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Moisture content, moisture-related properties and agricultural management strategies of the Benue floodplain vertisols in North Cameroon

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Vertisols are widespread in North Cameroon, but are undercultivated due to difficulties linked to their shrink-swell behaviour under different moisture conditions. Eighteen vertisol samples from five profiles representative of the studied area (Benue floodplain in North Cameroon) were studied to establish a relationship between moisture and physico-chemical characteristics and supplement data for planning sustainable agricultural management. The main results revealed that the soils are deep, dark grey, heavy clayey, with high coefficients of linear extensivity, low organic matter and low electrical conductivity. At field capacity, they showed a very low bulk density, high porosity and a high void ratio. Oven-dry soils exhibited very high bulk density, very low porosity and very low void ratio. This high reversibility of properties with changing moisture content is related to high smectitic mineralogy. The moisture properties revealed very high water-holding capacity, very high available water and very high readily available water. Most of the physico-chemical characteristics correlated well with the moisture parameters. The principal component analysis revealed a reduction of 17 initial variables to two principal components (PC1 and PC2) explaining over 70% of the total variance. The PC1 clustered 12 soil and soil moisture variables indicating strong correlation between moisture and physicochemical properties. Management practices for crop production must be primarily directed at moisture control.

Key words: Vertisols, soil moisture, soil suction, land evaluation, Benue floodplain.

INTRODUCTION

Soil and water are the basic natural resources for agricultural production (Duchaufour, 1997; Chow et al., 2012). Soil water is indispensable in ecosystem's productivity: it intervenes directly in plant nutrition as a transporter of dissolved plant nutrients, and indirectly as a principal pedogenetic factor controlling the majority of soil forming processes (Western et al., 2004; Yerima et al., 2013; Wubie 2015; Bhattacharyya et al., 2016). Soil moisture is a key variable in the water and energy cycles and its accurate representation and measurement is required for estimation and prediction of infiltration, evaporation, runoff, ground heat fluxes, etc (Liu et al., 2010). Soil water is thus essential for adequate development of crops and is dependent on soil properties

(Reichert et al., 2010; Chow et al., 2012). Vertisols are heavy clay soils that occur mainly in the intertropical zone with contrasting wet and humid seasons (Eswaran and Cook, 1988; Chow et al., 2012). They constitute a considerable agricultural potential but adapted management is a precondition for sustained production (Seini-Bouker et al., 1992; Fassil, 2009; Fassil and Yamoah, 2009; Azinwi Tamfuh et al., 2012). The key agricultural potentials of vertisols are their extremely rich chemical fertility and occurrence in extensive plains where reclamation and mechanical cultivation can be envisaged (Azinwi Tamfuh et al., 2016). However, their physical features and their difficult water management problems constitute a limitation to their agricultural exploitation (Yerima et al., 2013). The heavy clay texture and dominance of expansive clays of smectitic type result in a narrow soil moisture range between moisture stress in the dry season and water excess in the rainy season (Ambassa-Kiki et al., 1996; Özsoy and Aksoy, 2007). The susceptibility of vertisols to waterlogging is the most important factor that reduces the actual growing period (Azinwi et al., 2012). Water, thus, greatly affect the exploitability of vertisols during tillage, weeding and harvest (Astatke et al., 1995). In North Cameroon, vertisols cover a total surface area of 1100 ha, specifically in the Benue floodplain and the Chad basin (Brabant and Gavaud, 1985; Jones et al., 2013; Djoufac Woumfo et al., 2006). They are chemically very fertile soils (Ambassa Kiki et al., 1996; Azinwi Tamfuh et al., 2005). However, due to their vertic properties under different moisture conditions, they remain undercultivated. Although interest in estimating vertisol moisture content has been strong, the relationship between moisture content and other vertisol characteristics that affect agricultural management is still not fully understood. The aim of the present work was: (1) to study the main vertisol physico-chemical properties; (2) to determine the soil moisture content and moisture tension; and (3) to highlight the influence of soil properties on moisture storage and agricultural management strategies. The study's interest is both fundamental (to supplement the available database on vertisols) and applied (for better management and protection/conservation of these soils). Besides, it would be possible to provide soil information to use especially for agricultural purposes, farm planning and other engineering practices.

MATERIALS AND METHODS

Study site description

The study site is the Benue River floodplain at the centre of the Benue trough in North Cameroon, between latitude 08°30´ to 09°40´ N and longitude 12°25´ to 016°00´ N (Figure 1). This seasonally flooded plain is rich in alluvial deposits, about 35 m thick, composed mainly of sands, gravels and clays (Ngounouno, 1993). It is under a tropical climate with two contrasted seasons: a humid season from May to October and a dry season from November to April (Figure 2). The total annual precipitation is 1033 mm and the mean monthly temperature is 28.2°C, typical of a classical sudanian climate (Etia, 1980). The total annual evapotranspiration, insolation and average relative humidity range are 1920 mm, 2974 h and 42-71%, respectively (Olivry, 1986). The Benue River, principal collector, with its numerous tributaries constitutes a dense and dendritic pattern (Olivry, 1986). Most of the streams are seasonal (except the Benue River) taking their rise either on the Mandara Mountains in the north of the Benue trough or the Adamawa highlands in the south (Olivry, 1986). The relief is diversified on both sides of the Benue trough, typified by irregular and uneven landforms with the highest point at Tchabal Mbabo (2460 m) and the lowest one in the Benue floodplain (<200 m altitude). The Benue trough is a rift formed within the Meso-to-Neoproterozoic granitic-gneissic basement and is entirely filled with continental sediments, precisely sandstones of the Middle to Upper Cretaceous (Ngounouno et al., 1997). The natural vegetation, which is the Sudanian savannah, has been strongly replaced by crops (notably sorghum) and human settlement (Letouzey, 1980). The major soils are raw mineral, lightly evolved, hydromorphic, ferrallitic, vertisolic, halomorphic, ferruginous and fersiallitic soils (Gavaud et al., 1976; Brabant and Gavaud, 1985). In the Benue trough, a ground water underlies the alluvial deposits, the sandstones and the weathered basement (Brabant and Gavaud, 1985; Njitchoua et al., 1995). At the beginning of the dry season, this water is less than 4 m deep (Brabant and Gavaud, 1985). Its lateral extension is variable from one stream to another and along the same stream. It is less than 3 km wide on either sides of streams and becomes shallower with increasing distance away from the stream bed.

METHODOLOGY

Five profiles (P_1, P_2, P_3, P_4 and P_5) were dug on vertisols along the Benue floodplain and described; horizon per horizon and profile per profile. These five profiles, representative of the studied site, were selected on different land use systems which include sorghum cultivation (Garoua, Bounguel and Poumpoumre), Badoudi (grassed savannah, previously under sorghum) and Karewa (rice cultivation)
The soil samples were collected for each horizon, packed in air-tied plastic bags and taken to the laboratory for further description and analysis. The soil analyses where done in the "Laboratoire d'Analyses des Sols et de Chimie d'Environnement" (for the physicochemical analyses) and the Soil Physics Laboratory (for the moisture contents), both in the Faculty of Agronomy and Agricultural Sciences (University of Dschang). So, for the physico-chemical properties, electrical conductivity was measured by conductimetry in a supernatant suspension of 1:5 soil: water ratio (FAO, 2006). Cation exchange capacity was determined by sodium saturation method (Rhoades, 1982). For the physical properties, bulk density (Db) was determined in reference to Archimedes' principle and particle density (Dp) was measured by pycnometer method (FAO, 2006). The organic carbon (OC) was measured by Walkley-Black procedure (Nelson and Sommers 1982).'

