Global Advanced Research Journal of Agricultural Science (ISSN: 2315-5094) Vol. 7(7) pp. 197-216, July, 2018 Issue.
Available online http://garj.org/garjas/home

Full Length Research Paper

Geostatistical modeling and agricultural perspectives of vertisol properties in the Benue Floodplain of North Cameroon

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Accepted 03 June, 2018

Vertisols are dark coloured soils which are widespread in the tropical zone. They are renowned to be chemically very fertile soils. However, due to their difficult workability imposed by most of their physical chracteristics, they remain agriculturally underexploited. The aim of the present work was, firstly, to study the spatial distribution of the main physico-chemical properties of the Benue watershed vertisols by statistical and geostatistical methods, and secondly, to highlight the agricultural significance of the spatial structure of these properties. So, vertisol samples were collected in two grids demarcated in two plots, one under sorghum and the other one under natural savannah of gramineae. Fieldwork was followed by a battery of laboratory analyses. The data obtained was analysed statistically and geostatistically based on kriging. The results showed that most of the vertisol properties among the two studied plots did not vary significantly (P>.05) when viewed at the soil series scale. Furthermore, the principal component analysis (PCA) enabled to reduce fifteen initial studied variables to four principal components explaining more than 70% of the total variance. Geostatistically, most of the vertisol characteristics under sorghum were best-fitted by a "pure nugget effect" with cyclic periodicity in some cases, while those under savannah were mostly best-fitted by a linear model. Such "pure nugget effect" might imply that, although with a generally lower fertility level, the vertisols subjected to cultivation under sorghum remained very fertile with a better homogenisation of the fertility parameters, compared to fallow ones under natural savannah that instead showed "islands" of fertility portrayed by cyclic periodicity associated with vegetation tuffs. Contour maps obtained by kriging could have great potential for designing strategies for site-specific management.

Keywords: vertisols, spatial variability, agronomic value, Benue floodplain, North Cameroon.

INTRODUCTION

Vertisols constitute a soil class easily identifiable by their heavy clayey texture, their dark colour and their unique physical attributes as stress cracking in the dry season, surface ponding in the rainy season, slickensides, etc (FAO, 2006). Much work has already been published on vertisols, based on mainly their nature, inventory and spatial distribution (Nalovic, 1969; Hervieu, 1967; Blockuis et al., 1970; Gavaud et al., 1975; Brabant and Gavaud, 1985; Yerima, 1985; Mamo et al., 1988; Podwojewski, 1992; Raunet, 2003), geochemistry (Banenzoue et al., 2001; Özsoy and Aksoy, 2007; Azinwi Tamfuh et al., 2011), mineralogical composition (Buhmann and Schloeman, 1995; Nguetnkam et al., 2007), geotechnical properties (Jones and Holtz, 1973; Ekodeck, 1976; Ekodeck and Eno Belinga, 1977; Fredlund, 1996; Likiby, 2010), agronomic aspects (Humbel and Barbery, 1974; Ndaka et al., 2001; Mvondo Ze, 2002) and surface properties as bleaching earths (Kamga et al., 2001; Nguetnkam, 2004; Djoufac Woumfo et al., 2006; Nguetnkam et al., 2008). Most of these works reported that swelling and shrinking upon wetting and drying as well as some physico-chemical properties make the agricultural use of vertisols very difficult (Jutzi and Abebe, 1987; Dudal and Eswaran, 1988; Mondo Ze, 2002; Fassil Kebede and Yamoah, 2009). This explains why their agricultural potentials have not yet been fully exploited in many parts of the world, especially in the Sub-saharan zone despite their high chemical fertility in the natural state and their wide geographical distribution (Humbel and Barbery, 1974; Barber, 1979; Bull, 1988; Esu and Lombin, 1988; Mamo and Haque, 1988; Tabi et al., 2012). One of the most appropriate techniques for maximum exploitation of soil characteristics is the statistical and geostatistical treatment of data (Webster, 1977; Isaacks and Srivastava, 1989; Webster, 1985; Goovaerts, 1998; Hengl, 2007; Jahknwa and Ray, 2014). It is the most important way to gather knowledge to prepare soil maps through spatial interpolation of point-based measurements of soil properties. This technique already provided reliable and very exploitable results on a practical point of view such as in environmental modeling and precision agriculture (Isaacks and Srivastava, 1989; Webster and Oliver, 1992; Goovaerts, 1998; Goovaers and Glass, 2014; Jahknwa and Ray, 2014 ; Goovaerts et al., 2016; Goovaerts, 2017a, Goovaerts, 2017b). The technique, however, remains wanting in sub-saharan Africa, apart from works of few authors like Folorunso et al. (1986, 1988), Yerima et al. (1989, 2009) and Mainam et al. (2002). This can be due to some major constraints involved in the use of this type of mathematical technique like its long and fastidious nature, high number of georeferenced measurements and samples, and the great multiplicity of laboratory analyses. The main aim of the present work was, firstly, to study the spatial distribution of the main physico-chemical properties of vertisols by statistical and geostatistical methods, and secondly, to highlight the agricultural significance of the spatial structure of these vertisol properties.

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MATERIALS AND METHODS

Study site

The studied site is the Benue floodplain at the centre of the Benue watershed (Fig. 1). The total annual precipitation is 1033 mm and the mean yearly temperature is 28°C, defining a classical Sudanian climate, or tropical climate with two contrasted seasons: a humid season (May to October) and a dry season (November to April) (Etia, 1980). The Benue River, main collector, with its numerous seasonal tributaries form a dense and dendritic drainage network (Olivry, 1986). The relief landforms are very diverse and uneven on either sides of the Benue floodplain with Tchabal Mbabo being the highest point (2460 m). Between them lies a trough which is a rift formed within the Meso-to Neoproterozoic granitic-gneissic basement and is entirely filled with continental sediments (sandstones) of the Middle to Upper Cretaceous (Kock, 1959; Schwoerer, 1965; Maurin and Guiraud, 1990; Ngounouno, 1993; Ngounouno et al., 1997). The vegetation is the Sudanian savannah domain (Letouzey, 1980). The major soils are topomorphic vertisols associated to small soil groups like raw mineral soils, lightly evolved soils, hydromorphic soils, halomorphic soils, ferruginous soils and fersiallitic soils (Gavaud et al., 1975; Muller and Gavaud, 1976; Brabant and Gavaud, 1985).

The Benue floodplain is rich in alluvial deposits, about 35 m thick, mainly sands, gravels and clays (Koch, 1959; Schwoerer, 1965). On the Benue floodplain, a number of activities have converged, mainly agriculture, cattle-rearing, fishing, commerce, etc (Gavaud et al., 1975). There is an ethnic specialization of activities and a delimitation of a land surfaces reserved for each type of activity. The exploited land surface has strict time delimitation based on seasons, but very little spatial delimitation, and cattle often move freely into farmland at post-harvest although there is no formal association between farming and pastoral activities and this often leads 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 (early sorghum and cassava farm) and on vertisols (muskwari farm). Greater details about the studied site, other associated parameters such as site-specific vegetation types, land use patterns, physiography, meteorological processes and soil forming processes are described in Gavaud et al. (1975).

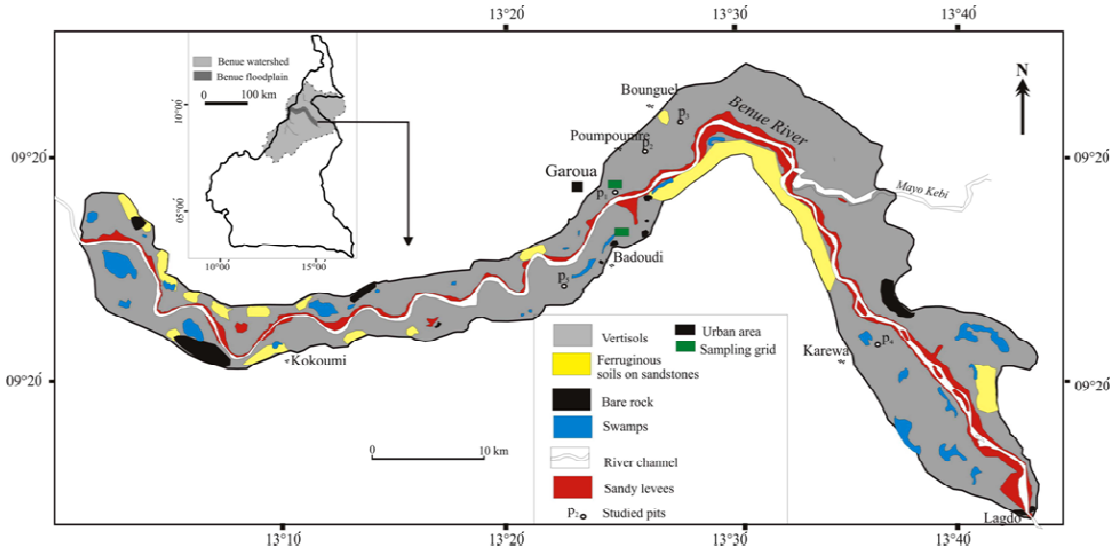

Figure 1. Geographical location of the Benue floodplain and position of sampling points.

