg$).

Potassium

The average concentration of exchangeable potassium (K^+) varies from 0.16 to 0.01 $cmol^+/kg$ against the norm of 0.2 to 0.4 $cmol^+/kg$ in the north of the cotton basin. The exchangeable potassium content is moderate in these three departments (Korhogo, Ferkessédougou and Boundiali). The department of Mankono in the centre has more or less sufficient proportions of potassium (0.2 $cmol^+/kg$).

Sum of exchangeable bases

The concentration of sum of exchangeable bases in the north of the cotton basin varies from 1.62 to 2.94 $cmol^+/kg$ against the norm of 5 to 10 $cmol^+/kg$. The centre of the basin has an exchangeable cation concentration of 2.82 $cmol^+/kg$.

TABLE 1 Evaluation criteria for soil fertility classes in the cotton basin.

Characteristics	Level of fertility				
	Very high (no limitations) Degree 0	High (low limitation) Degree I	Average (moderate limitations) Degree II	Low (severe limitations) Degree III	Very low (very severe limitations) Degree IV
N (%)	> 0.08	0.08-0.06	0.06-0.045	0.045-0.03	< 0.03
Sum of Exchangeable Bases (SEB) ($cmol^+/kg$)	> 10	10-7.5	7.5-5	5-2	< 2
BS (%)	> 60	60-50	50-30	30-15	< 15
CEC ($cmol^+/kg$)	> 25	25-15	15-10	10-5	< 5
pH	5.5-6.5 6.5-7.2	5.5-6.0 7.2-7.8	5.5-5.3 7.8-8.3	5.3-5.2 8.3-8.5	< 5.2 >8.5

14

TABLE 2 Average Physico-chemical parameters and level of fertility soils in the North and Central cotton zone in 2013.

Parameters	Unit	KOROGHO	FERKESSEDOUGOU	BOUNDIALI	MANKONO
		Average values			
pH		6.3 Degree 0	6.4 Degree 0	6.4 Degree 0	6.4Degree 0
N	%	0.071 Degree I	0.096 Degree 0	0.062 Degree I	0.064 Degree I
CEC	Cmol$^+$/kg	6.65 Degree III	5.72 Degree III	7.28 Degree III	4.28 Degree IV
BS	%	38.62 Degree II	48.75 Degree II	24.42 Degree III	39.76 Degree II
SEB (Ca^{2+}, Mg^{2+}, K^+, Na^+) Sum of Exchangeable Bases	Cmol$^+$/kg	2.55 Degree III	2.94 Degree III	1.62 Degree IV	2.82 Degree III
Most limiting factors		SEB,CEC	CEC,SEB	SEB	CEC
Soil fertility class		IV	IV	IV	IV
Level of fertility		Very low level	Very low level	Very low level	Very low level

Degree 0: Very high (no limitations), Degree I: High (low limitation), Degree II: average (moderate limitations), Degree III: low (severe limitations), Degree IV: very low (very severe limitations).

pH and CEC

The northern cotton zone has pH values ranging from 6.3 to 6.4, compared with the reference value of 6.5 to 7.5. The cation exchange capacity varies from 5.72 to 7.28 cmol$^+$/kg against the norm of 10 to 25 cmol$^+$/kg. The average CEC per department is low and below average. In the centre, specifically in the department of Mankono, we have a pH of 6.4, and a cation exchange capacity of 4.28 cmol$^+$/kg which is low compared to the average.

Base saturation

The northern cotton zone has base saturation rates (BS) that vary from 24.42 to 48.75% against the norm of 40 to 60%. The centre of the cotton basin has a saturation rate of 39.76% which is moderately low.

Sodium and calcium

The average concentration of exchangeable sodium (Na^+) varies from 0.07 to 0.06 cmo$^+$/kg against the norm of 0.3 to 0.7 cmol+/kg in the north of the cotton basin. The department of Mankono in the centre has a sodium level of 0.12 cmol+/kg. The average concentration of exchangeable Calcium (Ca^{2+}) varies from 0.92 to 2.0 cmol$^+$/kg against the norm of 2.3 to 3.5 cmol$^+$/kg in the north of the cotton basin. The department of Mankono in the centre has low proportions of calcium (0.93 cmol$^+$/kg).

