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Morphology, Physico-chemical Characteristics, Nutritional Status and Fertility Capability Classification of the Benue Floodplain Vertisols in North Cameroon

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Authors' contributions

All authors designed, analyzed and interpreted the results as well as prepared, read and approved the final manuscript.

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ABSTRACT

Vertisols are one of the most fertile soils in the tropics but crop production is often limited by physical features related to shrink-swell movement under different moisture conditions making management strategies mostly tilted towards soil moisture control. However, most crops planted on vertisols often show signs of nutritional deficiencies whose causes are not yet fully understood. The

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main aim of the present work was therefore to characterize the vertisols of the Benue floodplain, to highlight some potential causes of nutritional deficiencies and to attempt a fertility suitability classification (FCC) of those soils. The work was done in the field and in the laboratory. The main results revealed that those soils, with a depth of 2-2.5 m above the water table, showed a dark grey color, a heavy clayey texture. Physico-chemically, they were characterized by high cation exchange capacity (CEC), high sum of exchangeable bases (S), high base saturation (S/T ratio), low organic carbon (OC), high total available phosphorus (TAP), low total nitrogen (TN) and high C/N ratio (10-26.5). The nitrogen versus pH equilibrium revealed that despite the suitable pH(H_2O), close to neutrality, TN was deficient and limiting to plant growth. The Ca/Mg/K ratio revealed a cationic imbalance for Ca, Mg and K. The other equilibrium factors like potassium versus texture, sum of bases versus texture, CEC versus texture equilibrium and individual exchangeable bases versus CEC equilibrium revealed a very rich chemical fertility for the studied soils. Despite this richness, the heavy clayey texture and cationic imbalance of the different nutrients indicated limited nutritional uptake by plants, suggesting that management strategies for crop production on vertisols should not only be geared towards water management, but also towards nutrient balance.

Keywords: Vertisols; soil fertility; nutritional balance; soil classification; benue floodplain.

1. INTRODUCTION

Vertisols, like any other soils, constitute a multi-complex system comprised of mineral and organic, liquid and gaseous phases which confer to them certain physical, chemical and biological properties [1]. They are characterized by at least 30% clay fraction, the abundance of smectite clay minerals, a high CEC and a high base saturation [2]. They are chemically very fertile in the natural state and this particularity makes them very attractive for agricultural purposes [3,4]. However, their physical properties related to shrinking and swelling makes their agricultural exploitation very difficult [5-7]. This explains why their agriculture potentials have not yet been fully exploited in many parts of the world, especially in the Sub-saharan zone where widespread areas of vertisols are either left fallow or used for grazing and woodland for charcoal burning [8]. The works of [1,9-11] showed that total levels of nutrients are rarely indicative of plant nutrient availability. The optimum plant growth and crop yield depends not only on the total amount of nutrients present in the soil at a particular time but also on their availability which is in turn controlled by soil properties like texture, organic carbon and calcium carbonate contents, CEC, pH, etc [12]. The vertisols of north Cameroon are characterized by a heavy clayey texture, low organic carbon content, low nitrogen content, high exchangeable calcium and calcium carbonate and at times salinity/alkalinity problems [13]. These soil conditions are not favourable for adequate availability of soil nutrients to plants [11]. The Benue floodplain of north Cameroon is under this zone. So, the present investigation was undertaken on the Benue floodplain vertisols of North Cameroon to highlight the nutritional status of available nutrients, their relationship with soil properties, potential causes of nutritional deficiencies and to attempt a fertility capability classification. Thus, it would be possible to provide soil information to use especially for agricultural purposes and farm planning. The results obtained will provide data to farmers on the appropriate management strategies to be adopted on such soils for optimum food productivity. The study´s interest is both fundamental in order to supplement the available database on vertisols and applied in view of better management and protection/conservation of these soils.

2. MATERIALS AND METHODS

2.1 Study Site

The Benue floodplain is located at the centre of the Benue watershed in North Cameroon between latitudes 8° and 10°N (Fig. 1). It is centrally dissected by the Benue River, main collector, characterised by a close to 30 m thick alluvial flat which attains 5-10 km width on both sides of the river and contains numerous meanders which remain flooded throughout the rainy season [14]. The general landscape is characterised by an extensive horizontal plain whose monotony is interrupted here and there by small hills or “inselbergs” of 200-800 m altitude. It is a confined sedimentation basin which receives flood waters from numerous tributaries of the Benue River [15]. The flooded zones are separated from the main channel by raised sandy beaches [14]. The main physical characteristics of the studied site are summarised in Table 1. The vegetation is a seasonally flooded prairie which is strongly modified by farming activities [16]. Vertisols constitute the most abundant soil group, often associated with ferruginous soils (Fig. 1).

On the Benue floodplain, a number of activities have converged like agriculture, cattle-rearing, fishing, commerce, etc [18]. There is an ethnic specialization of activities and delimitation of land surfaces reserved for each type of activity. The exploited land surfaces have strict time delimitation based on seasons, but very little spatial delimitation, and cattle often move freely into farmland at postharvest often leading to farmer-grazer conflicts. Each village holds a rainy season farmland either on the slopes or on the terrace as well as dry season farms on the raised sandy beaches (sorghum, cassava) and on vertisols (muskwaari).

2.2 Sample Collection and Laboratory Analyses

Five vertisol profiles were finely described in the field followed by sample collection. Each profile was georeferenced using a Global Position System Receiver (Magellan Mark). The samples were packed in air-tight plastic bags and transferred to the laboratory for further processing and analysis. The physico-chemical analyses were done in the Laboratory of Soil Science and the Laboratory of physico-chemistry of mineral materials (University of Yaoundé I). Thus, the particle size distribution was measured by Robinson´s pipette method [19]. The pH-H_2O was determined in a soil/water ratio of 1:2.5 and pH-KCl in a soil/KCl ratio of 1:2.5 using a glass pH-meter [20]. The organic carbon (OC) was measured by Walkley-Black procedure [21]. Total nitrogen (TN) was measured by the Kjeldahl