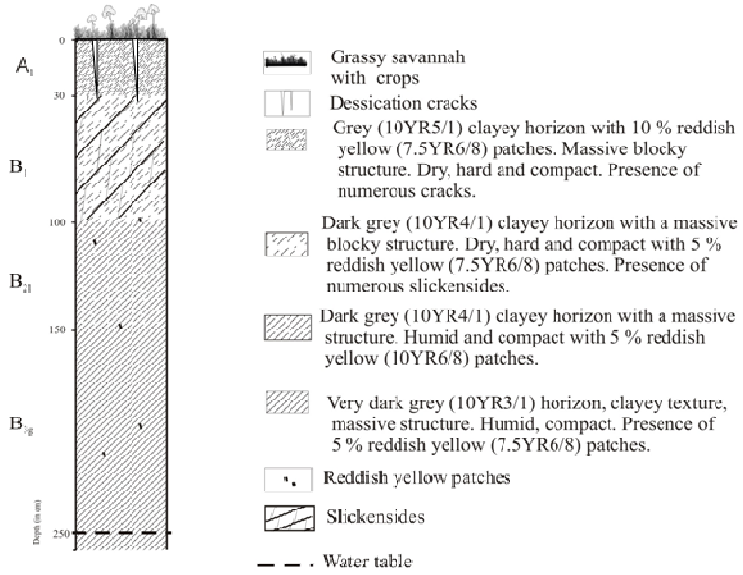

Figure 2. Morphological organization of the vertisol profile at Garoua (P1).

Out of five vertisol profiles in the Benue floodplain, two most representative were selected at Badoudi and Garoua for detailed description and only one is shown (Fig. 2). Thus, with a depth of about 2.00 to 2.50 m above the water table, these soils show four main horizons from bottom to top: a dark grey horizon with hydromorphic patches (B_{3g}), dark grey horizon (B_{21}), dark grey horizon with slickensides (B_1) and a surficial grey humiferous horizon (A_1) with desiccation cracks. Also, different horizons show a heavy clayey texture, very massive structure, high bulk density, very low porosity and a high compacity. Physico-chemically, the studied soils show a high cation exchange capacity (26-42.00 meq/100g), high sum of bases (74.30-94.23 meq/100g), high base saturation, low organic carbon and a very high C/N ratio (Table 1). The CEC-to-clay ratio ranges from 0.53 to 0.71 suggesting mixed to dominant smectitic mineralogy (FAO 2006). Geochemically, Si (50.35-59.23 % SiO_2) and Al (16.52-21.61 % Al_2O_3) are the dominant elements, marked by a Si/Al ratio of 2.27 to 2.94 (Table 2). Contents of Na, Mg, Ca and K range from 0.53 to 0.92 % Na_2O, 1.20 to 1.38 % MgO, 1.00 to 1.38 % CaO and 1.77 to 2.18 % K_2O.

Table 1. Physico-chemical characteristics of the topomorphic vertisols from the Benue watershed.

Property / Horizon (Depth)	Particle density	Bulk density	Porosity (%)	Clay (%)	pH-H_2O	pH-KCl	ΔpH	TOC(%)	OM(%)	T N(%)	TAP (ppm)	Exchangeable bases (me/100g) Ca	Mg	Na	K	S (Meq/100g)	CEC (Meq/100g)	BS (%)	CEC:clay ratio	C/N
Garoua profile (P1)																				
A_1(0-30 cm)	2.5	1.8	28.0	62.50	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	74.30	0.56	26.20
B_1 (30-100 cm)	2.6	2.1	19.0	70.00	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	78.40	0.53	18.00
B_{21} (100-150 cm)	2.6	2.1	19.0	72.50	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	92.02	0.55	24.00
B_{3g} (150-250 cm)	2.6	2.2	15.4	75.00	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	88.43	0.56	26.00
Badoudi profile (P5)																				
A_1(0-30 cm)	2.6	1.8	30.7	46.6	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	99.01	0.71	11.45
B_1 (30-110 cm)	2.6	2.0	23.1	54.2	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	98.33	0.65	11.00
B_{21} (110-160 cm)	2.6	2.2	15.4	68.00	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	95.00	0.55	07.20
B_{3g} (160-215 cm)	2.6	2.2	15.4	58.26	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	97.21	0.67	13.00

TOC: total organic carbon; OM: Organic matter content; TN: Total nitrogen; TAP: total available phosphorus;
S: sum of exchangeable bases; CEC: cation exchange capacity; BS: base saturation.

Table 2. Major element composition of the vertisols from the Benue floodplain (% oxide)

Oxide (%) / Horizon (depth)	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_3	LOI	Total	Si/Al
Garoua profile (P1)													
A_1(0-30 cm)	53.46	18.88	6.72	0.08	1.06	1.16	0.87	1.85	1.02	0.09	14.64	99.89	2.50
B_1(30-100 m)	53.29	18.79	6.60	0.06	1.34	1.00	0.88	2.18	1.01	0.16	14.61	99.89	2.40
B_{21}(100-150 cm)	53.40	19.07	6.89	0.09	1.38	1.38	0.92	2.11	1.11	0.19	14.03	100.17	2.40
B_{3g}(150-250 cm)	53.15	20.66	7.20	0.06	1.20	1.20	0.53	1.77	1.08	0.21	13.07	99.88	2.27
Badoudi profile (P5)													
A_1(0-30 cm)	59.23	20.67	6.03	0.03	1.54	0.31	0.56	1.87	0.68	0.2	09.73	100.51	2.86
B_1(30-60 cm)	59.22	19.2	7.55	0.04	1.59	0.86	0.64	1.67	1.31	0.01	8.88	99.99	3.08
B_{21} (60-120 cm)	58.04	20.19	7.96	0.01	1.03	1.01	1.23	1.02	1.25	0.13	8.76	100.56	2.87
B_{3g} (120-215 cm)	58.42	20.05	5.45	0.02	1.01	1.2	1.44	1.54	0.86	0.18	10.18	100.17	2.91

LOI: Lost on ignition.
Error margin: <1%: SiO_2, Al_2O_3 and Fe_2O_3; <2 % for MnO, K_2O and TiO_2; <10 % for MgO, CaO, Na_2O and P_2O_5.

METHODS

The vertisol samples were collected in mid-november (transitional month) to avoid rainy season floods and dry season overdesiccation. The sampling of the plough layer for soil quality assessment in relation to management practices was justified because the Benue floodplain has for many decades been used for the cultivation of counter-season sorghum with recent and progressive incorporation of other rain-fed and irrigated shallow-rooted crops like rice

and cotton (Gavaud et al. 1976). Based on land use, two sites were selected under natural savannah and sorghum crops in Badoudi and Garoua, respectively. Two sampling grids of 160 x 100 m were demarcated (Fig. 3). A total number of 54 composite surface (0-30 cm depth) samples were collected in each plot at a lag distance of 20.00 m in reference to Chevallier (1999) and Hengl (2007). Each sampling point was georeferenced using a Global Position System Receiver (Magellan mark). The samples were packed in air-tied 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) as well as at the International Institute for Tropical Agriculture (IITA) Nkolbissong, Yaoundé. Thus, the particle size distribution was measured by Robinson´s pipette method (FAO, 2006). The pH-H2O 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 (McLean, 1982). The organic carbon (TOC) was measured by Walkley-Black procedure (Nelson and Sommers, 1982). Total nitrogen (TN) was measured by the Kjeldahl method (Bremner and Mulvaney, 1982). Available phosphorus was determined by concentrated nitric acid reduction method (Olsen and Sommers, 1982). Exchangeable bases were dosed by ammonium acetate extraction method (Thomas, 1982) and cation exchange capacity (CEC) was measured by sodium saturation method (Rhoades, 1982). Statistical and geostatistical analyses.

Before developing and modeling the variograms, proximity to normal distribution was checked by Kolmogrov-Smirnov (K-S), kurtosis and skewness statistics (Steel and Torrie, 1980; Paz-Gonzalez et al., 2000). A log-normal transformation enabled to give more symmetrical distributions that satisfied assumptions of subsequent analyses and to make statistical estimates more efficient (Journel and Huijbregts, 1978). Statistical analysis was performed using the SPSS software program (SPSS Inc., Version 12.0). The data were analyzed by ANOVA and Tukey's test to detect significant differences ($P<0.05$) between means.