Soil fertility status of the northern (Korhogo, Ferkessédougou, Boundiali) and central (Mankono) cotton zones in 2021

Particle size distribution

In 2021, the soils in the north and centre of the cotton basin were sandy-loamy. The silt content varies from 16 to 7.8%. The clay content varies from 5.08 to 2.73%. The sand content is between 86.33 and 78.97%. The proportions of clay are globally low and lower in the three northern departments of the cotton basin (Korhogo, Ferkessédougou, and Boundiali). The central zone of the cotton basin has a clay content of 3.98%, silt of 13.68% and sand of 81.04% (Table 3).

Average total nitrogen

The average total nitrogen (N_T) content in the north and centre of the cotton basin is at an average value of 0.07 against the norm of 0.1 to 0.15%. Overall, the soils in the northern and central parts of the cotton basin study area are largely poor in total nitrogen.

Magnesium

The average concentration of exchangeable magnesium (Mg^{2+}) varies from 0.98 to 0.68 cmol$^+$/kg against the norm of 1 to 1.5 cmol$^+$/kg. Only the department of Ferkessédougou recorded concentrations that tend towards moderate limitations. The department of Mankono in the centre of the cotton basin has an average magnesium threshold (0.99 cmol$^+$/kg) which also tends toward moderate limitations.

Potassium

The average concentration of exchangeable potassium (K^+) varies from 0.35 to 0.33 cmol$^+$/kg against the norm of 0.2 to 0.4 cmol$^+$/kg. The exchangeable potassium is average in these three departments (Korhogo, Ferkessédougou and Boundiali). The department of Mankono in the centre has high proportions of potassium (0.50 cmol$^+$/kg).

Sum of exchangeable bases

The concentration of the sum of exchangeable bases in the north of the cotton basin varies from 3.89 to 4.43 cmol$^+$/kg against the norm of 5 to 10 cmol$^+$/kg. The centre of the basin has an exchangeable cation concentration of 5.52 cmol$^+$/kg.

pH and CEC

The northern cotton zone has pH values ranging from 6.5 to 6.8, compared to the reference value of 6.5 to 7.5. Overall, the pH

TABLE 3 Average Physico-chemical parameters and level of fertility soils in the North and Central cotton zone in 2021.

Parameters	Unit	KOROGHO	FERKESSEDOUGOU	BOUNDIALI	MANKONO
		Average values			
pH		6.5 Degree 0	6.6 Degree 0	6.8 Degree 0	7.1 Degree 0
N	%	0.071 Degree I	0.068 Degree I	0.068 Degree I	0.067 Degree I
CEC	Cmol+/kg	6.93 Degree III	7.28 Degree III	7.43 Degree III	8.10 Degree III
BS	%	55.15 Degree I	59.19 Degree I	58.54 Degree 1	59.38 Degree 1
SEB (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) Sum of Exchangeable Bases	Cmol+/kg	3.89 Degree III	4.42 Degree III	4.43 Degree III	5.52 Degree II
Most limiting factors		CEC, SEB	CEC,SEB	CEC,SEB	CEC
Soil fertility class		IV	IV	IV	III
Level of fertility		Very low level	Very low level	Very low level	low level

was neutral in 83% of cases and basic in only 17% of cases. The Cation Exchange Capacity varied from 7.43 to 6.93 $cmol^{+}/kg$ against the standard of 10 to 25 $cmol^{+}/kg$. The average CEC per department is low and below average. In the centre, specifically in the department of Mankono, we have a pH of 6.95, i.e. neutral, with a cation exchange capacity of 8.10 $cmol^{+}/kg$, which is low compared to the average.