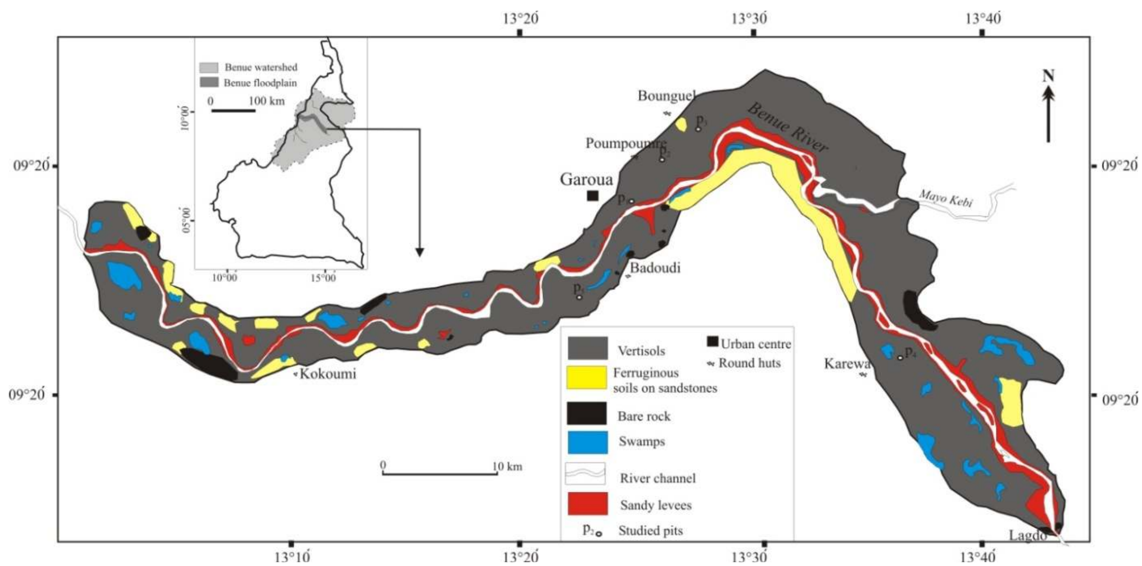

Fig. 1. Map showing position of the Benue floodplain in Cameroon, the different soil types in the Benue floodplain according to Gavaud et al. [17] and the studied pits

Table 1. studied site characteristics

Sites	Garoua brasserie	Poumpoumré	Bounguel	Badoudi	Karewa
Geographic coordinates	9°15´00˝N, 13°24´00˝E	9°20´00˝N, 13°28´00˝E	9°24´00˝N, 13°31´00˝E	10°13´36˝N, 13°34´28˝E	09°11´34˝N, 13°20´59˝E
Altitude (m)	175	180	178	174	191
Precipitation	1033	1000	1000	1000	886
Temperature(°C)	28	28	28	28.6	28.2
Slope gradient (%)	<1	<1	1-2	<1	<1
Parent rock	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium
Bedrock	Granite-gneiss	Granite-gneiss	Granite-gneiss	Granite-gneiss	Granite-gneiss
Soil occupation	Millet	Millet	Millet	Fallow	Rice
Irrigation	none	none	none	none	Irrigated

method [22]. Total available phosphorus (TAP) was determined by concentrated nitric acid reduction method [23]. Exchangeable bases were determined by ammonium acetate extraction method [24] and cation exchange capacity (CEC) was measured by sodium saturation method [25]. Total phosphorus was determined by ICP-AES [19]. Aluminium toxicity was checked by the Kamprath method [26]. Comments on soil physico-chemical data were done according to critical values of soil properties and nutrients from Euroconsult [27] and Tabi et al. [28]. Version 4 of the fertility capability classification (FCC) was used to identify soil fertility limitations according to Tabi et al. [28] and Sanchez et al. [29].

3. RESULTS AND DISCUSSION

3.1 Soil Morphology

The morphological features of the five vertisol profiles are presented in Appendix 1. Globally, these soils, with a depth of 2-2.5 m above the water table, showed a grey to dark grey color, a heavy clay texture, very hard when dry but sticky and plastic when wet. Surficial cracks were present and developed to a depth of over 50 cm as well as slickensides at the middle part of the profiles. The presence of these features is related to vertic movements with changing moisture conditions [17]. Numerous dark millimeter-sized nodules were present in the sandy fraction. Quartz grains were mainly angular to sub-angular revealing short fluvial transport distance of the parent material of the vertisols [14].

3.2 Physico-chemical Characteristics

The vertisols showed a clayey to heavy clayey texture (Appendix 1). The pH-H_2O ranged from 5.6 to 7.2 and revealed acidic to slightly basic soils. Excluding Garoua Brasseries, pH-H_2O was lower at the surface than at middle part of all the profiles indicating the leaching front in agreement with [2]. The pH-KCl was less than pH-H_2O; it generally increased with depth for all the regions apart from Garoua where an opposite trend was observed. The organic carbon was low to moderate for all the soils and more represented in the surface horizons than in the sub-surface ones where a sharp decrease was observed in all the profiles. The total nitrogen contents varied from 0.02% to 0.1% (Appendix 2). Such low values could be related to poor drainage imposed by the heavy clayey texture and slow transformation of organic matter [2]. The total available phosphorus varied from 0.12 to 75.53 ppm (Appendix 2). The sum of exchangeable bases of all the profiles ranged from 24.36 to 37.14 cmolc kg^{-1} of soil (Appendix 2). Values increased regularly with profile depth. Calcium was the dominant exchangeable cation, with contents ranging from 15.20 to 26.60 cmolc kg^{-1}, which was about 60 to 70% of total bases. It was followed by magnesium (6.9 to 11.60 cmolc kg^{-1}), while sodium and potassium showed more modest values of 0.52 to 1.78 cmolc kg^{-1} and 0.40 to 1.99 cmolc kg^{-1}, respectively. Calcium and magnesium increased with depth, while sodium and potassium showed an opposite trend (Appendix 2). The CEC varied from 26 to 42 cmolc kg^{-1}, and generally increased from the surface to the base of all the profile. Aluminium toxicity was not detected in all the profiles. Thus, the studied vertisols are chemically very rich but deficient in nitrogen.