The geostatistical analysis was based on variogram analysis and ordinary kriging (Journel and Huijbregts, 1978; Isaaks and Srivastava, 1989; Zakậi Şen, 1990). Among the different methods of interpolation of soil properties, inverse distance weighting and ordinary kriging are the most important (Webster and Oliver, 1992). From a theoretical standpoint, ordinary kriging is the optimal interpolation method (Goovaerts, 1997). However, its correct application requires an accurate determination of the spatial structure via variogram construction and model-fitting, requiring at least 50 to 100 samples to obtain a reliable spatial structure (Webster, 1987).

The level of accuracy of kriging was checked by cross-validation (Davis, 1987). Among the three indices used, mean absolute error (MAE) and mean squared error (MSE) enabled to measure the accuracy of prediction, whereas goodness-of-prediction (G) permitted to check the effectiveness of prediction (Voltz and Webster, 1990).

MAE is a measure of a sum of residuals, that is, predicted value minus observed value (Voltz and Webster, 1990). The mathematical expression is:

$$\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N}[|z(x_i) - \hat{z}(x_i)|].$$

where $\hat{z}(x_i)$ is the predicted value at location *i*. Small MAE values indicate few errors. The MAE measure, however, does not reveal the magnitude of error that might occur at any point and hence, making the calculation of MSE necessary. Squaring the difference at any point gives an indication of the magnitude.

$$\mathrm{MSE} = \frac{1}{N}\sum_{i=1}^{N}[z(x_i) - \hat{z}(x_i)]^2.$$

Small MSE values indicate more accurate estimation, point-by-point.

The *G* value gives an indication of how effective a prediction might be relative to that which could have been derived from using the sample mean alone (Voltz and Webster, 1990).

$$G = \left(1 - \frac{\sum_{i=1}^{N}[z(x_i) - \hat{z}(x_i)]^2}{\sum_{i=1}^{N}[z(x_i) - \bar{z}]^2}\right) \times 100,$$

where $\bar{z}$ is the sample mean. A *G* value of 100 indicates perfect prediction, while a negative value indicates that the predictions are less reliable than using sample mean as the predictors.

RESULTS

Descriptive statistics

In Garoua, Kolmogorov-Smirnov (K-S) tests revealed normal probability distribution fit for all the parameters (Table 3). Also, apart from ECa (exchangeable calcium), sum of bases, CEC and base saturation (BS), the rest were positively skewed. The coefficients of kurtosis revealed relatively peaked distribution for sand, TOC, TAP, ECa and EK (exchangeable potassium), and a relatively flat one for the remaing parameters (Table 3). In Badoudi, K-S test of raw data revealed that apart from TOC, C/N, TAP, EK and Mg/K, all other vertisol properties were fitted in normal distribution (Table 3). Also, all the soil

Table 3. Shape parameters of the probability distribution (n=54)

Variable / parameter	Clay (%)	pH-H_2O	TOC (%)	TN (%)	C/N	TAP (ppm)	Exchangeable bases (me/100g) Ca	Mg	K	Na	S (me/100g)	CEC (me/100g)	BS (%)	Mg/K	Ca/Mg
Raw data for Garoua plot															
Skew	0.39	0.59	1.07	0.62	1.37	1.22	-0.23	0.26	1.18	0.25	-0.41	-0.30	-0.26	4.39	0.57
Kurtosis	-0.87	-0.50	1.47	-0.616	1.96	1.36	0.075	-0.5	1.1	-0.473	-0.32	-0.631	-0.909	23.38	0.30
K-S stat	0.14	0.16	0.11	0.16	0.19	0.16	0.09	0.06	0.15	0.09	0.08	0.09	0.13	0.245	0.12
Raw data for Badoudi plot															
Skew	87	0.77	1.04	0.003	185.48	477.94	11.49	4.42	0.52	0.27	17.49	31.17	110.06	4210.96	0.49
Kurtosis	9.33	0.88	1.02	0.06	13.62	21.86	3.39	2.10	0.72	0.52	4.18	5.58	10.49	64.89	-0.49
K-S stat	0.16	0.14	0.48	0.43	0.59	0.68	0.15	0.26	0.51	0.43	0.13	0.15	0.12	1.04151	0.11
Log-transformed data for Garoua plot															
Skew	0.16	0.36	-0.27	-0.08	-0.26	-0.60	-0.71	-0.28	-0.01	-1.003	0.62	-0.58	-0.66	0.856	-0.32
Kurtosis	-0.96	-0.80	-0.10	-0.70	0.48	0.55	0.77	-0.51	-0.10	1.24	-0.62	-0.35	-0.23	2.143	-0.01
K-S stat	0.12	0.15	0.11	0.09	0.09	0.08	0.11	0.06	0.08	0.15	0.16	0.12	0.13	0.101	0.08
Log-transformed data for Badoudi plot															
Skew	-1.58	-0.20	-0.60	0.37	-1.62	-0.57	-0.73	-0.52	-0.58	0.14	-0.27	-0.63	-1.98	2.078	-0.38
Kurtosis	4.55	1.002	0.91	-0.48	7.30	-0.42	-0.38	0.97	-0.14	-0.96	-0.10	-0.12	3.96	5.79	-0.01
K-S stat	0.14	0.13	0.12	0.09	0.11	0.12	0.14	0.07	0.09	0.09	0.11	0.13	0.24	0.161	-0.08

Remark:

skew (skewness): measure of asymmetry in data distribution (a positive skew indicates a longer tail to the right, a negative skew indicates a longer tail to the left and a perfectly symmetric distribution (normal distribution) has a skew equal to 0).

Kurtosis: measure of the sharpness of the data peak (conventionally, the value of this coefficient is compared to 0 which is the coefficient of kurtosis for a normal distribution or bell-shaped curve, meanwhile a value greater than 0 indicates a peaked distribution and a value less than 0 indicates a flat distribution).

K-S stat (Kolmogorov-Smirnov goodness of fit test statistics): largest difference between an expected cumulative probability distribution and an observed frequency distribution (Critical K-S stat, α of 0.05= 0.182). The expected distribution refers to the normal probability distribution with mean and variance equal to the mean and variance of the sample data. The observed frequency distribution is a stepped function that increases by 1/n with each step, where n is the number of values in the data set.

characteristics were positively skewed in Badoudi, except for Ca/Mg. In Garoua, clay, ECa and CEC were negatively skewed while the rest of the parameters were positively skewed (Table 3). The coefficients of kurtosis revealed a relatively peaked distribution for clay, pH.H_2O, TOC, TN, EK and ENa (exchangeable sodium), and a relatively flat one for TAP, ECa, EMg (exchangeable magnesium), S and CEC. Thus, after the log-normal transformation of the original data, all the vertisol characteristics were normal or closer to normal distribution (Table 3). The C/N ratio ranged from 0.79 to 76 in Badoudi, and 3.71 to 70.00 in Garoua (Table 4). The Ca/Mg ratio, an index of calcium-magnesium fertility, ranged from 0.79 to 4.70 in Badoudi, and 1.24 to 5.63 in Garoua. The Mg/K ratio globally varied from 1.96 to 20.79 in Badoudi, and 2.1 to 52.61 in Garoua (Table 4). These ranges do not only suggest normal EK and EMg levels in Garoua and Badoudi, but also risky zones of EK deficiency in Badoudi and those of EMg deficiency in Garoua (Dabin, 1964). Among the soil characteristics in Garoua, TAP displayed a high CV, meanwhile clay, pH, ECa, S, T and BS displayed a low CV, and the remaining ones showed a moderate CV. In Badoudi, soil nitrogen, C/N ratio, EK, ENa and Mg/Ca ratio showed a high CV, while clay, pH and BS displayed a low CV and the rest showed a moderate CV.

Statistically, apart from clay, ENa and Mg/K ratio, means of the remaining soil properties did not show any significant difference (P>0.05) for the two studied plots (Table 5).

The Pearson (linear) correlation between soil variables revealed that highest coefficients occured between clay and pH-H_2O, sum of bases and Mg or Ca, CEC and sum of bases, Mg and Ca/Mg ratio, Ca and Ca:Mg ratio, total organic C and total available P or total N (Table 6). Although a good number of the variables were correlated with each other, the explanation and interpretations of the patterns seemed difficult due to existence of redundancies. This justified the use of the principal component analysis (PCA). The PCA revealed that, in each of the two plots,

Table 4. Summary statistics of the different vertisol properties (n=54).