Base saturation

The base saturation (BS) varies from 55 to 59% against the norm of 40 to 60%. Compared to the negative charges available on the clay-humus complex, most of the soils are well saturated with exchangeable cations in the north of the cotton basin. The centre of the cotton basin has a saturation rate of 60% which is considered acceptable.

Sodium and calcium

The average concentration of exchangeable sodium (Na^{2+}) varies from 0.06 to 0.07 $cmol^{+}/kg$ against the norm of 0.3 to 0.7 $cmol^{+}/kg$ in the north of the cotton basin. The centre, on the other hand, has a level of 0.06 $cmol^{+}/kg$ of sodium. The average concentration of exchangeable Calcium (Ca^{2+}) varies from 2.8 to 3.2 $cmol^{+}/kg$ against the norm of 2.3 to 3.5 $cmol^{+}/kg$ in the north of the cotton basin. The department of Mankono in the centre has high proportions of calcium (3.8 $cmol^{+}/kg$).

Limiting chemical parameters of soils in the cotton basin for the period 2013 and 2021

When averaging over all soil profiles of a district, most of the chemical parameters of the soils in the cotton basin for both periods show a high degree of soil fertility limitations. In all districts, the average top soil has more than one severe limitations, except the department of Mankono in 2021. Both, Cation Exchange Capacity (CEC) and the sum of Exchangeable Bases (SEB) were in 2013 and 2021 the most limiting factors for cotton production in the departments of (Korhogo and Ferkessédougou) (Table 3 and 4). In Boundiali in 2013 the base saturation (BS) was most limiting. The average total nitrogen (N_{Totoal}) content was not limiting the cotton

TABLE 4 Soil fertility status for the year 2013 and 2021 with results/differences.

Parameters	Unit	KOROGHO			FERKESSEDOUGOU			BOUNDIALI			MANKONO		
		2013	2021	D	2013	2021	D	2013	2021	D	2013	2021	D
		Average values											
pH		6.3	6.5	0.2	6.4	6.6	0.2	6.4	6.8	0.4	6.4	7.1	0.7
N	%	0.071	0.071	0	0.096	0.068	0.03	0.062	0.068	0.01	0.064	0.067	0.003
CEC	Cmol+/kg	6.65	6.93	0.3	5.72	7.28	1.6	7.28	7.43	0.15	4.28	8.10	3.82
BS	%	38.62	55.15	16.5	48.75	59.19	10.4	24.42	58.54	34.12	39.76	59.38	19.62
SEB (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) Sum of Exchangeable Bases	Cmol+/kg	2.55	3.89	1.3	2.94	4.42	1.48	1.62	4.43	2.81	2.82	5.52	2.7
Most limiting factors		SEB,CEC			CEC,SEB			SEB, CEC			CEC		
Level of fertility		Very low level			Very low level			Very low level			low level		

D: Differences

production in the four departments of the study area during the both periods 2021 and 2013. The pH was close to neutral throughout the cotton basin study area. However, not all pH values were limiting for cotton production. All soils in the four departments of the study area were close to soil fertility class IV with a very low fertility level except in Mankono, where soil fertility class was on average III in 2021. Among the soil samples that were taken during the period 2021, topsoils in Mankono had, on average, the highest soil fertility. The department with the lowest level of soil fertility was Korogho according to the values of soil chemical properties.

The difference in soil physico-chemical properties between the 2013 and 2021 periods

The different boxplots highlight the most significant variabilities of each year (box length) and the differences between the 2013 study and the 2021 measurements (median) (Figure 2A-D),. In general, many soil fertility indicators changed significantly ($P \leq 0.05$) as revealed by the comparison of means using the ANOVA statistical test. The pH_{H2O} has a mean value of 6 and showed a slightly increasing trend, which was significant in Boundiali and Mankono. Nevertheless, differences were observed within each department of the study area.

The soil texture is one of the most important properties of soil, and it greatly affects agricultural production, land use and management. Soil texture is directly related to nutrient retention and drainage capacity. Soil texture in the field is not easily changed and is therefore considered a permanent soil attribute. In this study, the dominant soil texture in the study area at the depth of 0-20 cm was sandy loam texture with a very low proportion of clays (Figure 3).