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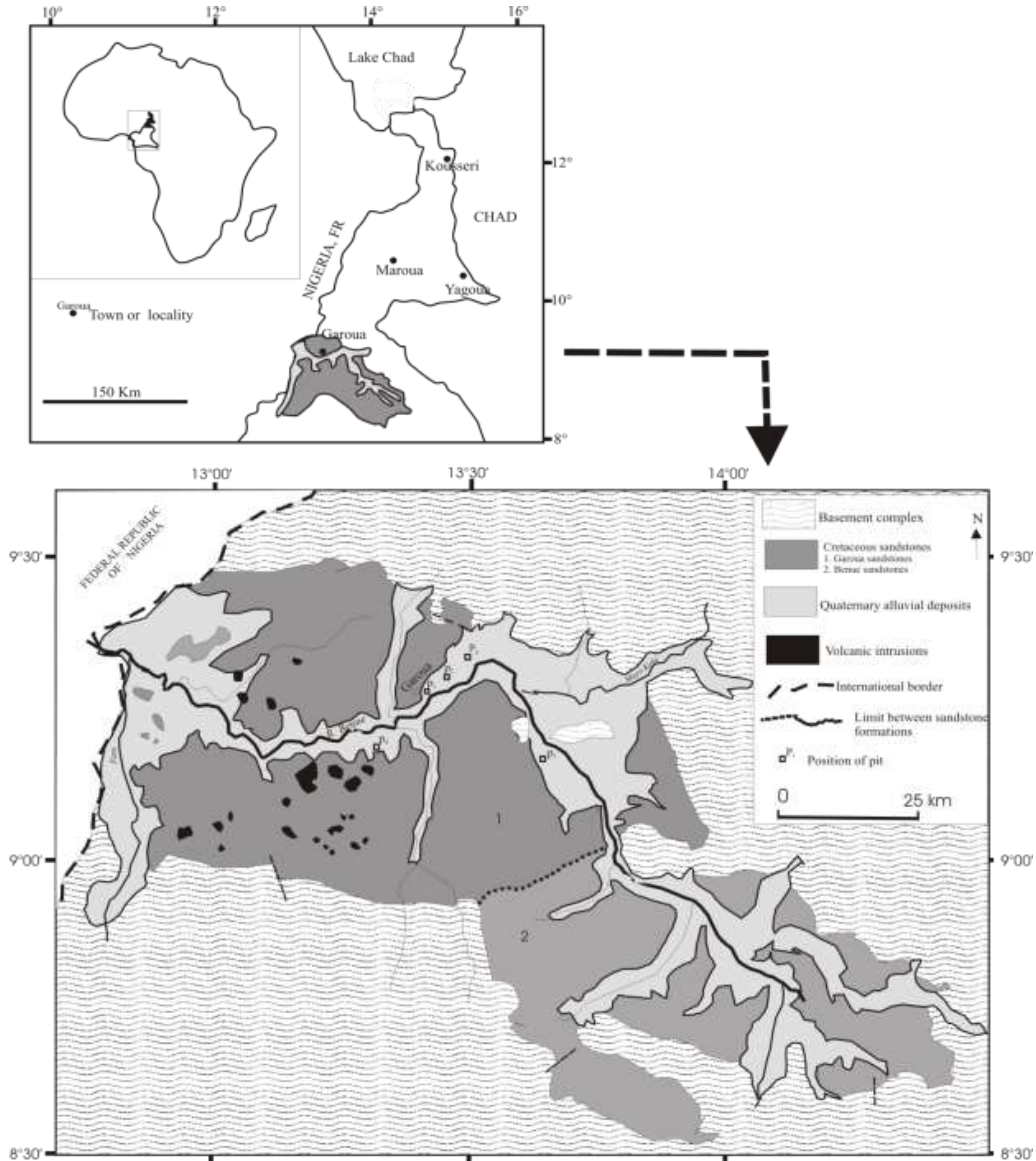

Figure 1. Benue trough in North Cameroon: geology and position of sampled pits in the alluvial floodplain (modified from Ngounouno, 1997).

Porosity (P) and void ratio (e) were deduced from the particle (Dp) and bulk densities (Db):

$$P = \left(\frac{Dp - Db}{Dp} \right) \times 100 \quad \text{(Duchaufour, 1997)} \qquad (1)$$

$$e = \left(\frac{Dp}{Db} \right) - 1 \quad \text{(Oicha et al., 2010)} \qquad (2)$$

The particle size distribution was measured by Robinson's pipette method (FAO, 2006), organic carbon by Walkley-Black method

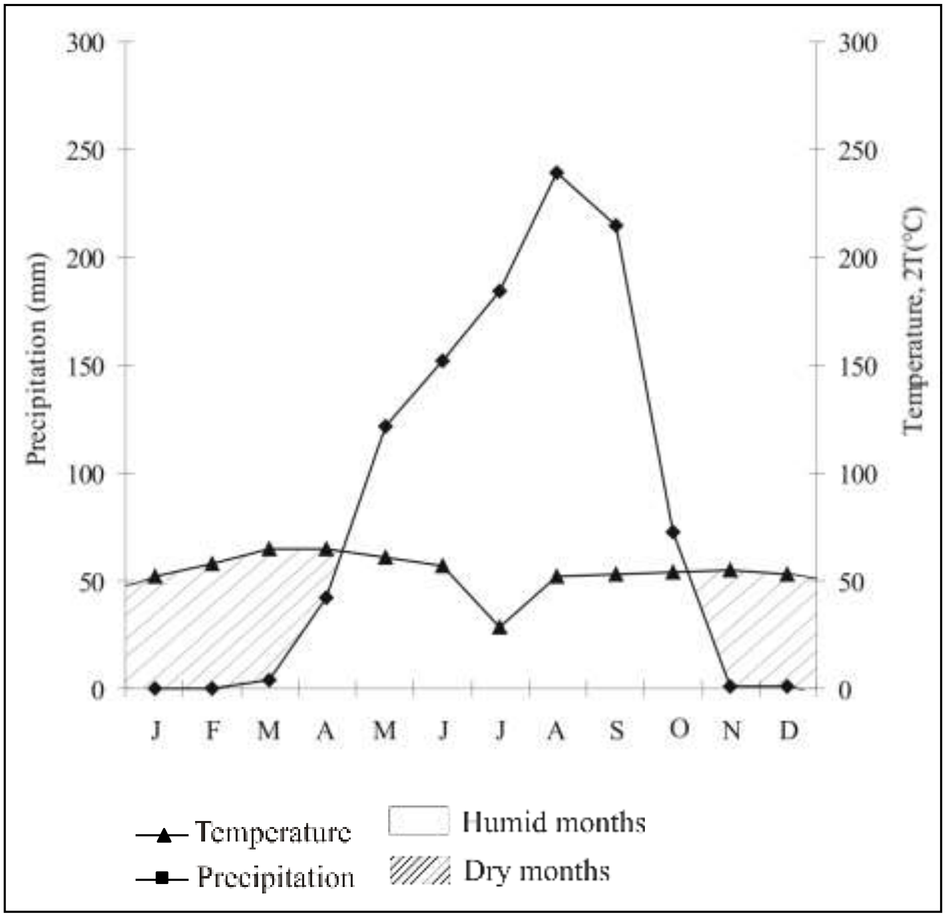

Figure 2. Bagnouls and Gaussen's rainfall-temperature curves for the study region (data from Garoua Meteorological Station from 1970 to 2000).

(Nelson and Sommers, 1982). The air-filled porosity (air capacity) was calculated as the difference between total porosity and field capacity (Duchaufour, 1997). The coefficient of linear extensivity (COLE) was calculated as the difference in bulk density at field capacity (Dbfc) and bulk density at oven-dry (Dbod) stated as follows (Grossman et al., 1968):

$$COLE = \left(\frac{Dbod - Dbfc}{Db}\right)^{1/3} - 1. \quad (3)$$

The linear extensivity (LE) of each soil horizon was calculated as the product of its thickness (in cm), multiplied by its COLE (FAO, 2006). The LE of each soil profile was obtained as the sum of products for all soil horizons (FAO, 2006). The permeability of individual soil horizons was estimated from permeability-related soil properties and matching them with standard charts (Van Gool et al., 2005).

Concerning the soil moisture characteristics, hygroscopic water content was determined by noting the weight-loss of an air-dried sample, after subjecting it to an oven temperature of 105°C for 24 h (FAO, 2006). The field capacity was measured by centrifugation at 1000 *g* (1 bar) for 30 minusing a crushed soil sample previously water-saturated (Jabiol, 2001). The permanent wilting point (PWP) was measured using a pressure membrane apparatus (Duchaufour, 1997). The capillary water (CW) was calculated as the difference between the hygroscopic water and the field capacity water content (Vilain, 1997). The unavailable water content (UW) was obtained as the difference between the capillary water and permanent wilting point water content (Baize and Jabiol, 1995). The available water reserve (AWR), water-holding capacity (WHC), available water capacity (AWC) and the readily available water capacity (RAW) were calculated as follows:

$AWR = FC - PWP$ (Baize and Jabiol, 1995; Lozet and Mathieu, 1986) (4)

$AWC = \left(\frac{Db \times E \times (FC - PWP)}{100}\right)$ (Duchaufour, 1997) (5)

$RAW = MAD \times AWC$ (Lozet and Mathieu, 1986; Bruand and Duval, 1996) (6)

$WHC = 2 \times AWC$ (GEPPA, 1981) (7)

Where, AWR is the available water reserve (%); AWC is the available water capacity (mm/m); FC is the moisture content at field capacity (%); PWP is the moisture content at permanent wilting point (%); RAW is the readily available water capacity (mm/m); MAD is the management allowed deficiency (about 2/3 for the studied soils); WHC is the water- holding capacity (mm/m); Db is the bulk density (g/cm^3); E is the thickness of horizon (dm).