Property / Parameters	Clay (%)	pH-H_2O	TOC (%)	TN (%)	C/N	TAP (ppm)	Exchangeable bases (me/100g)				S (me/100g)	CEC (me/100g)	BS (%)	Ca/Mg	Mg/K
							Ca	Mg	K	Na					
Garoua plot															
Range	43-80	4.9-8.5	0.53-5.3	0.04-0.27	3.71-70	3-105	13.39-30	4.33-13	0.39-3.52	0.2-2.43	23.03-39.49	26-49	62.75-100	1.24-5.63	1.95-20.79
Mean (± SD)	58.6^a (±9.33)	6.19^a (± 0.88)	2.11^a (± 1.02)	0.134^a (± 0.06)	23.41^a (±13.62)	32.01^a (± 21.86)	22.26^a (± 3.39)	8.18^a (± 2.10)	1.41^a (± 0.72)	1.22^b (± 0.52)	32.70^a (± 4.18)	38.42^a (±5.58)	85.55^a (±10.49)	2.93^a (±0.94)	7.15^a (±3.85)
CV (%)	15.91	14.21	48.51	43.34	58.18	68.29	15.23	25.71	50.99	42.72	13.00	14.60	12.03	32.00	54.00
Badoudi plot															
Range	32-84	5.2-9.3	0.56-4.46	0.04-0.38	0.79-76	9.1-88.1	9.49-39.33	4.8-17.0	0.26-3.81	0.13-1.98	22.9-53.64	26.3-54.66	58.73-100.93	0.79-4.70	2.10-51.61
Mean (± SD)	63.28^b (±9.49)	7.17^b (±0.85)	1.94^a (±0.71)	0.13^a (±0.08)	19.10^a (±11.69)	41.93^a (±20.65)	26.45^a (±8.72)	11.03^a (±2.57)	1.44^a (±0.79)	0.63^a (±0.43)	39.24^a (±8.97)	41.32^a (±7.25)	92.99^a (±9.78)	2.50^a (±0.96)	11.75^b (±10.31)
CV (%)	14.99	11.85	36.55	61.06	61.18	49.24	32.98	23.30	55.28	67.97	22.84	17.54	10.51	39.00	87.75

SD: standard deviation; CV: Coefficient of variation; means in the same column followed by same letters are not significantly different at $p < 0.05$.

Table 5. Summary of correlation coefficients between vertisol characteristics

Variables	Clay	pH-H_2O	TOC	TN	C:N	TAP	Ca	Mg	K	Na	S	CEC	BS	Mg/K	Ca/Mg
Garoua plot															
Clay	1														
pH-H_2O	0.95**	1													
TOC	-0.10	-0.18	1												
TN	-0.04	-0.12	0.75**	1											
C:N	-0.25	-0.27*	0.16	0.27*	1										
TAP	0.17	0.14	0.68**	0.56**	-0.12	1									
Ca	0.27*	0.18	0.28*	0.23	-0.30*	0.30*	1								
Mg	0.44**	0.47**	-0.14	-0.25	-0.18	0.10	-0.20	1							
K	0.04	0.04	0.25	0.04	-0.09	.205	0.03	0.27*	1						
Na	-0.10	-0.16	-0.19	-0.13	-0.04	-0.37**	-0.08	0.15	-0.01	1					
S	0.54**	0.48**	0.05	0.01	-0.38**	0.24	0.71**	0.42**	0.18	0.19	1				
CEC	0.62**	0.60**	-0.03	0.04	-0.17	0.08	0.44**	0.26	-0.01	-0.01	0.57**	1			
BS	-0.13	-0.17	0.06	-0.05	-0.23	0.14	0.21	0.09	0.15	0.21	0.35*	-0.57**	1		
Mg /K	0.10	0.12	-0.24	-0.12	-0.03	-0.20	0.04	0.19	-0.71**	0.06	0.08	0.14	-0.07	1	
Ca /Mg	-0.22	-0.27*	0.25	0.29*	-0.02	0.09	0.57**	-0.88**	-0.11	-0.20	-0.02	-0.06	0.06	-0.24	1
Badoudi plot															
Clay	1														
pH-H_20	0.68**	1													
TOC	0.21	0.15	1												
TN	0.03	0.15	0.75**	1											
C:N	0.11	0.03	0.001	-0.22	1										
TAP	0.14	0.23	0.77**	0.74**	-0.17	1									
Ca	0.33*	0.56**	0.22	0.29*	-0.24	0.30*	1								
Mg	0.17	0.42**	0.26	0.17	-0.05	0.25	0.21	1							
K	0.04	-0.21	-0.10	-0.09	-0.10	-0.05	-0.35*	-.27*	1						
Na	-0.09	-0.30*	-0.09	-0.14	.051	-0.19	-0.58**	-0.13	0.38**	1					

Table 5. Continue

S	0.38**	0.64**	0.25	0.27*	-0.24	0.32*	0.95**	0.48**	-0.32*	-0.51**	1				
CEC	0.50**	0.76**	0.18	0.19	-0.04	0.22	0.85**	0.45**	-0.24	-0.47**	0.91**	1			
BS	0.04	0.09	0.18	0.12	-0.40**	0.31*	0.54**	0.15	-0.14	-0.17	0.53**	0.22	1		
Mg/K	-0.05	0.23	0.08	0.11	-0.01	0.05	0.36**	0.49**	-0.73**	-0.37**	0.42**	0.35**	0.06	1	
Ca/Mg	0.08	-0.09	-0.21	-0.70**	0.22	-0.34*	-0.03	0.03	0.03	0.01	0.01	0.04	0.07	-0.07	1

** Correlation is significant at the 0.01 level.
* Correlation is significant at the 0.05 level.

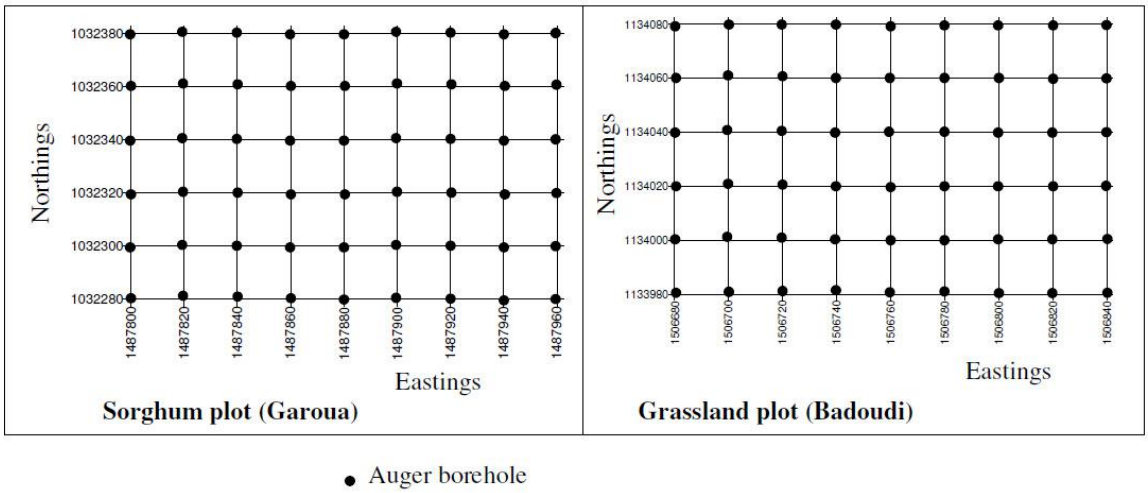

Figure 3. Sampling grids in the two studied plots (A: Sorghum plot in Garoua; B: Savannah plot in Badoudi).

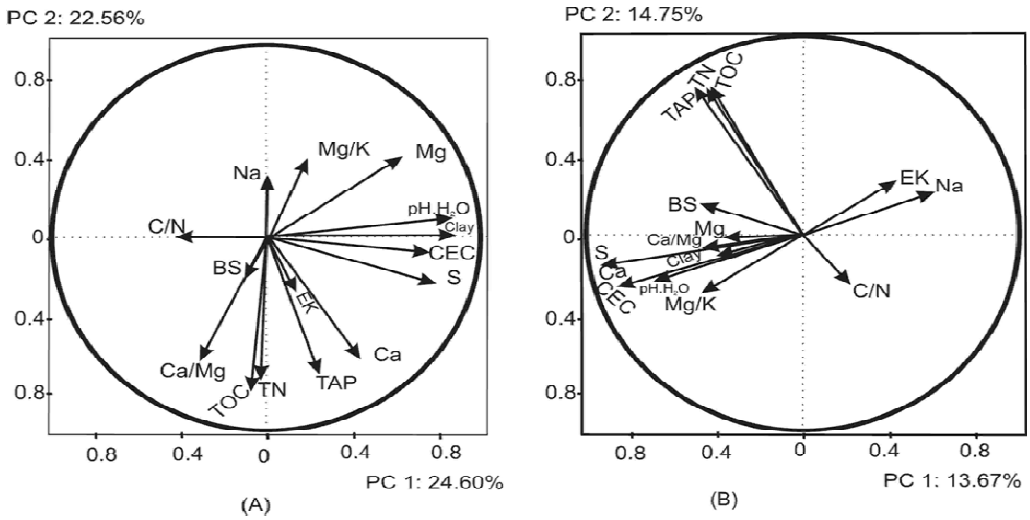

Figure 4. Plot of the correlation coefficients within a circle of unit radius in the plane of the first two principal axes. (A) Garoua (B) Badoudi.

four principal components explained more than 70 % of the total variance for fifteen variables studied (Table 7). The four principal components in Badoudi include S/Ca/CEC/pH (PC1), TOC/TAP/TN (PC2), exchangeable K (PC3) and base saturation (PC4). Those in Garoua are clay/pH/S/CEC (PC1), TOC/TN/TAP (PC2), Ca:Mg/soil Mg (PC3) and clay (PC4). The representation of the first two principal components in a correlation circle showed the separation of the initial soil characteristics on the factor axis based on their factor loading (Fig. 4). Thus, proximity

Table 6. First four eigenvectors from the PCA of the soil variables.