In Korhogo department we observe a variation of chemical elements mainly exchangeable base concentrations like K^+

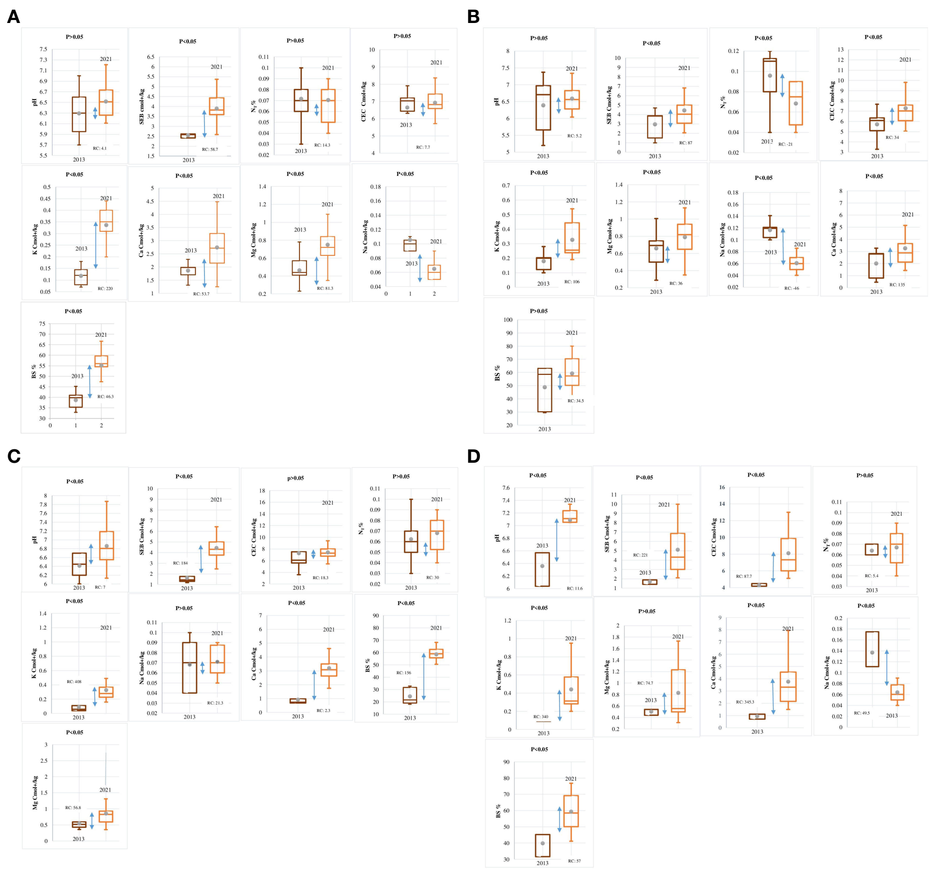

FIGURE 2
(A) Boxplots of changes in soil chemical properties for the period 2013-2021 in Korogho. RC: Relative Changes. **(B)** Boxplots of changes in soil chemical properties for the period 2013-2021 in Ferkessedougou. RC: Relative Changes. **(C)** Boxplots of changes in soil chemical properties for the period 2013-2021 in Boundiali RC: Relative Changes. **(D)** Boxplots of changes in soil chemical properties for the period 2013-2021 in Mankono RC: Relative Changes.