3.3 Micronutrient Composition

The composition of micronutrients was in the following trend: Fe>Mn>Zn>Cu (Table 2). Their levels in the surface horizons were within the permissible range for normal plant growth [30, 31]. Except for Garoua Brasseries (Table 2), all the Fe/Mn ratio values were less than 1.5 indicating a potential Mn toxicity in those vertisol sites caused by cationic imbalance of the two metals [32].

3.4 Nutrient Availability Ratios and Nutrient Balance

These two parameters enabled to assess the actual fertility status of the vertisols without addition of fertilizers. Thus, base saturation (S/T ratio) globally ranged from 74.30 to 94.23% (Appendix 3). It increased with depth of all profiles except in Bounguel where a slight decrease was observed in the middle horizon. The Na/T ratio (exchangeable sodium percentage) was very low and ranged from 1.17 to 5.09 in all the sites studied; these values are typical of non-saline and non-sodic soils [2]. These low values are of no concern since they do not present any danger to plants. The C/N ratio ranged from 7.20 to 26.5 (Appendix 3). High values indicate slow decomposition and low mobilization rate of organic matter [2].

The TN/pH (total nitrogen in ‰-to-pH ratio) globally ranged from 0.16 to 0.03 (Appendix 3); the ratio values of all the studied profiles were highest at the surface and decreased with depth.

This trend indicates a slight decrease in chemical fertility with depth based on TN/pH balance [9]. The N-pH binary diagram (Fig. 2) of Dabin [33] showed that despite a suitable pH of all the vertisol horizons for crop cultivation, the total nitrogen remained low for a majority of them revealing that nitrogen is a limiting factor. The TN/TP (total nitrogen in ‰-to-total phosphorus ratio) values were globally higher for all the surface horizons and decreased depth-wise (Appendix 3). Thus, the TN/TP of surface to sub-surface horizons was above 0.05, indicating a potential risk of nitrogen deficiency [33]. The C/P ratio (or phosphorus mineralization index) were generally higher than 200 for most of the horizons, indicating a slow turn-over rate for soil available phosphorus [34]. The N/P ratio (or nitrogen mineralization index) ranged from 6.48 to 87.75 (Appendix 3). Such high values revealed potential risk of nitrogen deficiency. Low nitrogen levels could hinder available phosphorus uptake due to ionic imbalance [35]. The Mg/K ratio ranged from 3.47 to 22.45 in all sites studied suggesting a normal to optimal level of Mg and K in the soils [9]. The Ca/Mg equilibrium values ranged from 1.72 to 2.72. Apart from the B_V horizon of profile P5 in Karewa, all the other ratios were greater than 2 suggesting a balanced cationic equilibrium between Mg and Ca [9,10]. The Ca/Mg/K equilibrium revealed a relative concentration of Mg in all the profiles, with relative concentration coefficients ranging from 1.49 to 1.89 (Appendix 3). The cation equilibrium of the three bases was therefore unbalanced relative to the predefined optimum values (76% Ca, 18 % Mg and 6 % K) adequate plant nutrient uptake [11].

The Forestier's fertility indices [36] were extremely high (8.72 to 20.38), increasing with depth for all profiles (Appendix 2). The high indices are in agreement with the high sum of exchangeable bases of the vertisols [37]. A representation TN versus TP on the N-P binary diagram [33] revealed that the vertisols are medium to very rich in phosphorus (Fig. 3). The exchangeable potassium (K) versus texture chart (Fig. 4) according [10] revealed that the fertility level of the vertisols was low to very good. However, no sample was below the critical limit. Despite the good exchangeable potassium reserves of the vertisols, the heavy clayey texture remained a limiting factor for plant uptake [35].

The sum of exchangeable bases (S) versus texture chart (Fig. 5) in reference to Dabin [9] and Boyer [10] revealed that the base reserves were essentially good. Also, the forestier's index [36] values were all greater than 1 (Table 2) synonymous to chemically very rich soils.

Figs. 6, 7 and 8, adapted from Tabi et al. [40], enabled to further show that the concentrations of Mg and Ca (Figs. 5 and 6) were very high, but K concentrations varied significantly from low to high (Fig. 8). The high Ca and Mg contents could be related to the recent alluvial parent materials which are enriched in basic cations.

The Ca/Mg/K triangular diagram (Fig. 9) of Martin [36] revealed an excess of exchangeable calcium in the vertisols. The basic cations were imbalanced, although very close to the zone of optimum equilibrium. This might explain why the actual fertility status of the soil was good rather than very good or exceptional as indicated by most of the standard charts. The different horizon samples were more located towards the Mg axis (though Ca pole) which determined the direction of cationic equilibrium (Fig. 9). The distribution of cations suggested that cation balance could be a limiting factor to plant uptake of these three nutrients.

Table 2. Micronutrient concentrations and predefined crop growth levels for the vertisol surface (Ap) horizons of each studied site

Micronutrients (mg kg^{-1}) / Studied site and level	Fe	Cu	Zn	Mn	Fe/Mn
Garoua Brasseries	162.6	31.4	81.0	108.00	1.51
Poumpoumré	189.3	36.1	96.3	162.00	1.17
Bounguel	102.9	19.20	112.6	191.12	0.54
Badoudi	118.2	29.20	112.6	201.1	0.59
Karewa	136.0	12.06	26.90	122.1	1.11
Normal levels in plant [30].	50- 500	5-20	20-1000	1-400	1.5-2.5
Critical levels for plant growth [30]	50-150	20-100	300-500	100-400	-
Toxicity levels in plants [31]	>500	20-30	>500	>400	>2.5 (Fe toxicity) <1.5 (Mn toxicity)