Variables	Principal components (PC)			
Garoua plot				
	1	2	3	4
	Clay/pH/S/CEC	TOC/TN/TAP	K	BS
Clay	0.88*	0.01	-0.10	-0.16
pH-H_2O	0.86*	0.10	-0.10	-0.20
TOC	-0.08	-0.79*	0.19	-0.27
TN	-0.03	-0.73*	-0.03	-0.33
C:N	-0.43	0.00	-0.09	-0.49
TAP	0.24	-0.71*	0.24	-0.25
Ca	0.43	-0.63	-0.31	0.49
Mg	0.63	0.41	0.52	-0.18
K	0.13	-0.28	0.74*	-0.08
Na	0.00	0.32	0.20	0.42
S	0.79*	-0.24	0.09	0.43
CEC	0.75*	-0.08	-0.39	-0.20
BS	-0.06	-0.14	0.50	0.72*
Mg/K	0.18	0.41	-0.50	0.08
Ca/Mg	-0.32	-0.64	-0.48	0.37
Total loading[A]	3.69	3.08	1.98	1.84
Variance explained (%)	24.60	20.56	13.18	12.28
Cumulative variance explained (%)	24.60	45.16	58.35	70.63
Badoudi plot				
	S/Ca/CEC/pH	TOC/TAP/TN	Ca/Mg/Mg	Clay
Clay	-0.44	-0.12	-0.02	-0.74*
pH-H_2O	-0.71*	-0.23	-0.17	-0.50
TOC	-0.43	0.75*	-0.25	-0.09
TN	-0.45	0.75*	-0.11	0.07
C:N	0.21	-0.25	-0.39	-0.31
TAP	-0.51	0.75*	-0.10	-0.02
Ca	-0.92*	-0.15	0.30	0.07
Mg	-0.45	-0.01	-0.72*	-0.02
K	0.42	0.28	0.40	-0.53
Na	0.60	0.22	-0.06	-0.25
S	-0.95*	-0.16	0.10	0.00
CEC	-0.87*	-0.27	0.00	-0.26
BS	-0.48	0.16	0.39	0.30
Mg/K	-0.47	-0.30	-0.52	0.50
Ca/Mg	-0.53	-0.08	0.76*	0.08
Total loading[A]	5.35	2.21	2.01	1.69
Variance explained (%)	35.67	14.75	13.42	11.15
Cumulative variance explained (%)	35.67	50.41	63.85	75.00

Extraction method: Principal Component Analysis; A: Sums of squared loadings.
* Significant loadings exceeding ±0.70.

Table 7. Omni directional variogram parameters of the vertisols variables from logtransformed data.

Variogram Variables	model	Nugget (N)	Sill (S)	Power (ω)	slope	Range (m)	N:S (%)	GSD	Periodicity (m)	Cross validation		
										MAE	MSE	G
Garoua plot												
Clay	Spherical	0.0010	0.0049	-	-	70	20	Strong	-	3.98	15.90	8.99
pH	Spherical	0.0006	0.0038	-	-	70	16	Strong	-	5.98	35.78	11.45
TOC	PNE	0.0450	0.0450	-	0	-	100	Weak	12.5	7.93	62.95	-1.56
TN	PNE	0.0370	0.0370	-	0	-	100	Weak	10	11.20	125.74	-9.65
TAP	PNE	0.1030	0.1030	-	0	-	100	Weak	20	1.78	3.18	-14.98
Ca	PNE	0.0048	0.0048	-	0	-	100	Weak	-	2.52	6.36	7.54
Mg	Linear	0.0070	0.0070	-	1E-4	-	-	-	-	5.45	29.96	56.99
K	Spherical	0.0350	0.0499	-	-	57	70	Moderate	-	1.64	2.69	8.99
Na	PNE	0.0540	0.0540	-	0	-	100	weak	-	2.25	5.10	-6.98
CEC	Spherical	0.0015	0.0043	-	-	68	34	Moderate	-	2.49	6.23	3.14
Ca/Mg	PNE	0.7000	0.7000	-	0	-	100	Weak	10	3.14	9.91	-11.22
Mg/K	PNE	0.0600	0.0600	-	0	-	100	Weak	10	9.09	82.74	1.90
Badoudi plot												
Clay	PNE	0.0035	0.0350	-	0	-	100	Weak	25	5.20	27.04	-5.04
pH	Spherical	0.0015	0.0025	-	-	40	48	Moderate	-	2.88	8.32	-1.52
TOC	Linear	0.5500	-	-	0.0036	-	-	Strong	-	2.30	5.35	9.03
TN	Linear	0.0500	-	-	8E-5	70	-	-	-	1.55	2.42	11.45
TAP	Spherical	0.4000	1.0304	-		60	39	Moderate	-	1.71	2.93	13.35
ECa	Linear	0.0500	-	-	3.6E-5	-	-	Strong	-	3.04	9.30	14.67
EMg	Power	0.0080	-	0.014	-	100	-	-	-	3.05	9.28	-14.50
EK	Spherical	0.0420	0.0685	-	-	60	61	Moderate	-	2.08	4.36	1.03
ENa	Power	0.0450	-	0.026	-	160	-	-	-	3.06	9.38	-34.81
CEC	Power	0.0027	-	0.038	-	146	-	-	-	3.20	10.28	9.05
Ca/Mg	Linear	0.0190	-	-	0.0051	-	-	-	-	3.05	9.29	1.20
Mg/K	Linear	0.0450	-	-	0.0005	-	-	-	-	2.16	4.67	1.99

G: Goodness-of-prediction; GSD: grade of spatial dependence; MAE: mean absolute error; MSE: mean squared error; PNE: pure nugget effect.