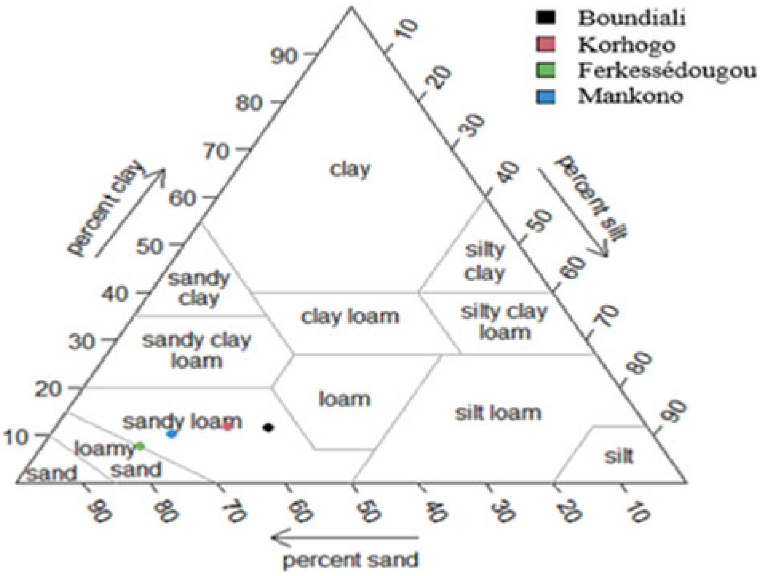

FIGURE 3
Textural triangle used in determining soil textural class.

which increased from 0.12 to 0.34 cmol$^+$/kg in 2021, Ca^{2+} which increased from 1.9 to 2.7 cmol$^+$/kg, Mg^{2+} which increased from 0.5 to 0.7 cmol$^+$/kg and Na^{2+} which decreased from 0.1 to 0.06 cmol$^+$/kg. The percentage of base saturation (BS) increased from 38 to 55% in 2021. Similarly, the sum of exchangeable bases (SEB) increased from 2.55 to 3.89 in 2021 cmol$^+$/kg.

In the department of Ferkessedougou a variation of the chemical elements can be observed. The concentrations of exchangeable bases have more or less increased. K^+ increased from 0.17 to 0.33 cmol$^+$/kg in 2021, Ca^{2+} from 1.9 to 3.3 cmol$^+$/kg, Mg^{2+} from 0.7 to 0.8 cmol$^+$/kg and Na^{2+} from 0.1 to 0.06 cmol+/kg. The percentage of total N decreased from 0.09 to 0.06%. The CEC increased from 5.7 to 7.2 cmol$^+$/kg in 2021. Similarly, the sum of exchangeable bases (SEB) increased from 2.94 to 4.42 in 2021 cmol$^+$/kg.

In the department of Boundiali a variation of the chemical elements can be observed. The concentrations of exchangeable bases have more or less increased. K^+ increased from 0.09 to 0.33 cmol$^+$/kg in 2021, Ca^{2+} from 0.9 to 3.2 cmol$^+$/kg, Mg^{2+} from 0.54 to 0.85 cmol$^+$/kg, Na^{2+} from 0.06 to 0.07 cmol+/kg. Similarly, the sum of exchangeable bases (SEB) increased from 1.62 to 4.43 in 2021 cmol$^+$/kg. The percentage of base saturation (BS) increased from 24 to 58%.

In Mankono department, the concentrations of exchangeable bases have more or less increased.K^+ which increased from 0.1 to 0.4 cmol$^+$/kg in 2021, Ca^{2+} which increased from 0.9 to 3.7 cmol$^+$/kg, and Na^{2+} which decreased from 0.1 to 0.06 cmol$^+$/kg. The CEC concentration increased from 4.7 to 8.1 cmol$^+$/kg in 2021. The percentage of base saturation (BS) decreased from 59 to 39% in 2021. Similarly, the sum of exchangeable bases (SEB) increased from 2.82 to 5.52 in 2021 cmol$^+$/kg.

Discussion

Comparison of physico-chemical data of soils in the cotton basin between the periods 2013 and 2021

Changes in soil quality can be assessed by measuring appropriate indicators and comparing them with desired values (critical limits or threshold levels) at different time intervals for a specific use in a selected agro-ecosystem (15). Soil properties during the periods 2013 to 2021 show significant differences in each department of the study area.