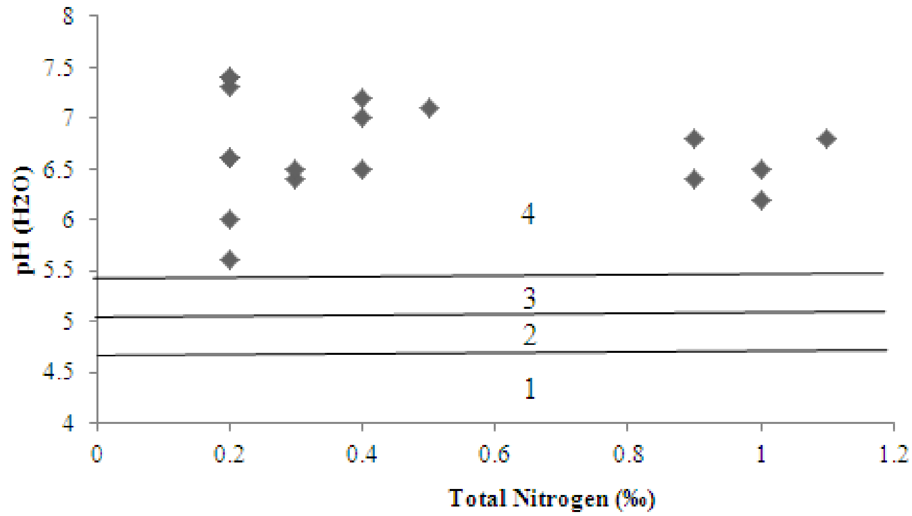

Fig. 2. Total nitrogen versus pH (H_2O) equilibrium diagram for soil fertility assessment [33]
(Fertility level: 1. low; 2. moderate; 3. good; 4. very good)

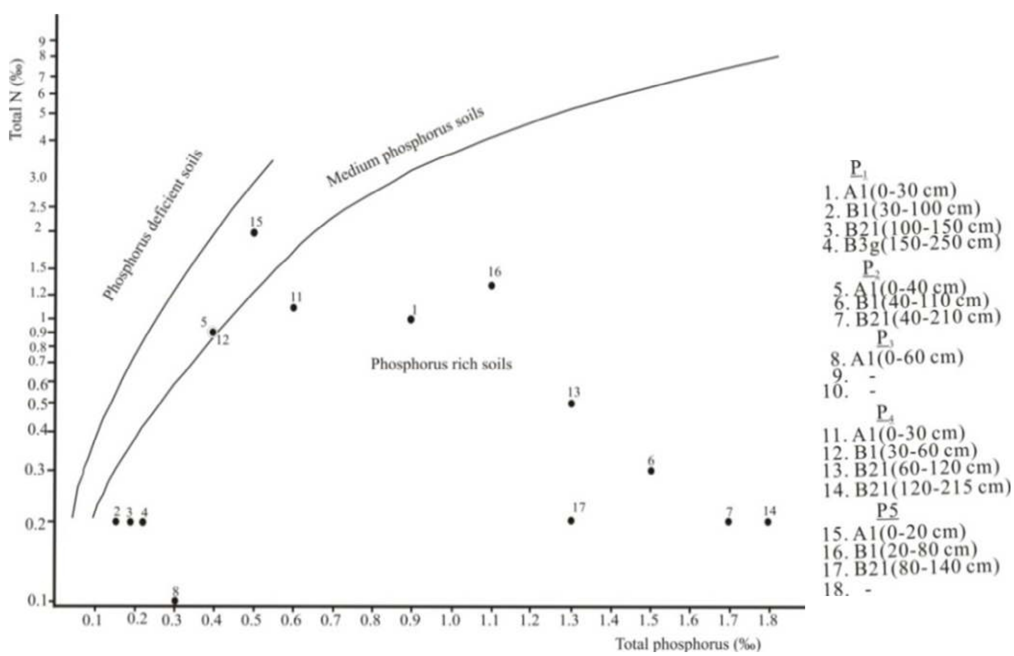

Fig. 3. Total nitrogen versus total phosphorus equilibrium diagram [38]

3.5 Fertility Limitation and Fertility Capability Classification (FCC) of the Vertisols

The system consists of two categorical levels of classification. The first (type/ substrata type), describes topsoil and subsoil texture and is expressed in capital letters. The second (condition modifier) consists of 17 modifiers defined to delimit specific soil conditions affecting plant growth with quantitative limits. Each condition modifier is represented as a lower case letter, while + or - indicate greater or lesser expression of the modifier. The main soil fertility limitations for crop cultivation included heavy clayey texture (C), waterlogging (g), organic matter depletion (m) and vertic properties (v). Such soils were thus classified as Cgmv in the FCC system (Table 3).

3.6 Suitability of the Studied Vertisols to Some Common Tropical Crops

The vertisols of the Benue floodplain, with a heavy clayey texture, are very hard when dry and show desiccation cracks, but sticky, plastic and impermeable when wet. They are chemically very fertile but deficient in nitrogen. They occur in an area with a relatively short rainy season and high mean annual temperatures. Based on their needs, sorghum and millet, compared to other cereals, will do well on vertisols as they are more tolerant to low levels of organic matter, exchangeable K, available P and total N. Shallow soils with a heavy clayey texture like vertisols are usually not suitable for the growth of maize, cotton and groundnuts. Nevertheless, millet will give optimum yields preferably on sandy clay soils with excellent drainage while rice will give optimum yields on silty clay soils with an impermeable sub-surface layer to retain excess water [35]. Sorghum and rice have a high tolerance to waterlogging than maize, cotton and groundnuts. On the other hand, sorghum is more tolerant to drought conditions than all other grain cereals due to its well-developed and finely branching root system, very small leaf area index which limits transpiration. The cultivation of cassava is not good on vertisols since this plant needs a deep (>100 cm), well drained and well aerated soil with a deep water table and a light structure. The cultivation of maize is not well adapted to vertisols mainly due to the heavy clayey texture, the low organic matter content and the high temperatures that prevail in north Cameroon. The growth of sugarcane requires abundant rainfall (1000-2000 mm) with four to five months of dry season, a temperature range of 15-35℃, well aerated soil structure and wide range of texture (25-75% clay), excellent sunlight, good drainage, a pH range close to neutrality, good phosphorus, nitrogen and potassium status. All those factors are met in the Benue floodplain apart from a low available P, total N and exchangeable K levels essential for sugarcane growth. Irish potatoes cultivation requires a near neutral pH as in the Benue floodplain, but excess water during the rainy season, desiccation cracks in the dry season, the heavy clayey texture and low organic matter contents are limiting factors to the growth of this crop. Pineapple requires a regular rainfall (1000-1500 mm), a light soil texture and a lightly acidic pH (5.5 to 6). Those conditions are not met in the Benue floodplain