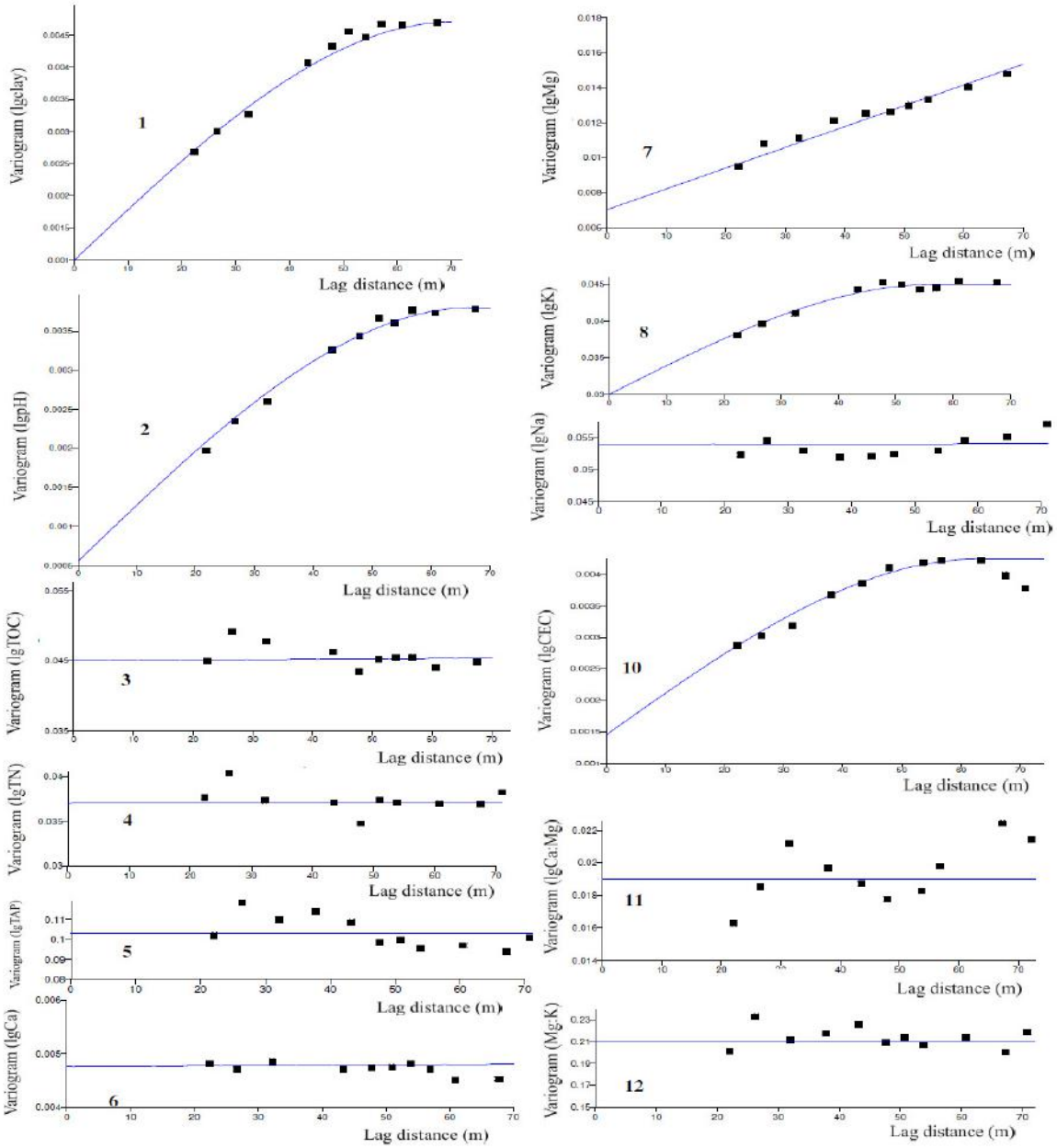

Fig. 5A. Variograms of the different vertisol characteristics in Garoua (1. Clay; 2. pH; 3. TOC; 4. TN; 5. TAP; 6: ECa; 7. EMg: 8. EK; 9. ENa; 10. CEC; 11. Ca/Mg ratio; 12. Mg/K ratio; solid variogram line: theoretical model; Points: experimental model).

is noted between TOC, TN and TAP as well as between pH, clay, S, CEC and ECa in Badoudi confirming the strong positive correlation between them.

Geostatistical analysis

Variogram modeling

The variogram analysis revealed that most of the soils characteristics in the Badoudi plot (grassed savannah) were fitted by a linear model while those in the Garoua plot (millet farm) were mostly fitted by a “pure nugget effect” model (Fig. 5A and B). The remaining soils properties in Garoua were fitted by the spherical (clay, pH, EK and CEC) and the linear (EMg) models. In Badoudi, power (CEC, ENa and EMg), spherical (pH-H_2O, TAP and EK) and “pure nugget effect” (clay) models were also observed (Fig.5B).

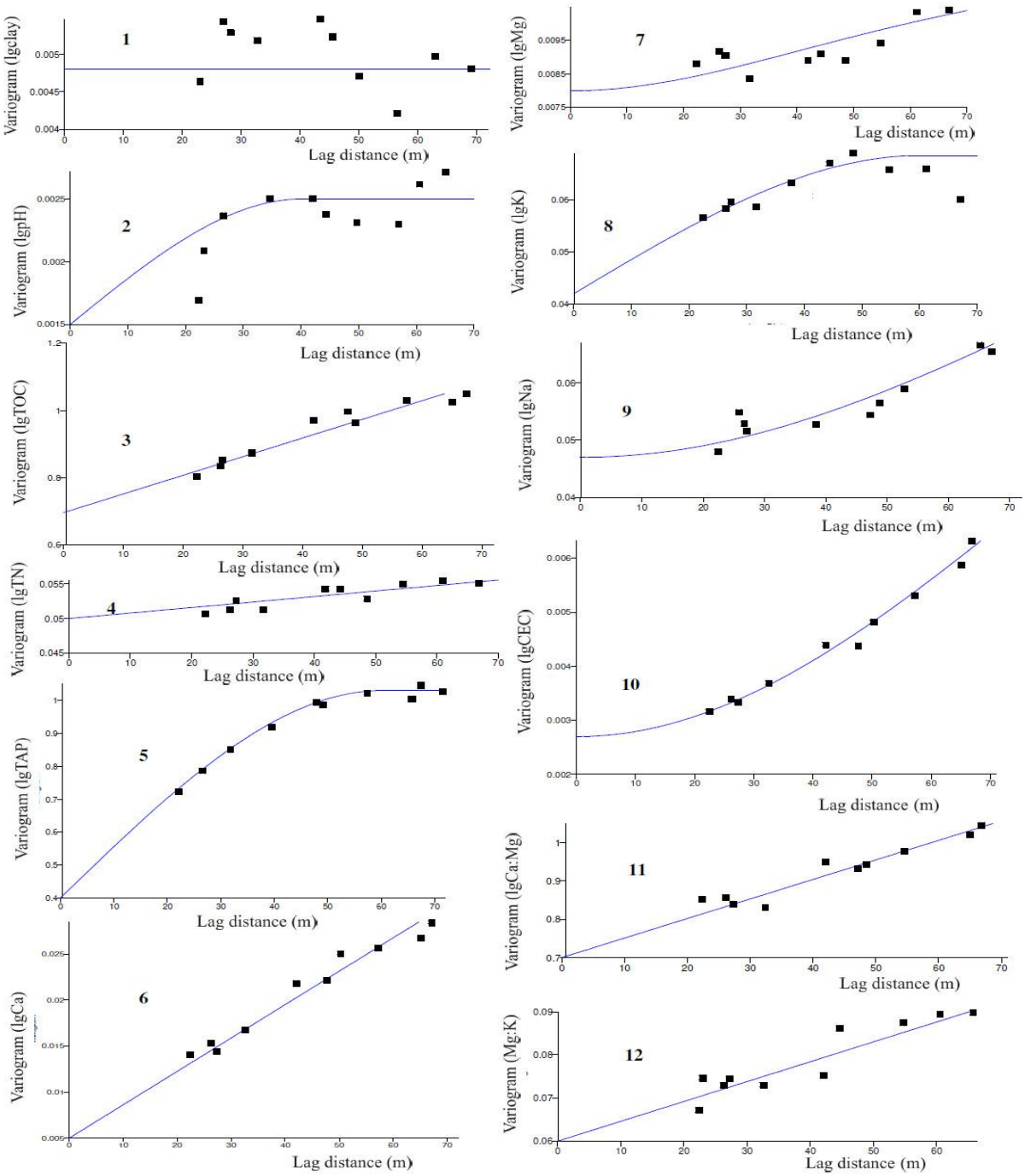

Fig. 5B. Variograms of the different vertisol characteristics in Badoudi (1. Clay; 2. pH; 3. TOC; 4. TN; 5. TAP; 6: ECa; 7. EMg: 8. EK; 9. ENa; 10. CEC; 11. Ca/Mg ratio; 12. Mg/K ratio; Solid variogram line: theoretical model; Points: experimental model).

Spatial distribution of the soil properties

The spatial map of clay in Garoua revealed an increase in clay contents from the centre to the peripheral part of the plot (Fig. 6A). However, the highest clay contents appeared as tiny spots inside the plot. In Badoudi, spots of very high clay contents were more represented than in Garoua, and some of them were below lower clay limits of true vertisols (Fig. 6B). The pH-H_2O in Garoua was low (slightly acidic) at the centre of the plot and increased towards the periphery where it attained neutrality to alkalinity (Fig. 6A). In Badoudi, pH-H_2O was globally