The department of Korhogo, shows a variation of chemical elements that in most cases have undergone a slight increase from 2013 to 2021. These variations were observed at the level of exchangeable bases such as Potassium, Calcium, and Magnesium. Sodium decreased from 2013 to 2021. We also observed a slight increase in the percentage of base saturation and the sum of exchangeable bases. Most of the land in the Korhogo region of northern Côte d'Ivoire has been continuously cultivated for several decades, with fallow land having virtually disappeared, resulting in a decline in soil nutrient levels during both periods, most notably in 2013. This could be explained by the agricultural practices used on the cotton farms in the

Korogho department, which are the overexploitation of the soil, inappropriate agricultural practices, and the use of insufficient chemical amendments. Indeed, in 2013, the entire Ivorian cotton basin was under the supervision of a single cotton company, CIDT (Compagnie Ivoirienne pour le Développement des Textiles). The latter had difficulty in meeting the need for mineral fertiliser and in monitoring farmers by implementing appropriate agricultural practices for cotton cultivation, which explains the low nutrient content of the soil in the period 2013. The appearance of new cotton companies over the last five years has made it possible to more or less make up for the nutrient deficits and to strengthen the training of cotton farmers in good agricultural practices. This has led to improvements in nutrient levels in the 2021 period.

The department of Ferkessédougou also shows changinges in soil chemical properties in the periods 2013 and 2021. These changes are noticeable in a significant increase of the content of exchangeable potassium, calcium and magnesium. Sodium content, however, is decreasing. The values of cation exchange capacity and the sum of exchangeable bases have increased significantly from 2013 to 2021. Nitrogen has decreased during this period.

The department of Boundiali shows an increase in the level of exchangeable bases such as calcium, sodium, potassium and magnesium. The concentration of exchangeable bases has increased significantly, as has of the base saturation.

The three departments belong to the same northern agro-ecological zone of the Cote d'Ivoire with extreme climatic conditions. The differences observed in soil nutrient levels during the period 2013 to 2021 show an improvement in soil fertility levels with respect to exchangeable bases and partly CEC, although the absolute concentrations remain low in relation to the nutrient requirements for cotton cultivation. This increase in exchangeable bases could be explained by the increasing use of mineral fertiliser and manure. The slightly increasing trend of total nitrogen, which is closely related to the soil organic matter content, in Korogho and Boundiali may also point to an increasing use of manure and improved legume fallows. However, the increases are not significant and in Ferkessedougou the total soil nitrogen content is even decreasing.

These innovations can be also explained by the close monitoring of the cotton producers by the National Agricultural Research Centre (CNRA) and the cotton companies, which have been providing credit facilities for the purchase of inputs for several years. This had obviously a positive impact on the balance of exchangeable cations and, probably also soil nitrogen ate least in Korohgo and Boundiali. Among the recommended practices in cotton cultivation are the use of available natural phosphates, the production of organic manure through composting, crop rotation, mulching of residues and their use as bedding. Also, the practice of concentrating organic manure on the "infertile" parts of the soil rather than diluting it by spreading it over the entire cotton plot has been introduced to cotton farmers. Although we are seeing an improvement, organic and mineral fertiliser inputs are still insufficient compared to exports, and there is a general deficit in nutrients, especially nitrogen and potassium. In the Côte d'Ivoire cotton basin, an application of 200 kg per hectare of bottom dressing (NPKSB) (15N-15P2O5-15K2O+6S+1B2O3) is applied after ploughing, or just after weed control (16). Then, 40-45 days after emergence, an application of 50 kg per hectare of urea is made. Organic fertilisation is not visibly popularised in the Ivorian cotton crop; it is done in a rudimentary way by some farmers with cattle herds and not by the vast majority.