Before calculating the wetting depth (D) of water in each soil layer, the volumetric water content was previously deduced as follows:

$$Vw = FC.\frac{Db}{Dw} \quad (8)$$

Where, V_w is the volumetric water content (at field capacity), FC is the gravimetric water content (at field capacity), Db is the soil bulk density, and Dw is the density of water (1 g cm^{-3}). The wetting depth was then given as:

$$D = Vw \ \text{x} \ E \quad (9)$$

Where, D is the wetting depth of a soil layer (in cm), E is the depth of the horizon (in cm).

The PWP-to-clay ratio was used to indicate the significance of the particle-size distribution. The CEC-to-clay ratio enabled to estimate clay mineralogy and clay dispersion of each layer (FAO, 2006).

Statistical analysis

The data were subjected to statistical analysis using Microsoft Excel 2010 and SPSS 16.0. Analysis of correlation coefficients and coefficient of variations were used to identify soil variables that correlate significantly and or not, respectively. The principal component analysis (PCA), by varimax rotation, enabled to do away with the problem of autocorrelation and to reduce the contributing soil factors to orthogonal principal components.

RESULTS

Morphology

The studied profiles showed the following morphological characteristics: Profile P_1 was dug at the east of Garoua Brasseries on latitude 9°15´N, longitude 13°24´E and an elevation of 175 m. Slope gradient was 0.6%, current land use was for counter-season sorghum cultivation. This pit was 2.5 m thick above the water table and presented four main horizons including, from surface to bottom (Figure 1); (a) the A1 (0-30 cm), grey (10YR5/1) horizon, which presented yellowish red patches (10 %) and voids (20 %). The presence of numerous deep (30-35 cm) and wide-opened (1-5 cm) cracks separating polygonal blocks (20 to 40 cm diameter) define a strongly expressed polyhedral macrostructure. Few dark brown dry leaves and roots were present, completely mixed up with the clayey matrix. Transition with the underlying horizon was gradual, marked by the disappearance of cracks, appearance of slickensides and light darkening of colour; (b) the B1 (30-100 cm), dark grey (10YR4/1) horizon was characterised by numerous smooth and shiny surfaces called slickensides that separated different blocks; their thicknesses varied between 5 and 10 cm. Transition to the next horizon was very gradual, marked by the disappearance of slickensides; (c) the B21 (100-150 cm), dark grey (10YR4/1) horizon, with clayey texture and massive and compact structure; reddish yellow (7.5YR6/8) patches (5%) were still present. Transition with the underlying horizon was gradual, marked by an intensification of dark colour; (d) the B3g (150-250 cm), very dark grey (10YR3/1) horizon, clayey and compact, with a massive blocky structure, 5% reddish yellow (7.5YR6/8) patches.

Profile P_2 (2.1 m above the water table) was implanted at Poumpoumré (latitude 9°20´N, longitude 13°28´E, altitude of 180 m) on a flat plain surface (0.3% slope). It showed three horizons above the water table which were morphologically very similar to those of profile P1. The land use was for sorghum cultivation without irrigation.

Profile P_3 (2.3 m above water table) was dug at Bounguel (latitude 9°24˝ N, longitude 13°31´ E and altitude 178 m). Slope gradient was about 1%; land use was for sorghum cultivation. This pit was morphologically very similar to the previous one.

Profiles P_4 at Badoudi (latitude 10°13´36˝ N, longitude 13°34´28˝ E and altitude 173.6 m) was implanted on a four-year old fallow with grassed savannah, previously under sorghum. This profile was 2.15 m above the water table and presented four horizons.

Pit P_5 (2.0 m above water table) was dug on a vertisol plot at Karewa (latitude 09°11´34˝ N, longitude 13°20´59˝ E and altitude 191 m) 40 km at SE Garoua. This pit shows four horizons which are morphologically similar to the previously described ones. The land is used for rice cultivation.

All the vertisol materials showed a clay texture, a massive blocky structure and became very hard when dry.

Physico-chemical characteristics

The bulk density at field capacity was low, ranging globally from 1.15 to 1.30 g cm^{-3} (Table 1). There was a slight decrease with depth in all profiles except P5 where values are maintained at 1.29-1.30 g cm^{-3} although increasing slightly with depth. At oven-dry state, the bulk density values were comparatively very high (1.80-2.20 g cm^{-3}) increasing slightly with depth. The particle density was constant at 2.60 g cm^{-3} except for the surface horizons of P_1, P_2 and P_3 which showed slightly lower values (Table 1). The coefficients of linear extensivity values were very high, ranging from 0.11 to 0.27 cm/cm (Table 1). They increased with depth for all the profiles, except for P_1 where values decreased slightly. The void ratio (e) values at field capacity were very high (1.05 to 1.26). These values increased with depth for all profiles except P_5 where they were almost constant increasing only slightly from 1.02 to 1.00 (Table 1). The void ratio values after oven-drying were relatively very low (0.18 to 0.44), increasing with depth for all the profiles (Table 1).

The total porosity at field capacity ranged between 48.80 % and 55.80 % (Table 1). All the vertisols profiles showed lower porosity values (at FC) at the surface than at depth. At oven-dry state, the porosity values dropped to 15.40-30.76 %. Contrary to porosity values at FC, the porosity at oven-dry state increased with depth of all the profiles (Table 1).

The particle size distribution analysis revealed that clay was the most abundant fraction in all the soil profiles, increasing gradually with depth. The clay contents were higher and comparable in P_1 and P_2 ranging from 62.50 to 75.00 % (Table 1). In all the studied profiles, the highest silt contents appeared at the surface, and then gradually decreased with depth; sand presented a reverse trend to those of clay and silt. The highest sand contents were observed in Bounguel (Table 1). Silt showed an inverse relationship with clay, marked by a silt-to-clay ratio which decreases with depth in all profiles (Table 1). The representation of the various particle size fractions on a textural triangle in reference to USDA (Robitale and Tremblay, 1997) revealed a clayey to heavy clayey texture for all the vertisol horizons (Figure 3).

The permeability rates of the studied vertisols varied from <0.06 to 0.20 cm/hour (Table 1). These intervals correspond to very slow to slow permeability soil classes according to Van Gool et al. (2005). The organic carbon was low to moderate for all the soils, but higher at the surface than in the sub-surface horizons (Table 1). The highest values were observed in Garoua (4.50%) and the lowest ones in Bounguel (Table 1). The bottom horizons revealed the lowest organic carbon contents. The CEC at pH7 was high and ranged from 26 to 46 me/100 g (Table 1). The values globally increased with depth in all the studied sites. The CEC-to-clay ratio ranged from 0.53 to 0.71 for all the profiles (Table 1). The lowest value appeared for A1 of P_3 and the highest one by B21 of P_2.

The electrical conductivity of the different vertisol profiles was very low, ranging from 0.46 to 1.84 mmhos per cm. Those values increased slightly with depth for all the profiles (Table 1). The highest values were recorded for P_4 while the lowest ones were shown by P_5. Nevertheless, electrical conductivity values did not vary much from one profile to the other.

Moisture characteristics

The hygroscopic water content ranged from 6.70 to 13.42% (Table 2). The values were quite comparable for all sites and showed a slight increase with depth for all the profiles (Table 2). The water-holding capacity increased with depth for all the profiles, except for P_1 which showed a zigzag trend. The values were globally moderate to very high for all horizons, ranging between 268.10 to 855.80 mm/m. The general observed trend was the appearance of lower values at the surface and higher ones at depth (Table 2). The readily available water ranged between 89.40 and 271.33 mm/m (Table 2). The available water capacity ranged between 134.04 and 407.00 mm/m (Table 2). Both parameters follow the same trend as the water-holding capacity (Table 2).

Globally, the sums of the water-holding capacity (1318.70 to 1901.50 mm), available water (659.40 to 950.75 mm) and readily available water (439.60 to 633.83 mm) are very high for all the profiles (Figure 4; Table 3) placing those vertisols under class 7 in reference to GEPPA (Table 4).

The moisture contents at field capacity (FC) generally ranged between 36.52 and 55.70%. The values of P_3 and P_4 were clearly lower than those of the other profiles (Table 2).

The water content at permanent wilting point (PWP) ranged between 22.70 and 35.17% (Table 2). For all the profiles, water content at PWP varied irregularly with depth. The lowest values appeared in the P_3 and P_4, just as for the field capacity values.

The soil-water characteristic curve (Figure 5) revealed an almost uniform mean water contents for all profiles, apart from P1 with slightly higher hygroscopic water content. Under moist and wet conditions, the different profiles presented different behaviours. But again, at saturation point (zero porosity), all the vertisol profiles behaved almost similarly; their maximum water capacity, that is when all pores are filled (pF=0), ranged between 52 and 60%.

The capillary water content was high for all the horizons and globally ranged from 27.26 to 46.00% (Table 2). The values for P_1 and P_2 were slightly higher than those of the rest of the profiles.

The air-filled porosity varied between 1.02 and 15.58 % (Table 2). The highest values were observed in P_3 and P_4 with maximum values of 15.48 and 11.38 %, respectively. The rest of the profiles did not attain 6.00%.