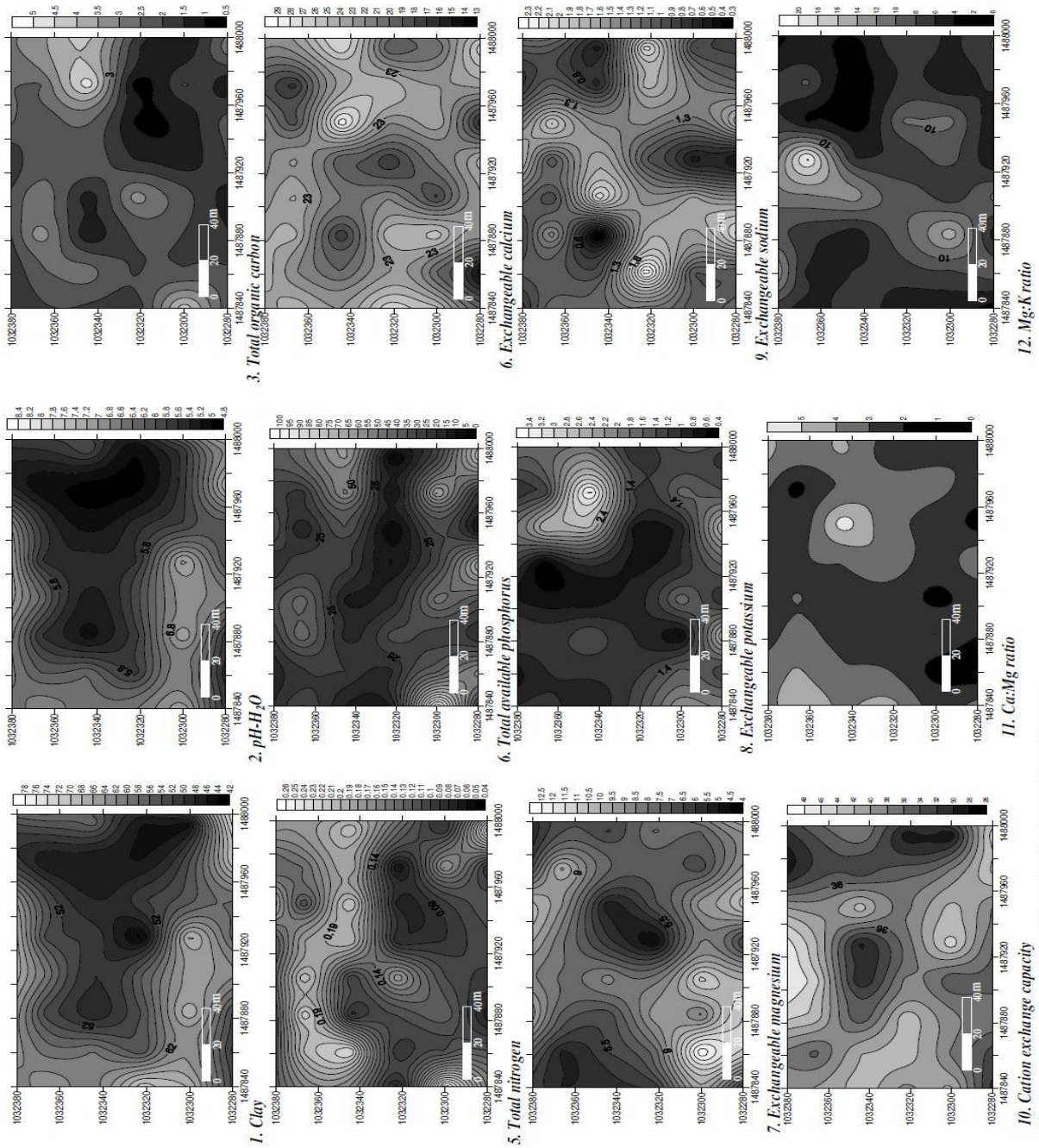

Fig. 6A. Isovalue maps of the different vertisol properties at Garoua.

highest at the centre of the plot, and then decreased towards the north and south. The lowest pH-H_2O values appeared at the south of the Badoudi plot (Fig. 6B). The map of TOC in Garoua showed areas of very low carbon enclosed within zones of moderate ones (Fig. 6A). Areas of high carbon contents were the least represented in the plot and occured only as tiny spots completely enclosed inside bands of moderate carbon contents. In Badoudi, a similar distribution of TOC was observed as in Garoua with the predominance of areas of low carbon contents enclosed in large bands of moderate contents (Fig. 6B). The high carbon zones occured as isolated islets within the plot. The spatial maps of TAP and TN in the studied plots were globally correlated with that of organic carbon in agreement with the results of the statistical analysis. The spatial pattern of exchangeable Ca (ECa) in Garoua revealed a spatial correlation with clay and pH-H_2O, marked by spots of high values in the entire plot. The areas of low ECa were randomly dispersed in the plot and values increase outwards from the centre, except in a few spots where the reverse trend was observed (Figs. 6A and 6B). In Badoudi, ECa was also correlated with pH-H_2O and clay, and the

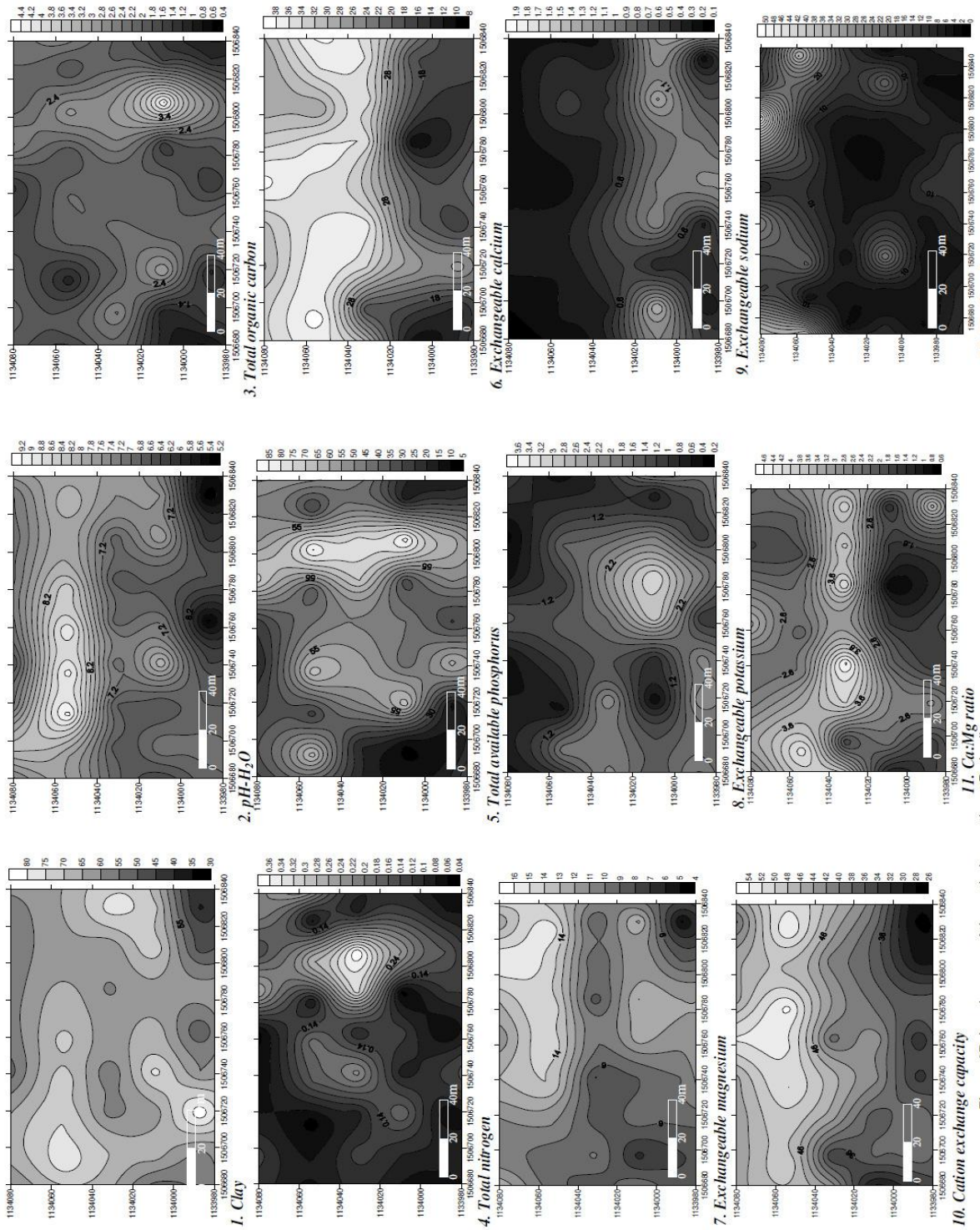

Fig.ure 6B. Isovalue maps of the vertisol properties at Badoudi.

highest contents were observed in the north of the plot (Fig. 6A). There was a slight decrease towards the north, but a sharp decrease was observed in the south of the savannah plot. The exchangeable Mg (EMg) in Garoua also portrayed some spatial correlation with ECa, pH-H_2O and clay in Garoua but this correlation seemed more evident in Badoudi (Figs. 6A and B). The spatial map of exchangeable K (EK) in Garoua revealed the presence of bands of low EK contents at the central and north western parts of the plot (Fig. 6A). There was an outwards increase from the centre towards the east and south. The maximum values were observed at the east where a large band of

high EK appeared and was surrounded by areas of moderate to low EK content. In Badoudi, the highest EK contents appeared in the middle of the plot, decreasing gradually outwards (Fig. 6B). There were tiny islets of very low EK mainly in the north, east and centre of the plot. The spatial map of ENa revealed low contents for the two plots. In Garoua, the highest and lowest ENa contents appeared as islets within zones of the intermediate values (Fig. 6A). In Badoudi, the ENa decreased globally from the south to the north (Fig. 6B). This trend was however interrupted by some isolated bands of low ENa contents in the south of the plot. The spatial maps of the CEC revealed zones of low, moderate and high CEC in Badoudi and Garoua (Fig. 6A and B). In Garoua, areas of low and high CEC occured as bands with zones of moderate CEC (Fig. 6A). Here, the spatial map of CEC was similar to that of clay, pH-H_2O, ECa and EMg in both plots (Fig. 6B). In Badoudi, CEC increased from the south to the north of the plot. In Garoua, the spatial pattern of Ca/Mg ratio revealed that low ratio values were weakly represented in the plot and forms only few tiny islets enclosed by the larger bands of high ratio values (Fig. 6A). In Badoudi, Ca/Mg map showed a band of very high ratios at the centre of the plot, while moderate values formed bands in the north and south of the central band. The zones of low Ca/Mg ratios occur mainly as islets within the other bands. The spatial map of Mg/K ratio in Garoua revealed a clear predominance of high values in the two studied plots (Fig. 6A and B). In Garoua, the different soil Mg/K ratio classes appeared as irregularly shaped bands (Fig. 6A). The highest values form a north-south trending zone at the centre of the plot, meanwhile in the east and west, there were alternating bands of lower and higher ratio values in a north-south direction. In Badoudi, the spatial map of Mg/K ratio showed a global north to south increase within the plot (Fig.6 B).