Despite the poor physico-chemical constraints of the soils in the cotton basin, the farmer's persist in growing cotton because it is more economical than other crops. Indeed, cotton cultivation is the main economic resource in the savannah areas of northern Côte d'Ivoire. Cotton is one of the main cash crops. Farmers derive most of their agricultural income from it, to the point that this crop is called white gold. In addition, the prices of cotton seeds are fixed each year by the Ivorian government and the agricultural subsidy provided by the cotton companies contribute to the maintenance of this crop by the producers of northern Côte d'Ivoire. Indeed, cotton contributes to the reduction of poverty in savanna region. Thus, producers are becoming more professional in their cooperative organisations in order to guarantee the financial profitability of production (17).

Evaluation of limiting soil properties

Critical limits determine the range of desirable values for a selected soil property that must be maintained for the normal functioning of the soil ecosystem. Within these critical limits, the soil is able to maintain its specific functions in ecosystems (15). The results of the particle size analysis of the soils studied during the periods 2013 and 2021 showed the dominance of sandy-silty textures that are often unfavourable for cotton cultivation. The physical properties of the soil are assumed to be constant over time, and little is known about their natural evolution (18). The proportions of sand and silt largely dominate that of clay throughout the study area, with over 80% sand. Clay levels were well below 10%. A clay deficiency is not conducive to water and nutrient retention. Clay is the element that conditions the fixation of mineral elements on the adsorbent complex (14). The high proportion of sand is thought to be related to the effects of ploughing and continuous land use, which causes leaching of fine particles (19). According to Parikh (20) and Pypers et al. (21), silty textured soils are often considered ideal for agriculture as they are easily cultivated by farmers and can be very productive for crop growth. We found that soil textures composed of loam > clay > sand improve cotton yield and promote good drainage (22). Thus, the results of the present study clearly indicate that the soils in the study area are not suitable for cotton cultivation. Soil pH has a huge influence on soil biogeochemical processes. Soil pH is described as the "primary soil variable" that influences a myriad of biological, chemical and physical soil properties and processes that affect plant growth and biomass yield (23, 24). Cotton is one of the most sensitive crops to low pH soils. The pH values obtained in the four departments of the study area were above the threshold (pH>5.5), i.e. weakly acid to neutral. This pH value varied slightly over the period 2013 to 2021. However, previous studies have shown that when soil pH falls below 5.5, cotton plants start to show symptoms of Al and Mn toxicity, which affects fibre quality (25). As soil pH is measured on a logarithmic scale, even a small change in pH indicates a large change in soil quality and therefore affects soil health and nutrient availability.

Soils in the cotton basin study area were deficient in total nitrogen (N_T). This deficit in total nitrogen observed over the period 2013 and 2021 could be explained by the fact that the cotton plots are not regularly fallowed over a long period in order to maintain high total nitrogen content. As clay minerals are the basis of the clay-humus complex, their low content largely contributes to the fast decomposition of organically bound nitrogen in these soils (26–28). The CEC content is low in the whole study area, which is explained by the low organic matter and clay content observed in the different soils of the cotton basin study areas. The results confirm those obtained by Solly et al. (29)Koull & Halilat (30) who found that CEC was intimately related to the organic matter and clay content of the soil. The clay content explains the binding of exchangeable cations to the clay-humus complex. There is therefore a strong effect of clay content that contributes to the total low CEC. In superficial soils, mainly the cation exchange capacity (CEC) and the sum of exchangeable bases (SEB) were limiting for all four departments of the study area (Korhogo, Ferkessédougou, Boundiali and Mankono). The quantitative values beyond which a further reduction of these properties is limiting depend strongly on the crop. For example, a CEC below about 10 $cmol^+/kg$ is a severe limitation that can reduce the yield of the cotton crop. This is a very important soil property that influences soil structure stability, nutrient availability, soil pH and soil response to fertilisers and other soil amendments (31). Percent base saturation (BS) is the percentage of CEC occupied by base cations Ca^{2+}, Mg^{2+}, Na^+ and K^+. Therefore, soils with a high percentage of base saturation are generally more fertile as they have little or no acidic cations and Al^{3+} which is toxic to plant growth. The soils with high BS contain greater amounts of the essential nutrient cations Ca^{2+}, Mg^{2+}, Na^+ and K^+, which are needed by plants (32).