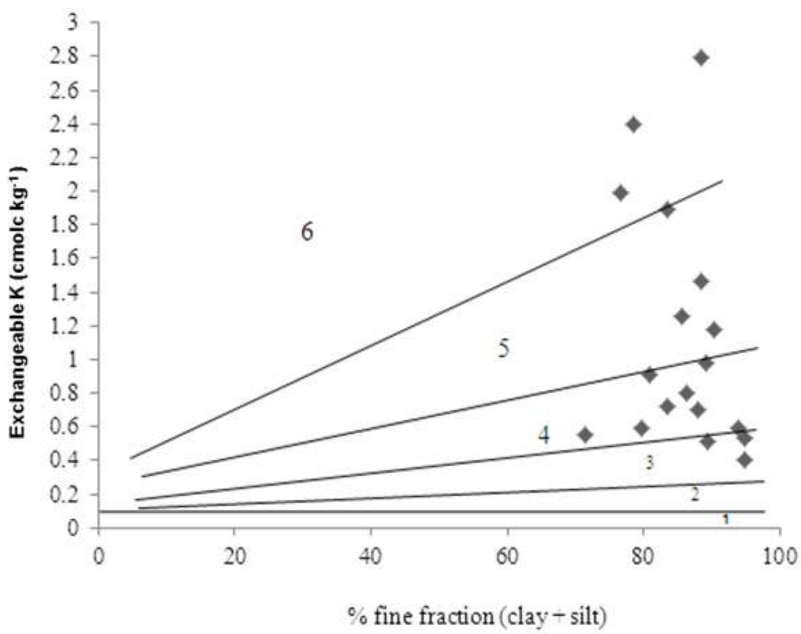

Fig. 4. Exchangeable potassium versus texture equilibrium diagram to assess potassium availability level to plants [10]

(Fertility level: 1. Critical; 2. very low; 3. low; 4. moderate; 5. good; 6. very good)

vertisols. Some of these factors can be overcome, but others cannot. Approaches to improve crop production should include selection of appropriate crop varieties, introduction of suitable cropping systems and chemical methods (right amounts and combination of nutrients) [41]. According to [35], sorghum, millet, rice and cotton seem to be best adapted to the actual nutritional status of the vertisols of the Benue floodplain.

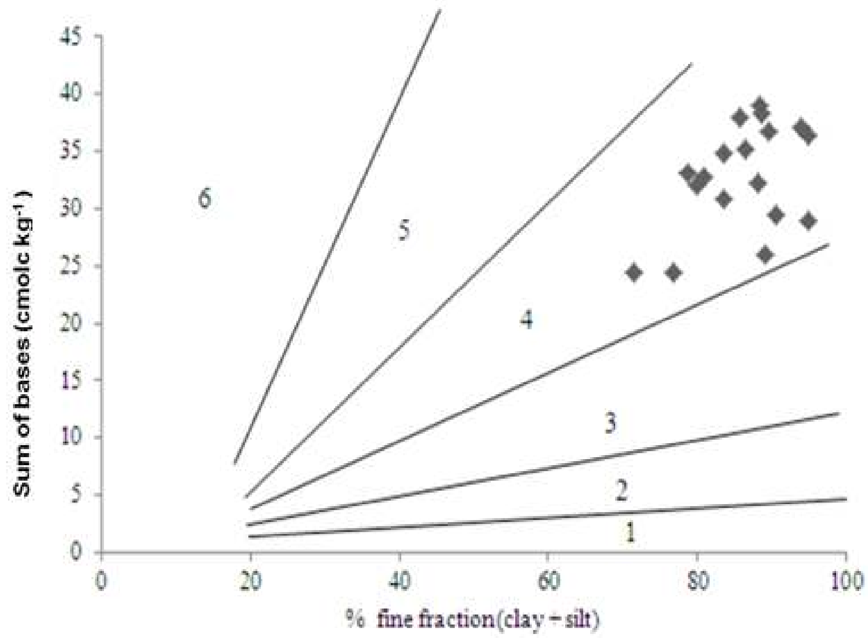

Fig. 5. Sum of exchangeable base versus texture equilibrium diagram to assess the availability level of basic cations to plants [10,39]

(Fertility level: 1. very low; 2. low; 3. moderate; 4. good; 5. very good; 6. exceptional)