The PWP-to-clay ratio ranged between 0.46 and 0.59 (Table 2). All ratio values were of the same order of magnitude and decreased slightly with profile depth in the studied sites.

Correlation and factor analysis of the soil characteristics

The Pearson correlation test showed that most of the vertisol physico-chemical characteristics were correlated with the soil moisture properties, either negatively or positively (Table 5). The Clay content correlated best with the moisture properties than any other physico-chemical characteristic. Bulk density at oven-dry state also correlated negatively well with the moisture characteristics while porosity at field capacity instead correlated positively with those properties. The air capacity showed

Table 1. Physico-chemical properties the Benue floodplain vertisols.

Soil properties Horizon (Depth)	Dbfc (g cm^{-3})	Dbod (g cm^{-3})	Dp (g cm^{3})	COLE (cm/cm)	LE	VRfc	VRod	Pfc (%)	Pod (%)	Particle size distribution (%)				Textural indices		Permeability		OC (%)	CEC7 (me/100 g)	CEC$_A$	CEC:clay ratio	ECse	SS (%)
										Sand	Silt	Clay	USDA class	TDI$_{ho}$	Silt:clay	Rate (cm/hr)	Class						
Profile P$_1$ (Garoua)																							
A$_1$(0-30 cm)	1.26	1.80	2.50	0.14	4.2	1.05	0.38	55.18	28.0	10.84	26.66	62.50	H	1	0.43	<0.06	VS	4.5	35.00	41.6	0.56	0.44	0.03
B$_1$ (30-100 cm)	1.17	2.10	2.60	0.22	15.4	1.22	0.24	55.0	19.00	6.3	25	70.00	H	1.12	0.36	<0.06	VS	0.48	37.00	51.5	0.53	0.50	0.03
B$_{21}$ (100-150 cm)	1.15	2.10	2.60	0.22	11	1.26	0.24	55.70	19.0	6.5	17	72.50	H	1.16	0.23	<0.06	VS	0.51	40.00	53.8	0.55	0.59	0.03
B$_{3g}$ (150-250 cm)	1.15	2.20	2.60	0.24	24	1.26	0.18	55.70	15.4	7.5	18.86	75.00	H	1.2	0.25	<0.06	VS	0.53	42.00	54.6	0.56	0.61	0.04
Profile P$_2$ (Poumpoumré)																							
A$_1$(0-40 cm)	1.18	1.90	2.50	0.27	10.8	1.11	0.32	52.80	24.0	10.7	22.5	68.00	H	1	0..33	<0.06	VS	2.82	39.00	49.06	0.57	0.46	0.03
B$_1$ (40-110 cm)	1.15	2.10	2.60	0.22	15.4	1.26	0.24	55.80	19.0	11.95	16.03	72.00	H	1.05	0.22	<0.06	VS	1.01	42.00	55.53	0.58	0.46	0.03
B$_{21}$ (110-210 cm)	1.15	2.10	2.60	0.22	22	1.26	0.24	55.80	19.0	6.4	20	75.00	H	1.1	0.27	<0.06	VS	0.71	46.00	59.44	0.61	0.73	0.05
Profile P$_3$ (Bounguel)																							
A$_1$(0-60cm)	1.28	1.80	2.50	0.12	7.2	0.95	0.38	48.80	28.0	24.96	31.68	45.00	C	1	0.70	0.06-0.20	S	1.76	26.00	49.96	0.57	0.52	0.03
B$_1$(60-150cm)	1.25	20	2.60	0.17	15.3	1.08	0.30	52.00	23.10	29.46	23.96	47.50	C	1.05	0.50	0.06-0.20	S	0.66	28.10	56.38	0.59	0.54	0.03
B$_{21}$(150-230 cm)	1.24	2.20	2.60	0.21	16.8	1.10	0.18	52.30	15.40	22.89	26.38	53.50	C	1.18	0.49	0.06-0.20	S	0.88	34.00	60.26	0.64	0.55	0.03
Profile P$_4$ (Badoudi)																							
A$_1$(0-30 cm)	1.3	1.80	2.60	0.11	3.3	1.00	0.44	50.00	30.76	20.01	34.3	46.60	C	1	0.74	0.06-0..20	S	2.17	33.10	61.72	0.71	1.12	0.07
B$_1$ (30- 110 cm)	1.26	2.00	2.60	0.17	5.1	1.06	0.33	51.50	23.10	16.83	29.4	54.20	C	1.16	0.54	0.06-0.20	S	1.67	35.40	59.15	0.65	1.60	0.10
B$_{21}$ (110-160 cm)	1.16	2.20	2.60	0.23	13.8	1.24	0.18	55.40	15.40	14.63	18.33	68.00	H	1.45	0.27	<0.06	VS	0.98	37.06	51.62	0.55	1.80	0.11
B$_{3g}$ (160-215 cm)	1.25	2.20	2.60	0.21	19.95	1.08	0.18	51.90	15.40	13.37	27.37	58.26	C	1.25	0.47	0.06-0.20	S	0.70	39.00	64.54	0.67	1.84	0.12
Profile P$_5$ (Karewa)																							
A$_1$(0-20 cm)	1.29	2.00	2.60	0.16	3.2	1.02	0.33	50.40	23.10	17.14	24.09	59.50	C	1	0.40	0.06-0.20	V	2.78	29.00	39.39	0.49	0.52	0.07
B$_1$(20-45 cm)	1.29	2.00	2.60	0.16	6.4	1.02	0.33	50.40	23.10	23.01	18.1	60.50	H	1.01	0.30	<0.06	VS	1.20	32.30	49.42	0.53	0.49	0.10
B$_{21}$ (45-140 cm)	1.3	2.20	2.60	0.19	11.4	1.00	0.18	50.00	15.40	13.53	21.7	66.75	H	1.12	0.33	<0.06	VS	0.87	35.92	51.21	0.54	1.08	0.12
B3g (140-200 cm)	1.3	2.20	2.60	0.19	11.4	1.00	0.18	52.52	15.40	12.7	16.11	72.50	H	1.21	0.22	<0.06	VS	0.91	38.54	50.65	0.53	1.44	0.12

Dbfc, bulk density at field capacity; Db_{OD}, bulk density at oven-dry state; Dp, particle density ; COLE, coefficient of linear extensivity (cm/cm); LE, linear extensivity; VRfc, void ratio at field capacity; VRpwp, void ratio at permanent wilting point; Pfc, Porosity at field capacity; P_{OD}, porosity at oven-dry state; C, clayey texture; H, Heavy clayey texture; TDI_{ho}, textural differentiation index of horizon ; OC, organic carbon; ECse, electrical conductivity in mmmhos/cm; in/h, cm per hour; S, slow; VS, very slow; CEC7, cation exchange capacity by ammonium acetate at pH7; CEC_A , apparent cation exchange capacity; SS, total water soluble salt.

a very strong negative correlation with permanent wilting point and field capacity (Table 5). Although a good number of the soil properties were correlated, the explanation and interpretations of some patterns were difficult due to existence of redundancies thus justifying the use of the principal component analysis.

The results of the principal component analysis enabled to observe a reduction of 17 original variables studied to only two components explaining 72.28% of the total variance expressed (Table 6). Component 1 alone explained 52.42% and had significant loadings on all the soil variables, except particle density, electrical conductivity, organic carbon, permanent wilting point and air capacity (Table 6). Component 2 had a significant loading of PWP explaining 19.86% of the total variance (Table 6). The graphical