In Korogho and Ferkessedougou departments, the most limiting factors in both periods (2013 and 2021) are SEB and CEC. The department of Boundiali has SEB as the most limiting factor in 2013 and SEB and CEC as the most limiting factors in 2021. In Mankono district, the most limiting factor in both periods (2013 and 2021) is only CEC. However, the fertility class between the two periods is different in Mankono. In 2013 we have fertility class IV which means that the fertility level is very low, and in 2021 the fertility class is III which means that the soil fertility level is low. In general, the cation exchange capacity and the sum of exchangeable bases during these two periods appeared to be strongly limiting for the cotton cultivation. In the Mankono department, during the 2021 period, the sum of exchangeable bases appeared to be also a limiting factor level. The soil fertility classification reveals that on average the soils in Korhogo, Boundiali and Ferkessédougou departments have lost their agricultural potential and are in class IV. This is due to the low content of the sum of exchangeable bases and the cation exchange capacity of the soils.

Soil fertility in arid and semi-arid conditions is limited by environmental extremes of hot and cold temperatures, as well as low water availability (33). The agro-climatic parameters present constraining characteristics for agriculture, especially in the North of the bassin (Korhogo, Ferkessédougou and Boundiali) which sometimes experiences severe droughts and the centre of Mankono with less severe climatic conditions (11). With a few exceptions, the soils have low fertility marked by low availability of cation exchange capacity and the sum of exchangeable bases. These limitations are due to the of organic matter and cation inputs (Ca^{2+}, Mg^{2+}, K^+) from external sources, as these areas are subject to high temperatures (promoting degradation of organic matter) and high rainfall intensities (erosion of topsoil and high leaching rates of cations) (5). Thus, conservation of topsoils and of soil water as well as efficient use of water is a prerequisite for increasing nutrient availability and uptake. The soils of the cotton plots in the departments of Mankono have higher vegetation cover to protect the soil from wind and water erosion than those in the northern departments of Korhogo, Ferkessédougou and Boundiali. Furthermore, one of the consequences that induce these limiting factors of soil fertility are unsustainable soil management practices and insufficient application of fertilisers. These results are in agreement with the work of (5, 14, 34) who demonstrated a rapid decline in soil chemical properties following intensive cultivation with inappropriate cropping practices. Thus, action plans that focus only on one factor, such as mineral fertiliser recommendations, are unlikely to be successful in improving soil fertility in most regions. Each of the priority factors needs to be improved in such a way that none of the identified priorities is limiting. For example, while it is clear that the use of mineral fertilisers in combination with organic matter from plant or animal debris can improve soil fertility and hence crop yields. Examples of such cropping systems are the implementation half-moon practices (35) and of improved, fallow systems. However, all these technical approaches need the inclusion of appropriate recommendations (the right rate, time and place or method), reliable extension services, access to financial resources and favourable policies in order to increase their adoption

Conclusion

The study demonstrated the relevance of soil physico-chemical parameters in the sustainable management of cotton productivity in the cotton-based cropping systems of Côte d'Ivoire. The results, showed that most of the soils in the study area were in a state of degradation and less favourable for cotton cultivation. The chemical analyses indicated mineral element deficiencies in the soils studied. The most limiting chemical properties are CEC and SEB. However, from 2013 to 2021 the content of exchangeable cations (Ca^{2+}, Mg^{2+} and K^{+}) and the base saturation increased significantly in all the departments which may be due to more intensive use of mineral fertilisers. It seems that farmers are gradually adopting sustainable crop and soil management Sustainable solutions like the frequent use of organic amendments such as manure, compost and crop residues, as well as the combination of organic amendments with chemical fertilisers.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

K-KHK, ENK, WAA and WA contributed to conceptualization and design of the study. TG and NO-P organized the database. KI drafted the original manuscript and performed the statistical analysis. All authors contributed to review and revision of the manuscript and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsoil.2022.959325/full#supplementary-material

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