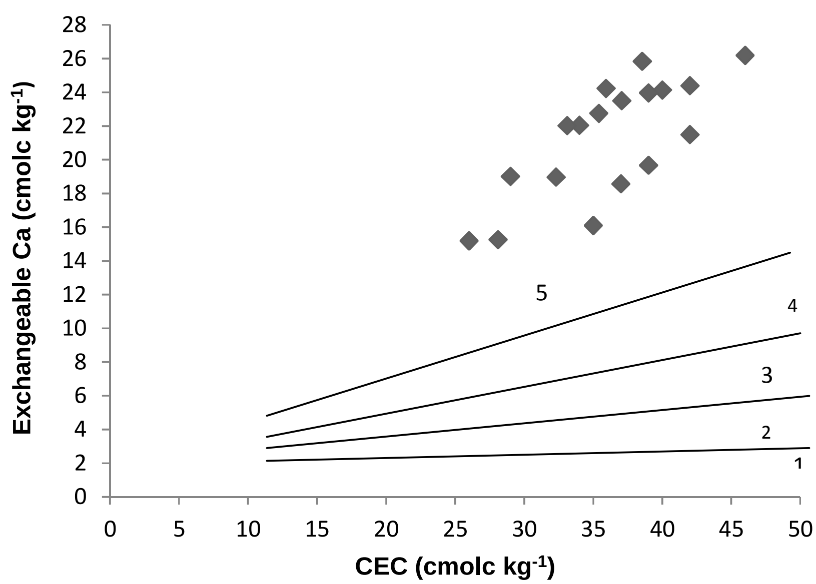

Fig. 6. Exchangeable Ca versus CEC equilibrium

(*Fertility level: 1. very low; 2. low; 3. moderate; 4. good; 5. very good)*

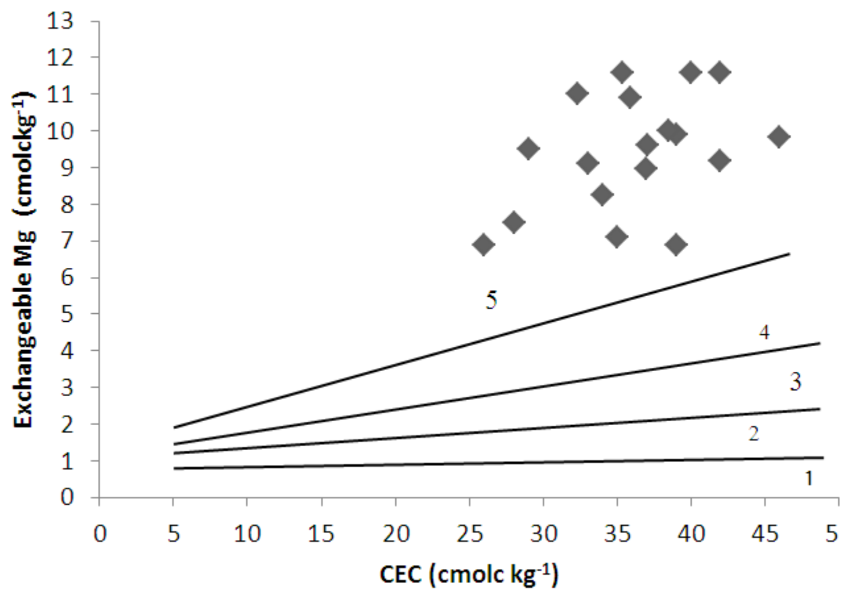

Fig. 7. Exchangeable Mg versus CEC equilibrium
(*Fertility level: 1. very low; 2. low; 3. moderate; 4. good; 5. very good)*

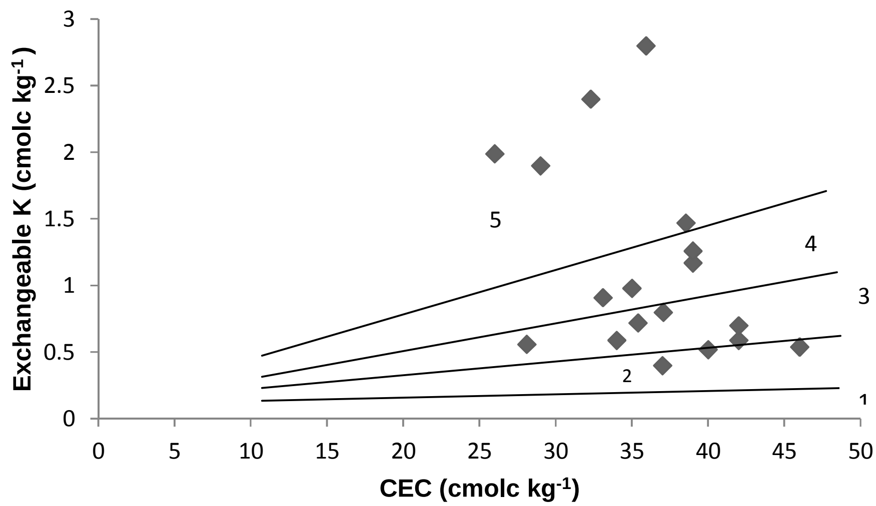

Fig. 8. Exchangeable K versus CEC equilibrium
(*Fertility level: 1. very low; 2. low; 3. moderate; 4. good; 5. very good)*

Table 3. Soil fertility limitations and fertility capability classification (FCC) units [27, 28]

Location	Type	Substrata type	Modifiers							
			a	b	e	g	k	m	v	FCC
Garoua Brasserie	C	-	-	-	-	+	-	+	+	Cgmv
Poumpoumré	C	-	-	-	-	+	-	+	+	Cgmv
Bounguel	C	-	-	-	-	+	-	+	+	Cgmv
Badoudi	C	-	-	-	-	+	-	+	+	Cgmv
Karewa	C	-	-	-	-	+	-	+	+	Cgmv

C = clay; a = aluminum toxicity; b = basic reaction; e = high leaching potential; g = waterlogging; k = low nutrient capital reserve; m = organic matter depletion; v = vertic properties

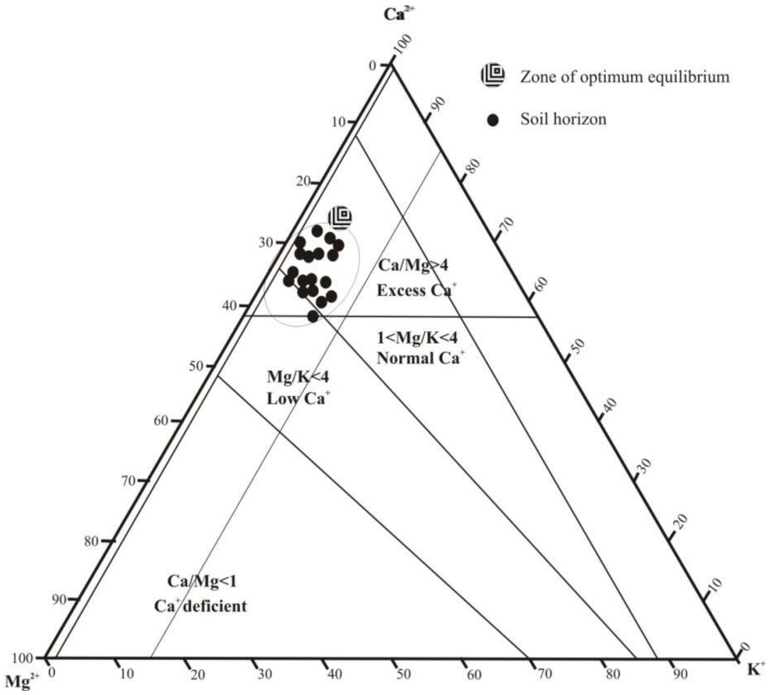

Fig. 9. Ca/Mg/K equilibrium diagram [11]