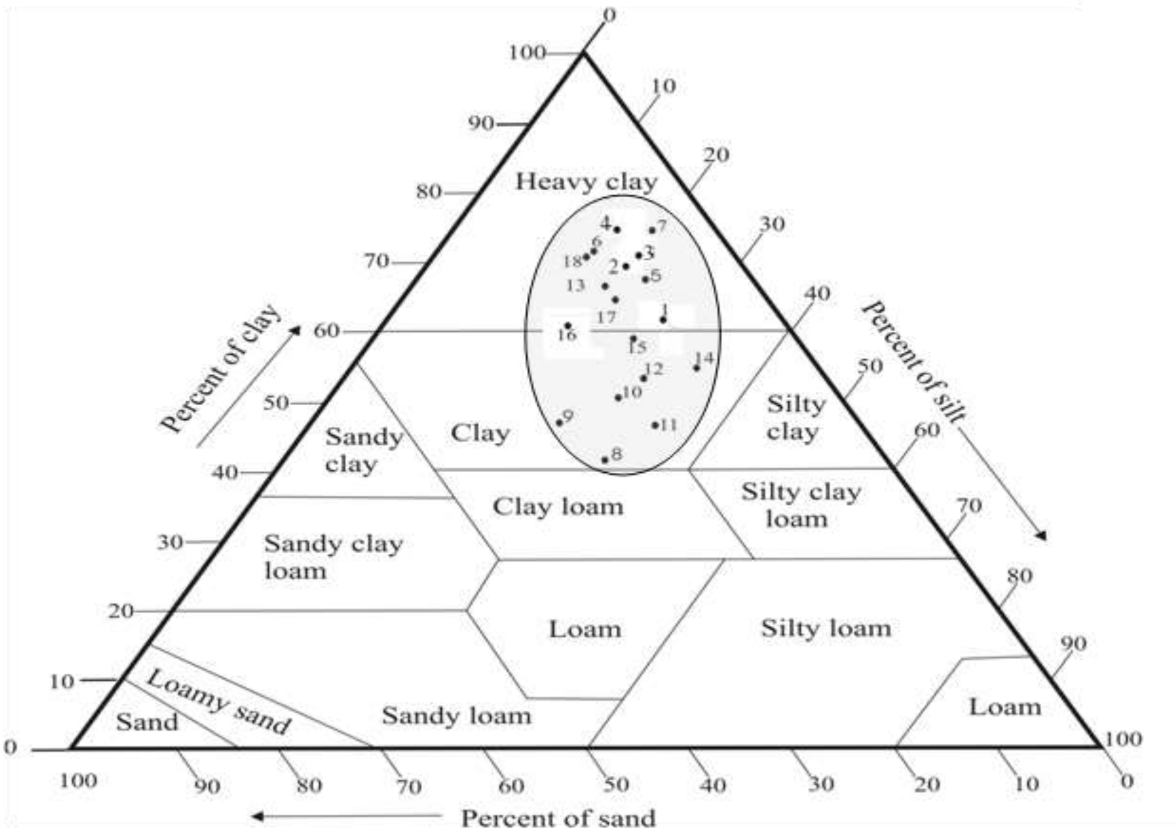

Figure 3. Textural classes of the vertisol samples in reference to the United States Department of Agriculture (Robitale and Tremblay, 1997). P1: **1**. A1 (0-30 cm); **2**. B1 (30-100 cm); **3**. B21 (100-150 cm); **4**. B3g (150-250 cm); P2: **5**. A1 (0-150 cm); **6**. B1 (40-110 cm); **7**. B21 (110-210 cm); P3: **8**. A1 (0-60 cm); **9**. B1 (60-150 cm); **10**. B21 (150-230 cm); P4: **11**. A1 (0-30 cm); **12**. B1 (30-110 cm); **13**. B21 (110-160 cm); **14**. B3g (160-215 cm); P5: **15**. A1 (0-20 cm); **16**. B1 (20-45 cm); **17**. B21 (45-140 cm); **18**. B3g (140-200 cm).

representation of the first two principal components on a factorial plane enables to note the dispersion of the soil variables based on their influence on one another (Figure 6).

DISCUSSION

Specificities of the studied vertisols

The Benue floodplain vertisols showed deep profiles, below the rooting zone which greatly increased the moisture retention capacity. In these vertisols, depth appears to be a very favourable factor enhancing the water-holding capacity and hence plant available water retention which is in agreement with the report of Laroche (1996) and Duchaufour (1997).

The heavy clayey texture was related to the flat topography, the highly contrasted climate and the alluvial parent material rich in fine clays derived from erosion, transportation and deposition of material from the upper parts of the landscape (Gavaud et al., 1976; Azinwi Tamfuh et al., 2012; Azinwi Tamfuh et al., 2016). The heavy clayey texture is favourable for a high water retention capacity (Laroche, 1996). According to Reichert et al. (2010), the vertisols with higher silt-to-clay ratios are probably less weathered, hence likely have higher smectite contents.

The bulk density was high at oven-dry state and low at field capacity and probably played a role in controlling pore space responsible for retaining water and air in the soil (Eswaran and Cook, 1988; Coulombe et al., 1996). Reports elsewhere reveal high bulk densities of about 1.30 to 1.80 g cm^{-3}, a times attaining 2.05 to 2.50 g cm^{-3} (Azinwi Tamfuh, 2012).

The very high COLE is an indication of the presence of high expansive smectite clays (Eswaran and Cook, 1988). The COLE denotes a fractional change in the clod dimension from a dry to a moist state (FAO, 2006). Hence, vertisols with relatively high smectite clays have the capacity to swell significantly when moist as well as to shrink and crack when dry (FAO, 2006; Gidigasu and Gawu, 2013; Azinwi Tamfuh et al., 2016; Diaz et al., 2016). This pedoturbation is vital in explaining some soil

Table 2. Moisture characteristics of the different vertisols profiles.

Soil properties horizon (Depth)	E (cm)	HW (%)	FC (%)	PWP (%)	AWR (%)	AWC (mm/m)	UW (%)	RAW (mm/m)	WHC (mm/m)	CW (%)	AC (%)	D (in/m)	PWP:clay ratio
Profile P_1 (Garoua)													
A_1(0-30 cm)	30	6.70	48.90	37.30	12.60	325.00	11.20	216.70	650.00	42.20	6.28	7.38	0.59
B_1 (30-100 cm)	70	8.10	49.72	32.22	17.50	367.50	9.40	245.00	735.00	41.62	5.28	6.98	0.46
B_{21} (100-150 cm)	50	9.70	55.70	33.60	22.10	378.00	12.40	252.00	756.00	46.00	3.90	7.69	0.46
B_{3g} (150-250 cm)	100	10.30	52.28	34.78	17.50	407.00	7.20	271.33	814.00	41.98	3.42	7.21	0.46
Profile P_2 (Poumpoumré)													
A_1(0-150 cm)	40	7.90	54.55	36.30	18.25	346.75	10.35	231.17	693.50	46.65	1.75	7.72	0.53
B_1 (40-110 cm)	70	8.80	52.52	34.42	18.10	380.00	9.91	253.33	760.00	43.72	3.28	7.25	0.48
B_{21} (110-210 cm)	100	9.30	53.62	35.17	18.45	387.50	9.15	258.33	775.00	44.32	2.18	7.40	0.47
Profile P_3 (Bounguel)													
A_1(0-60cm)	60	7.70	37.62	23.77	13.85	249.33	6.15	166.22	498.70	29.92	11.18	5.78	0.53
B_1(60-150cm)	90	7.90	36.52	22.76	13.80	275.00	5.86	183.33	550.00	28.62	15.48	5.48	0.48
B_{21}(150-230 cm)	80	10.80	38.06	25.86	12.20	327.88	15.06	218.58	655.80	27.26	14.24	5.66	0.48
Profile P_4 (Badoudi)													
A_1(0-30 cm)	30	11.10	38.64	25.34	13.30	343.00	2.20	228.67	686.00	27.54	11.36	6.03	0.54
B_1 (30- 110 cm)	30	12.30	41.09	27.74	13.35	307.00	1.05	204.67	614.00	28.79	10.41	6.21	0.51
B_{21} (110-160 cm)	60	11.80	52.01	32.56	19.45	427.92	7.65	285.25	855.80	40.21	3.39	7.24	0.48
B_{3g} (160-215 cm)	95	13.25	43.20	27.60	15.60	343.26	2.35	228.84	686.50	29.95	8.00	6.48	0.47
Profile P_5 (Karewa)													
A_1(0-20 cm)	20	11.10	49.16	32.36	16.80	134.04	5.70	89.36	268.10	38.06	0.80	7.61	0.54
B_1(20-45 cm)	40	10.30	45.80	29.60	16.20	324.50	5.90	216.33	649.00	35.50	4.60	7.09	0.49
B_{21} (45-140 cm)	60	11.80	48.98	31.86	17.14	377.00	5.30	251.33	754.00	37.18	1.02	7.64	0.48
B3g (140-200 cm)	60	13.42	50.00	34.42	15.58	399.00	2.16	266.00	798.00	36.58	2.52	7.80	0.47

E, thickness of horizon; UW, Unavailable water; HW, hygroscopic water (pF_7); FC, Moisture content at Field capacity (pF_3); PWP, Moisture content at permanent wilting point (pF4.2); AWR, Available water reserve; AWC, Available water capacity; RAW, Readily available water; WHC, water-holding capacity; AC, soil air capacity; CW, capillary water (pF_5); D, Water depth at field capacity (inch/metre).

physical features (wide-opened cracks in the dry season, surface ponding in the rainy season, slickensides) and pedogenic processes (Kovda et al., 2017).

The void ratios, high at field capacity and low at oven-dry state, are within the limits of 0.30 (moist) and 1.50 (dry) typical of expansive clays, but much higher than values reported for organic horizons (Jones and Holtz, 1973; Sridharan and

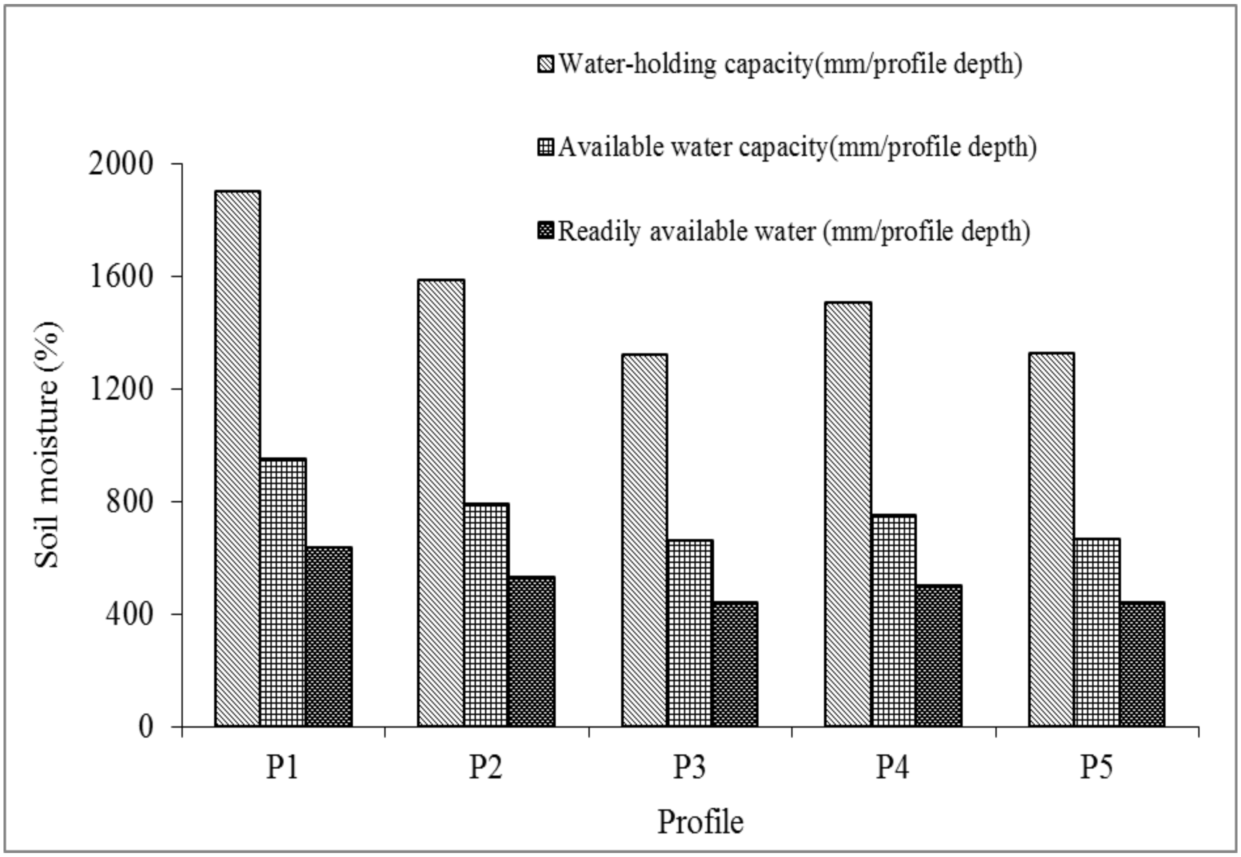

Figure 4. Global soil water retention capacities of the different vertisols profiles at different suction pressures.

Table 3. Global soil moisture properties, textural differentiation index and linear extensivity of the vertisol profiles.

Properties thickness (meters)	Moisture content (mm/profile depth)				TDI_p	LE_P
	WHC	TAWC	RAW	Class (GEPPA, 1981)		
P1 (2.5)	1901.50	950.75	633.83	Very high	1.21	54.60
P2(2.1)	1584.40	792.20	528.13	Very high	1.10	48.20
P3(2.3)	1318.70	659.40	439.60	Very high	1.24	39.30
P4(2.15)	1504.20	752.10	501.40	Very high	1.46	42.15
P5(2.0)	1324.98	662.50	441.67	Very high	1.22	32.50

WHC, Water-holding capacity; TAWC, total available water capacity; RAW, Readily available water; TDI_p, textural differentiation index of profile; LE_p, linear extensivity of profile.

Nagaraj, 2010). In the field, low void ratio values for vertisols are common in the dry season and higher ones in the rainy season in agreement with the shrink-swelling movements with moisture variation. The higher void ratios indicate possible reduction in permeability (Holtz and Kovacs, 1981). This phenomenon is related to the presence of smectite which has the capacity to absorb water molecules and free ions, and by so doing, limits pore space (Shainberg et al., 1988).

The air capacity was generally low for most horizons compared to the optimum root aeration value of 10.00% and the critical value of 5.00% required for optimum plant performance (Gidigasu and Bawu, 2013). Air capacity of the soils also tends to increase as the water content between pores and bulk density decreases (Reynolds et al., 2007). The low air contents of vertisols indicate a very low free water potential compared to the water-holding capacity of the soils. Thus, most of the water that

Table 4. Pearson linear correlation coefficients between vertisol characteristics.

	Dbfc	Dbod	Dp	COLE	VRfc	VRpwp	Pfc	Pod	Clay	OC	EC	FC	PWP	AWC	RAW	WHC	AC
Dbfc	1.00																
Dbod	-0.27	1.00															
PD	0.00	0.68**	1.00														
COLE	-0.73**	0.64**	0.16	1.00													
VRfc	-0.95**	0.46	0.30	0.73**	1.00												
VRpwp	0.35	-0.97**	-0.50*	-0.71**	-0.49*	1.00											
Pfc	-0.91**	0.54**	0.33	0.77**	0.97**	-0.57*	1.00										
Pod	0.32	-0.99**	-0.56*	-0.70**	-0.47*	0.99**	-0.55*	1.00									
Clay	-0.65**	0.55*	0.19	0.73**	0.68**	-0.60**	0.76**	-0.60**	1.00								
OC	0.23	-0.74**	-0.70**	-0.42	-0.44	0.71**	-0.47*	0.70**	-0.26	1.00							
EC	0.22	0.38	0.35	0.02	-0.11	-0.32	-0.03	-0.34	-0.04	-0.23	1.00						
FC	-0.64**	0.29	-0.04	0.63**	0.60**	-0.35	0.64**	-0.34	0.93**	0.04	-0.13	1.00					
PWP	-0.54*	0.19	-0.15	0.53*	0.47*	-0.26	0.53*	-0.26	0.88**	0.23	-0.15	0.95**	1.00				
AWC	-0.52*	0.50**	0.21	0.55*	0.56*	-0.56*	0.63**	-0.52*	0.62**	-0.45	0.31	0.45	0.41	1.00			
RAW	-0.52*	0.50**	0.21	0.55*	0.56*	-0.56*	0.63**	-0.52*	0.62**	-0.45	0.31	0.45	0.41	1.00**	1.00		
WHC	-0.52*	0.50**	0.21	0.55*	0.56*	-0.56*	0.63**	-0.52*	0.62**	-0.45	0.31	0.45	0.41	1.00**	1.00**	1.00	
AC	0.30	-0.25	0.03	-0.42	-0.29	0.27	-0.34	0.29	-0.82**	-0.13	0.04	-0.90**	-0.89**	-0.26	-0.26	-0.26	1.00

Dbfc, bulk density at field capacity; Db, bulk density at oven-dry state; Dp, particle density; COLE, coefficient of linear extensity; VRfc, void ratio at field capacity; VRpwp, void ratio at permanent wilting point; Pfc, Porosity at field capacity; Pod, porosity at oven-dry state; OC, organic carbon content; EC, electrical conductivity in mmmhos/cm; FC, field capacity; PWP, permanent wilting point; AWC, available water capacity; RAW, readily available water; WHC, water-holding capacity; AC, air capacity. **Correlation is significant at the 0.01 level (2-tailed); *Correlation is significant at the 0.05 level (2-tailed).

infiltrates into pores is retained in the profiles and causes vertic movements that in turn induce low permeability, surface ponding, poor aeration and floods in the rainy season (Duchaufour, 1997; Gidigasu and Gawu, 2013).

The organic carbon content of the vertisols, although very low, was almost evenly distributed throughout the profiles. This fact might be explained by the brassage and homogenisation of the whole profile by shrink-swell movements (Feller et al., 1996; Prusty et al., 2009; Temga et al., 2015). The low carbon contents of vertisols could be caused by prevailing dry conditions that hinder biomass production and instead amplify its mineralization rate (Aydinalp, 2010; Costa et al., 2015).