4. CONCLUSION

The main aim of the present work was to study the vertisols of the Benue floodplain and to highlight some causes of nutrient deficiencies in those soils. The main results revealed that those soils, with a depth of 2-2.5 m above the water table, show a dark grey color, a heavy clayey texture, Physico-chemically, they are characterized by high CEC, high sum of bases, high base saturation, low TOC, high TAP, low TN and high C/N ratio (10-26.5). The nitrogen versus pH equilibrium revealed that despite the suitable pH from crop production, nitrogen was deficient and liming plant growth. The Ca/Mg/K ratio revealed a cationic imbalance for Ca, Mg and K. The other equilibrium factors like potassium versus texture, sum of bases versus texture and cation exchange capacity versus texture equilibrium revealed a very rich chemical fertility for the studied soils. Despite this richness, the heavy clayey texture and cationic imbalance of the different nutrients indicated limited nutritional uptake by plants, suggesting that management strategies for crop production on vertisols should not only be geared towards water management, but also nutrient balance management. This work is important mainly as it provide soil information to use especially in agricultural purposes and farm planning. Specifically, approaches to improve crop production should include selection of appropriate crop varieties, introduction of suitable cropping systems and chemical methods (right amounts and combination of nutrients). The study´s interest is both fundamental in order to supplement the available database on vertisols to farmers and applied in view of better management and protection/conservation of these soils.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDICES

Appendix 1. Morphological and physical properties of the North Cameroon vertisols

Horiizon	Depth above water table (cm)	Munsell colour		Structure	Consistency		Rock fragments	Boundary	Roots	Clay	Sand	Silt	Textural class (USDA)
		Code	Colour		Dry	Wet							
Garoua Brasserie													
Ap	0-30	10YR5/1	G	3c, abk	h, f	s, p	n	g	c, f	62.50	10.8	26.66	Heavy clay
Bv	30-100	10YR4/1	DG	3m, abk	h, f	s, p	n	g	f, f	70.00	6.3	25.00	Heavy clay
B_{t1}	100-150	10YR4/1	DG	3c, abk	h, f	s, p	n	g	-	72.50	6.5	17.00	Heavy clay
B_{t2}	150-250	10YR3/1	VDG	3c, abk	h, f	s, p	a	-	-	75.00	7.5	18.86	Heavy clay
Poumpoumré													
Ap	0-40	10YR5/1	G	3c, abk	h, f	s, p	n	g	c, f	68.00	10.7	22.50	Heavy clay
Bv	40-110	10YR4/1	DG	3m, abk	h, f	s, p	n	g	f, f	72.00	11.95	16.03	Heavy clay
B_{t1}	110-210	10YR4/1	DG	3c, abk	h, f	s, p	a	-	-	75.00	6.4	20.0	Heavy clay
Bounguel													
Ap	0-30	10YR5/1	G	3c, abk	h, f	s, p	a	g	c, f	45.00	24.96	31.68	Clay
Bv	30-150	10YR4/1	DG	3m, abk	h, f	s, p	a	g	f, f	47.50	29.46	23.96	Clay
B_{t1}	150-230	10YR4/1	DG	3c, abk	h, f	s, p	n	-	-	53.50	22.89	26.38	Clay
Badoudi													
Ap	0-30	10YR5/1	G	3c, abk	h, f	s, p	a	g	c, f	46.60	20.01	34.30	Clay
Bv	30-110	10YR4/1	DG	3m, abk	h, f	s, p	a	g	f, f	54.20	16.83	29.40	Clay
B_{t1}	110-160	10YR4/1	DG	3c, abk	h, f	s, p	n	g	-	68.00	14.63	18.33	Heavy clay
B_{t2}	160-215	10YR3/1	VDG	3c, abk	h, f	s, p	a	-	-	58.26	13.37	27.37	Clay
Karewa													
Ap	0-20	10YR5/1	G	3c, abk	h, f	s, p	n	g	c, f	59.50	17.14	24.09	Clay
Bv	20-45	10YR4/1	DG	3m, abk	h, f	s, p	n	g	f, f	60.50	23.01	18.10	Heavy clay
B_{t1}	45-140	10YR4/1	DG	3c, abk	h, f	s, p	n	w	-	66.75	13.53	21.70	Heavy clay
B_{t2}	140-200	10YR3/1	VDG	3c, abk	h, f	s, p	n	-	-	72.50	12.7	16.11	Heavy clay

Soil properties

Structure			Consistency		Rock fragments	Horizon boundary
Size	Type	Grade	Dry	wet		
vf = very fine (G5 mm)	g = granular	w = weak (peds barely observable)	l = loose	s = sticky	n = none (0%)	a = abrupt
f = fine (5–10 mm)	abk = angular blocky	m = moderate (peds observable)	s = soft	p = plastic	c = common (5%–15%)	c = clear
m = medium (10–20 mm)	sbk = subangular blocky	s = strong (peds clearly observable)	h = hard		m = many (15%–40%)	g= gradual
c = coarse (20–50 mm)	l=lumpy				v = very few (0%–2%)	d = diffuse
vc = very coarse (>50 mm)	ma=massive				a = abundant (40%–80%)	
1 = weak; 2 = moderate; 3= strong;					d = dominant (>80%)	

A_p = ploughed layer (with desiccation cracks); B_v clayey horizon with slickensides; B_{t1}: clayey horizon with a massive structure; B_{t2}: dark grey horizon with hydromorphic patches

Appendix 2. Physico-chemical characteristics of the topomorphic vertisols from the Benue watershed