The hygroscopic water content increased with depth of all the vertisol profiles. Many authors have reported the capacity of a soil to retain humidity under laboratory conditions as a function of factors such as the texture, structure, organic matter content and the mineral composition (Astatke et al., 1995). Soils with heavy clayey texture and montmorillonitic mineralogy tend to hold their residual moisture stronger and will tend to show lower hygroscopic water contents than light textured non-smectitic soils (Cabidoche and Voltz, 1995; Laroche, 1996; Costa et al., 2015). This could justify the higher values for P_3 and P_4 despite their lower clay contents. Moreover, the CEC-to-clay ratio ranges from 0.53 to 0.71 suggesting mixed to dominant smectitic mineralogy according to FAO (2006). Previous studies (Nguetnkam et al., 2007; Azinwi Tamfuh et al., 2011) show that the studied vertisols are rich in smectite, associated to kaolinite and illite. The distribution of those clay minerals as well as organic matter with depth might be affecting the vertical distribution of hygroscopic water in

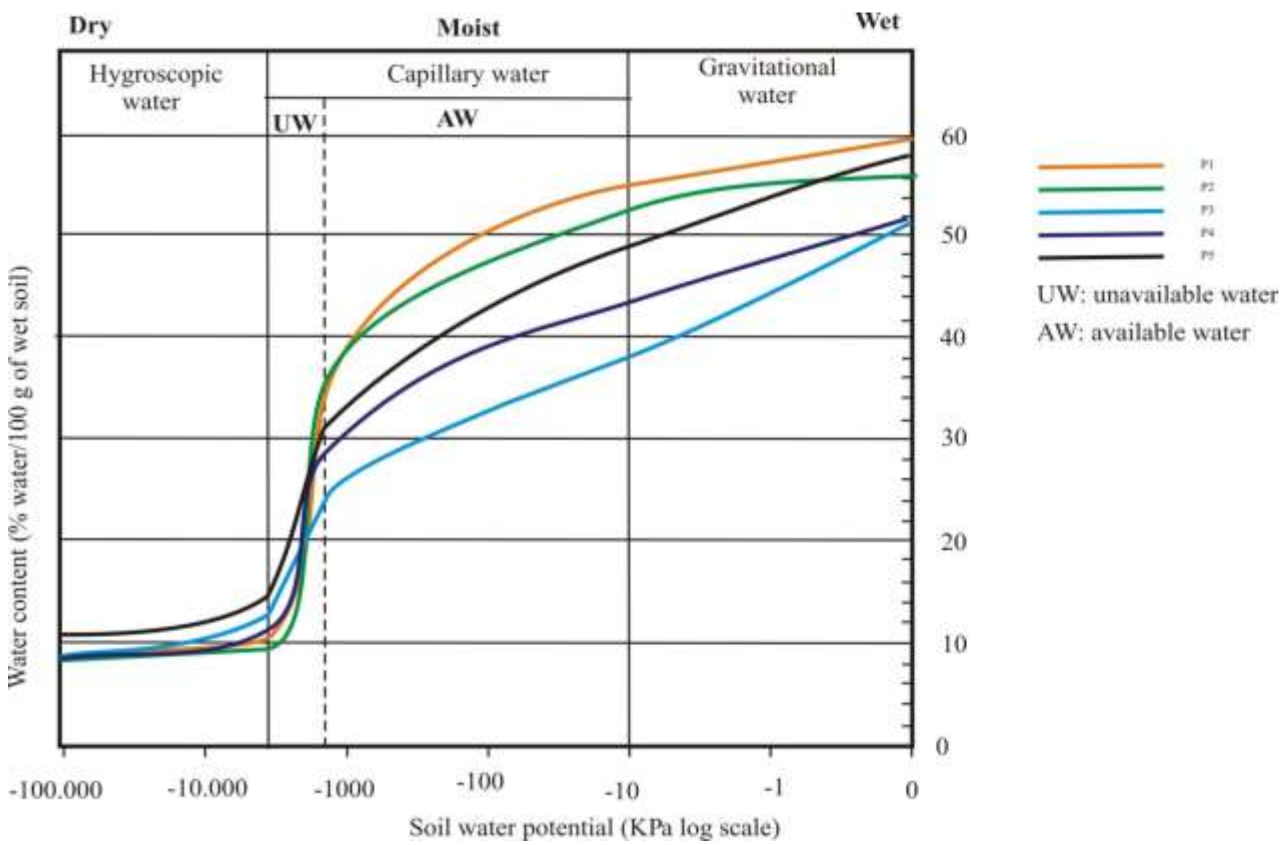

Figure 5. Soil-water characteristic (retention) curves of the different vertisol profiles (smooth curves fitted by cubic spline method).

Table 5. Distribution of soil water contents into classes (GEPPA, 1981).

Class parameter	1	2	3	4	5	6	7
Appreciation	Very low	Low	Low to moderate	moderate	Moderate to high	High	Very high
Water holding capacity (mm)	<60	60-100	100-150	150-300	300-450	450-600	>600
Available water (mm)	<30	30-50	50-75	75-150	150-225	225-300	>300
Readily available water (mm)	<20	20-35	35-50	50-100	100-150	150-200	>200

vertisols.

The capillary water of vertisols is high, held to soil particles by weak surface tension forces and is available to plants. During conditions of water stress, capillary water plays a vital role in maintaining crop performance. This is because soil desiccation is faster at the surface than at depth causing a higher water tension (pF) at the surface than at depth; this creates a water capillary current which moves from base to surface and, hence, water rises to the surface to be available to plants (Costa et al., 2015).

The moisture contents at field capacity and permanent wilting points were high for all the profiles, although lower for P_4 and P_5. These two parameters are mostly affected by the heavy clayey texture (Nordt and Driese, 2009). It seems that lower clay content tends to lower the field capacity and permanent wilting points like for P_3 and P_4. Similar results have been reported in Ethiopia by Page (1984) and Haider et al. (1988).

The water-holding capacity and plant available water capacity values were moderate to high for individual horizons, but global sums of values for each profile revealed very high water-holding and available water capacities according to GEPPA standards (GEPPA, 1981). The available water capacity of vertisols has been reported as 110.00 mm/m in Australia (Stace et al., 1968), 125.00 mm/m in the Sudan (Jewitt et al., 1979) and 230.00 mm/m in India (Gardner et al., 1988) for the uppermost metre depth of the soil profile. The moisture content in deeper layers decreases, apparently due to

Table 6. First two eigenvectors generated from the principal component analysis of the vertisol variables.

Variables	Principal components	
	PC 1	PC 2
	Clay /VIfc/VIod /COLE/AWC/RAW/ WHC / FC/Pfc/Pod/Dbfc/Dbod	PWP
Dbfc	-0.73*	0.35
Dbod	0.76*	0.52
Dp	0.38	0.65
COLE	0.84*	-0.08
VIfc	0.82*	-0.14
VIpwp	-0.80*	-0.43
Pfc	0.88*	-0.12
Pod	-0.79*	-0.45
Clay	0.89*	-0.36
OC	-0.55	-0.69
EC	0.17	0.54
FC	0.73*	-0.62
PWP	0.63	-0.71*
AWC	0.80*	0.10
RAW	0.80*	0.10
WHC	0.80*	0.10
AC	-0.53	0.58
Total loadings[A]	8.91	3.37
% variance explained	52.42	19.86
Cumulative % variance explained	52.42	72.28

Extraction method, Principal Component Analysis. Dbfc, bulk density at field capacity; Dbod, bulk density at oven-dry state; Dp, particle density; COLE, coefficient of linear extensity; VIfc, void ratio at field capacity; VIpwp, void index at permanent wilting point; Pfc, Porosity at field capacity; Pod, porosity at oven-dry state; OC, organic carbon content; EC, electrical conductivity in mmmhos/cm; FC, field capacity; PWP, permanent wilting point; AW, available water; RAW, readily available water; WHC, water-holding capacity; AC, air capacity; A, Sums of squared loadings; * Significant loadings exceeding ±0.70.

compression effect on matric potential (Rawls et al., 1982; Costa et al., 2015). These parameters are mostly affected by clay contents, profile depth, bulk density, and organic matter contents (Baize and Jabiol, 1995; Kamgang et al., 2011; Fasina et al., 2015). Duchaufour (1997) reported that particle size is inversely proportional to the force required to hold the water in the profile; this implies that the energy developed by a plant to extract this water may also be very high for those vertisols. The abundance of clayey fraction and a flat topography (<1% slope) further favour their water-holding potentials. Specifically, some factors like the hardness and presence of cracks when at dry state, high plasticity at humid state, very low infiltration rate and surface ponding could equally affect the water-holding capacity of vertisols.

The PWP-to-clay ratio ranged from 0.4 (well dispersed clays) to 0.6 (poorly dispersed clays). The surface horizons show higher ratios close to 0.6 for all studied profiles indicating that the organic matter might be playing a vital role in water retention (since it increases water content at 1500 kPa) and also helps to stabilise clays. However, the FAO (2006) reported that other soil-related factors might be causing deviation from the 0.4 value like the presence of low activity clays, and the occurrence of clay minerals within sand and silt fraction.

Repercussions of moisture properties on agricultural management strategies

Soil moisture has a major influence on a range of hydrological processes including flooding, erosion, solute transport and land–atmosphere interactions, as well as a range of geographic and pedogenic processes (Western et al., 2004; Patil et al., 2012; Fasina et al., 2015).

The high water retention of vertisols ensures safer and more productive cropping (Duchaufour, 1997; Gardner et al., 1988). It can assist crops to survive and even to grow during prolonged dry periods. Also, a high moisture-storage capacity permits crops to continue to grow for

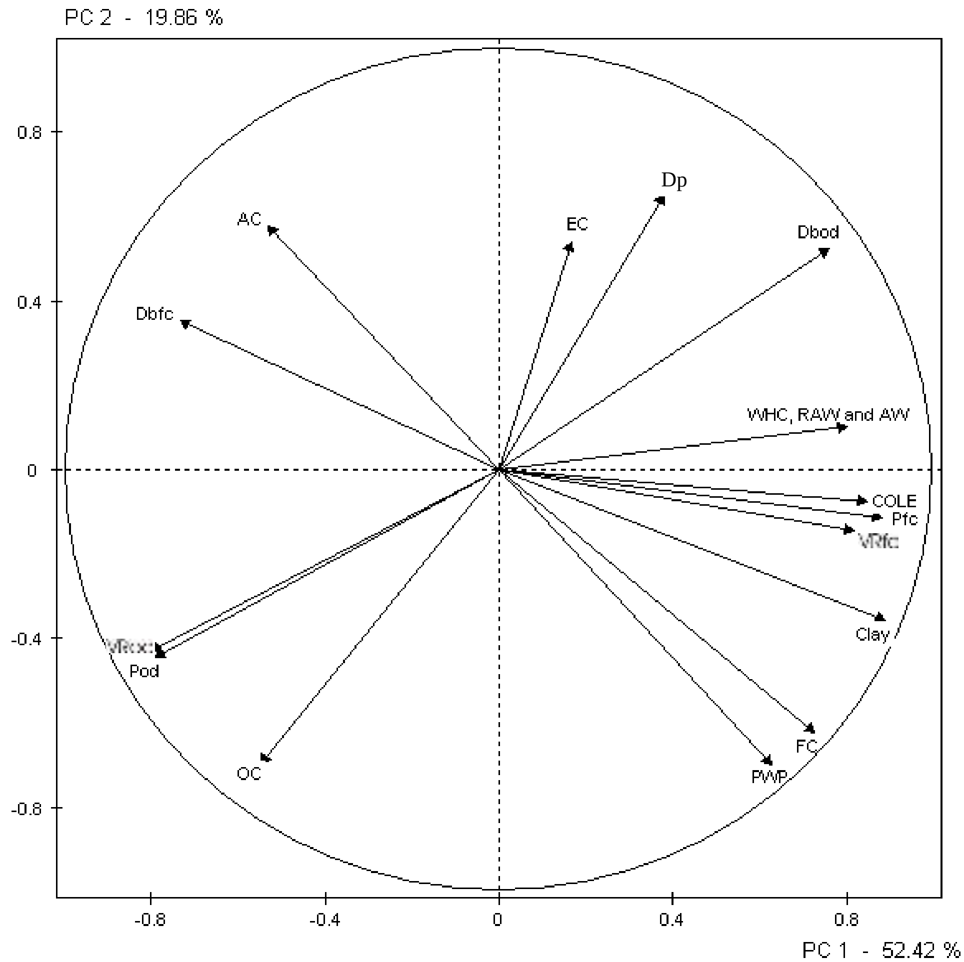

Figure 6. Graphical plots of the first two principal components on a factorial plane. Dbfc, bulk density at field capacity; Dbod, bulk density at oven-dry state; Dp, particle density; COLE, coefficient of linear extensity; VRfc, void ratio at field capacity; VRpwp, void ratio at permanent wilting point; Pfc, Porosity at field capacity; Pod, porosity at oven-dry state; OC, organic carbon content; EC, electrical conductivity; FC, field capacity; PWP, permanent wilting point; AW, available water capacity; RAW, readily available water; WHC, water-holding capacity; AC, air capacity.

several weeks after the cease of the rainy season ended,making it possible to cultivate two crops per year. However, despite their agricultural potentials, the vertisols presented numerous constraints to agricultural exploitation.

Their high plasticity causes them to stick to farm tools thus making tillage and weed control very difficult in the rainy season. The high bulk density is detrimental to plant growth on vertisols because few roots can penetrate a soil with bulk density above 1.60 g cm^{-3} (Cabidoche and Voltz, 1995; Likibi, 2010; Li et al., 2014). Tillage on vertisols is extremely difficult in the dry state, unless high energy machinery is used. Eswaran and Cook (1988) showed that optimum bulk density for plant growth is attained only when the vertisol structure offers the highest air content, since soil air is in continuous competition with soil water. Soil aeration and the possibility of normal plant development are indissociable and water storage capacity is an indicator of gaseous transfer (Duchaufour, 1997). This implies that a high air capacity enables an uninterrupted root and plant development. However, when all the pores become water-saturated during periods of flooding, air content reduces drastically hence compromising root respiration (Laroche, 1996; Pal et al., 2012; Li et al., 2014).

The surficial desiccation cracks of vertisols have several indirect effects on the crop performance (Kovda et al., 2017). Due to shrinkage and cracking, the water is not readily available to the roots, although the cracks might favour infiltration of water to deeper parts of the profile following the first rains (Eswaran and Cook, 1988; Pal et al., 2012).

In North Cameroon, attempted solutions involve developing management innovations to mitigate these constraints. Thus, farmers simply do not grow crops during the rainy season but rather on residual moisture of non-tilled soils at the end of the rains (Ambassa-Kiki et al., 1996). Also, most vertisols have simply been reserved for grazing, charcoal burning, forest reserves and small post-rainy season farming (Seiny Boukar et al., 1992; Ambassa-Kiki et al., 1996; Patil et al., 2012). Sowing into a dry seedbed ahead of the rains, growing crops on a raised bed to provide drainage and using furrows and waterways to conduct excess water from a watershed are all part of mitigation measures. Moisture conservation while inducing uniform soil wetting and maintaining suitable surface tilth requires deep tillage prior to the first rains. Mulching with plant residues, addition of non-vertisolic soils (alfisols, tank-silt, laterite, etc) could considerably help to drain excess water faster than the traditional flat seed beds (Astatke et al., 1995). This would enable early planting as opposed to traditional late planting. An established network of contoured ditches often help channel run-off and keep much of the surface water from causing erosion. Also, enclosed basins without drainage outlet, as earth-bunded rice plots, have been reported (Ambassa-Kiki et al., 1996). Similar types of land management systems have already been practised in Ethiopia for several decades (Desta, 1988). Some countries with vertisols (Argentina, Australia, Ghana, India, etc) have directed special attention to surface drainage through cambered beds, ridges, furrows, bunding, broadbanks, increasing fallow moisture accumulation by decreasing soil evaporation and storm runoffs, using rain when it falls by opportunity cropping, and matching crop strategies to plant available water and climate (Seiny Boukar et al., 1992; Coulombe et al., 1996; Corbeels, 2015). Moisture conservation during the dry season and removal of excess water during the wet season are crucial management practices clearly differentiating vertisols from other soil groups (Eswaran and Cook, 1988). The very high available water capacity of vertisol calculated from field capacity and permanent wilting point is often deceptive as not all the water is readily available to plants in the absence of water stress (Corbeels, 2015). At the end of the rainy season, the challenge is to reduce evapo-transpiration losses and conserve soil moisture so that a succeeding crop can be grown using stored moisture (Gardner et al., 1988).

Over all, vertisols form a considerable agricultural potential, but adapted management is a precondition for sustained production. Management practices for crop production ought to be primary directed at water control in combination with conservation of their fertility level.

Conclusions

The present work reveals that the topomorphic vertisols of the Benue floodplain in north Cameroon show deep profiles (2.00-2.50 m above the water table), a dark grey color, a heavy clayey texture, high coefficients of linear extensively (0.11-0.27 cm/cm), low organic matter and very low electrical conductivity. At field capacity, they show a very low bulk density, high porosity and a high void index. At oven-dry state, they exhibit very high bulk density (1.80-2.20 g cm^{-3}), very low porosity and very low void index. This high degree of reversibility with changing moisture content is related to vertic movements imposed by dominant montmorillonitic mineralogy. The moisture properties revealed very high water-holding capacity, very high plant available water, very high readily available water and very low air contents. Most of the vertisol characteristics are significantly correlated with the soil water properties, either negatively or positively; clay content best correlated with most of the soil properties. The PCA revealed a reduction of the 17 original variables to two principal components that explained more than 70.00% of the total variance expressed. These results suggest a strong relationship between the soil physico-chemical and moisture properties indicating that management practices for crop production on vertisols must be primarily directed at water control.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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