Properties / Horizon (Depth)	pH-H_2O	pH-kcl	ΔpH	TOC (%)	OM (%)	T N (%)	TAP (ppm)	Exchangeable bases (cmolc kg^{-1})				S (cmolc kg^{-1})	CE C (cmolc kg^{-1})	Total P (%)
								Ca	Mg	Na	K			
Garoua Brasseries														
Ap	6.2	5.3	0.9	2.62	4.50	0.10	75.53	16.11	7.11	1.78	0.98	26.00	35.00	0.09
Bv	6.6	5.3	1.3	0.36	0.62	0.02	13.91	18.58	8.98	1.03	0.40	29.00	37.00	0.16
B_{t1}	6.0	4.8	1.2	0.48	0.83	0.02	10.87	24.15	11.60	0.52	0.52	36.81.	40.00	0.19
B_{t2}	5.6	4.8	0.8	0.52	0.90	0.02	30.87	24.40	11.60	0.59	0.59	37.14	42.00	0.21
Poumpoumré														
Ap	6.4	5.2	1.2	1.62	2.82	0.09	60.40	19.68	6.90	1.15	1.17	29.43	39	0.04
Bv	6.4	5.3	1.07	0.58	1.01	0.03	16.80	21.50	9.17	0.78	0.70	32.15	42	0.15
B_{t1}	6.6	5.6	0.99	0.41	0.71	0.02	12.60	26.20	9.84	0.79	0.54	36.37	46	0.17
Bounguel														
Ap	6.5	5.4	1.1	1.02	1.76	0.10	39.53	15.20	06.90	1.26	1.99	24.36	26.00	0.03
Bv	6.5	5.7	0.80	0.38	0.66	0.03	18.31	15.27	07.51	1.16	0.56	24.50	28.10	<0.001
B_{t1}	7.2	6.20	1.00	0.51	0.88	0.04	13.12	22.05	08.23	1.17	0.59	32.04	34	<0.001
Badoudi														
Ap	6.8	6.0	0.8	1.26	2.17	0.11	81.20	22.03	9.10	1.76	0.91	32.80	33.10	0.2
Bv	6.8	5.9	1.1	0.98	1.67	0.09	38.00	22.76	11.60	1.72	0.72	34.80	35.40	0.01
B_{t1}	7.1	5.9	1.2	0.36	0.98	0.05	22.10	23.51	9.60	1.88	0.80	35.15	37.06	0.13
B_{t2}	7.3	6.2	1.1	0.26	0.70	0.02	12.23	23.98	9.89	1.78	1.26	37.91	39.00	0.18
Karewa														
Ap	6.5	5.6	0.90	1.02	2.78	0.04	44.32	19.02	9.50	0.40	1.90	30.82	29	0.05
Bv	7.0	6.2	0.80	0.7	1.2	0.04	19.60	18.98	11.02	0.70	2.40	33.12	32.3	0.11
B_{t1}	7.4	6.2	1.00	0.51	0.87	0.02	07.10	24.24	10.92	0.98	2.80	38.94	35.92	0.13
B_{t2}	7.4	6.4	0.80	0.53	0.91	0.02	2.36	25.85	10.01	0.91	1.47	38.24	38.54	<0.001

A_p = ploughed layer (with desiccation cracks); B_v clayey horizon with slickensides; B_{t1}: clayey horizon with a massive structure; B_{t2}: dark grey horizon with hydromorphic patches; S: sum of exchangeable bases

Appendix 3. Nutrient ratios of the different vertisol studied profiles

Parameters / Horizon (Depth)	C/N ratio	TN/pH	TN/TP ratio	N/P ratio	C/P ratio	N/P ratio	Mg/K ratio	Ca/Mg ratio	S/T ratio (%)	Ca/Mg/K (%)	CRC	Forestier's INDEX ($S^2/(A+Lf)$)
Garoua Brasseries												
Ap	26.20	0.16	0.11	13.24	346.88	6.85	7.26	2.27	74.30	66.6/29.4*/4	1.63	8.72
Bv	18.00	0.03	0.125	14.38	258.81	3.55	22.45	2.07	78.40	66.5/32.1*/1.4	1.78	10.19
B_{t1}	24.00	0.03	0.11	18.40	441.58	1.41	22.30	2.08	92.02	66.58/32*/1.4	1.77	16.73
B_{t2}	26.00	0.04	0.01	6.48	168.45	1.58	19.66	2.10	88.43	66.7/31.7*/1.6	1.76	16.95
Poumpoumré												
Ap	18.00	0.14	2.25	14.90	268.21	3.91	5.89	2.85	75.46	70.9/24.9*/4.2	1.38	10.50
Bv	19.33	0.05	0.20	17.86	245.24	2.43	13.10	2.34	76.54	68.5/29.2*/2.2	1.62	12.64
B_{t1}	20.50	0.03	1.18	13.87	325.40	2.17	18.22	2.66	79.06	71.6/26.9*/1.4	1.49	15.24
Bounguel												
Ap	10.20	0.15	0.33	25.30	258.08	5.17	3.47	2.20	93.70	63.1/28.6*/8.26	1.58	9.37
Bv	13.00	0.05	-	16.38	207.54	4.73	13.41	2.03	87.18	65.4/32.2*/2.4	1.78	9.62
B_{t1}	22.00	0.06	-	30.48	388.72	3.65	13.95	2.68	94.23	71.45/26.7*/1.9	1.48	15.36
Badoudi												
Ap	11.45	0.16	0.2	13.55	155.17	5.36	08.9	2.72	99.01	68.8/28.4*/2.8	1.57	15.22
Bv	11.00	0.13	0.13	32.14	257.87	4.9	14.7	2.15	98.33	64.9/33.1*/2.1	1.84	16.75
B_{t1}	07.20	0.07	0.007	22.62	162.9	5.34	10.8	2.73	95.00	69.3/28.3*/2.4	1.57	16.60
B_{t2}	13.00	0.03	0.003	16.35	212.59	4.7	6.81	2.70	97.21	68.3/28.6*/3.6	1.57	20.38
Karewa												
Ap	25.50	0.06	0.8	9.03	230.14	1.3	5.0	1.73	94.10	62.5/31.2*/6.6	12.58	2.06
Bv	17.5	0.06	0.36	29.41	357.14	2.11	4.59	1.89	97.60	58.6/34.0*/7.4	15.28	1.72
B_{t1}	25.5	0.03	0.15	28.17	718.31	2.52	3.9	1.60	92.22	63.9/28.8*/7.4	18.42	2.23
B_{t2}	26.5	0.03	-	87.75	2245.76	2.38	6.8	1.49	100	68.5/26.8*/3.9	18.86	2.58

A_p = ploughed layer (with desiccation cracks); B_v clayey horizon with slickensides; B_{t1}: clayey horizon with a massive structure; B_{t2}: dark grey horizon with hydromorphic patches

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