Cross-validation of kriging

The cross-validation analysis revealed that all the MSE values were different from zero indicating the presence of inacurracies in all the spatial data estimations (Table 8). MSE is very unreliable since a MSE of zero is practically impossible in interpolation (except at sampling points). The goodness-of-prediction (*G*) values values were all below 100 indicating that none of the predictions was perfect. However, a good fit ($G>0$) was observed for clay, pH.H_2O, ECa, ECa, EK, CEC and Mg/K in Garoua, and TOC, TN, TAP, ECa, EK, CEC, Ca/Mg and Mg/K in Badoudi (Table 8). The rest of the variables with a $G<0$ indicate a poor fit for the variogram models suggesting that, for these variables, predictions using kriging are less reliable than using sample mean alone as the predictor.

DISCUSSION-INTERPRETATION

Significance of the mathematical approach to the study of vertisols

The statistical analysis revealed that all the vertisol properties followed a log-normal distribution. Under natural grassland, many soil variables tend to conform to normal distribution because of homogenizing influence of biotic factors (Roosi et al., 1992; Chien et al., 1997; Chandra et al., 2016). Nevertheless, when grassland is mixed with shrubs, normality of soil variables tends to give a skewed distribution (Nael et al., 2004; Cantú-Silva et al., 2010). Also, factors that might distort normality are vegetation removal, farming activity, grazing or erosion (Schlesinger et al., 1990). Some of the vertisol characteristics showed a strong positive correlation such as TOC, TN and TAP as well as clay, ECa, EMg, sum of bases and CEC. Many authors indicate a positive relationship between soil organic matter and the capacity of the soil to supply essential plant nutrients including TN, TAP and EK (Rezaei and Gilkers, 2005). The strong relationship existing between clay, ECa, EMg, sum of bases and CEC is consistent with the high smectite content imposing a strong affinity for basic cations (Duchaufour, 1977; Chandra et al., 2016). Most of the vertisol properties did not vary significantly ($P>0.05$) among the two studied plots when considered at the scale of the soil series (Duchaufour 1997). The PCA further permitted to note inherent soil fertility status (exchangeable bases), acidity, TOC, TN and TAP contents and soil texture (which reflects soil moisture conditions). Although these results are site-specific, analogous trends have been documented by Salami et al. (2011) and Tabi et al. (2013).

Geostatistically, most of the vertisol properties in Badoudi were best-fitted by a linear model while those in Garoua were best-fitted by a “pure nugget effect” model. The “pure nugget effect” of TOC, TN, TAP and ECa, Ca/Mg and Mg/K (in Garoua), and clay (in Badoudi) suggest either the absence of a spatial pattern or the presence of a high spatial variability at distances shorter than the 20 m lag distance adopted for the present study (Folorunso et al., 1988; Oliver, 1987). The “pure nugget effect” (or white noise) reflects randomly distributed patterns and the fact that changes in semi-variance with increasing lag distance are not significant (Webster, 1990; Goovaerts, 1998). Thus, total variance exists at all scales of sampling without autocorrelation in data points (Webster and Oliver 1992). This observation ties with the works of Gonzalez and Zak (1994), Kabir et al. (1994) and Chevallier (1999) who attributed such a behaviour to possible sources of variation like plant cover distribution, cracking patterns and swell-shrink property. In the Garoua

plot, a periodicity was observed in the distribution model of TOC, TAP, TN, Ca/Mg and Mg/K, in addition to the "pure nugget effect", while in Badoudi this phenomenon was observed only for clay. In effect, periodicity, regular or not, reflects cyclic repetition of properties in space showing a mosaic structure (Webster, 1977; Krasilnikov and Sidorova, 2008). This indicates the intervallic appearance of homogeneous patches in two-dimensional spaces or contour maps of those properties (Chevalier, 1999). This phenomenon, already observed by Webster (1977) in some Australian vertisols, was attributed to the presence of intervallic microlows and microhighs of gilgai microrelief. Gilgai microrelief is however absent in north Cameroon vertisols. The presence of a linear model suggests the existence of a spatial trend and the grade of this trend increases with increase in the slope of the linear variogram model (Webster and Oliver 1990). The steep slope portrayed by the linear variograms of TOC, TN, ECa and Ca/Mg in Badoudi and EMg in Garoua was consistent with a strong grade of spatial dependence (Jongman et al., 1995; Nael et al., 2004). Samsonova et al., (1999) reported such a strong linear trend for acidity and EK in a vertisol field where fertilizers were irregularly applied. Similar distribution of ECa was reported in a field where one portion was limed and the other was not (Webster, 1995). An interesting interpretation of a linear distribution of soil properties was proposed by Burrough (1983) who suggested that soil variation has the same nature as Brownian motion and thus could be described as a fractal. A fractal reflects an unlimited growth of variance with increasing lag distance, that is, the soil contains some structural elements of various scales bearing evidence of self-similarity (Krasilnikov, 2008). However, there are serious doubts that the distribution of soil properties really has fractal nature (Webster, 2008). But then, Burrough (1983) remarked that infinite increase of variance could a times indicate nested processes rather than fractal (Brownian) behaviour. The spherical model for some of the vertisol properties suggests that they are spatially dependent and that the semi-variance first rises and then levels off at the sill, indicating the distance beyond which samples become independent called the range (Sidorova and Fyodorov, 2008). The sill (plateau) suggests the presence of an unexplained microvariability in the samples due to heterogeneity of sampling sites and the fact that the properties only change at distances longer than the 20 m lag distance (Arrouays et al., 2000; Cucunubá-Melo et al., 2011). The power model for EMg, ENa and CEC in Badoudi describes a near parabola marked by a constant increase in variance alongside a concurrent increase in lag distance (Nael et al., 2004). This model with a quadratic shape reflects a drift in dataset (Goovaerts, 1997). The variograms of all the vertisol characteristics showed a positive nugget variance which could indicate sampling error, short-range or micro-scale variability, and random and inherent variability (Wang et al., 2009).

The Nugget-to-sill ratio, an index of GSD of soil properties (Camberdella et al., 1994), for Garoua, revealed a strong spatial dependence for clay and pH, meanwhile ENa, EK, CEC showed a moderate spatial dependence. In Badoudi, a strong spatial dependence was noted for CEC, a moderate one for pH, TOC and TAP. Almost all soil properties exhibit variability at all scales, no matter how small it is, as a result of the dynamic interactions between natural environmental factors like climate, parent material, vegetation, topography, landuse, etc (Chevallier, 1999). The soil characteristics with strong GSD, like clay and pH.H_2O (Garoua) as well as CEC (Badoudi), could be controlled by the intrinsic variability, while the weak ones might be controlled by extrinsic ones (Camberdella et al., 1994). The moderate GSD of EK, ENa, CEC (in Garoua) and pH, TOC, TAP, EMg, EK, ENa (Badoudi) could be linked to both intrinsic and extrinsic pedogenic processes. These environmental factors affect the soil microclimate by influencing the distribution of energy, plant nutrients, organic matter, runoff and runon processes, natural drainage, soil exposure, wind and precipitation (Wang et al. 2009; Baishya et al., 2017). Also, the TOC, TN, ECa, Ca/Mg and Mg/K with a stronger spatial pattern in Badoudi compared to Garoua might suggest a greater influence of intrinsic factors in Badoudi and greater extrinsic ones in Garoua in agreement with the landuse systems (Camberdella et al., 1994). Jahknwa and Ray (2014) noted in some northern Nigerian vertisols that inherent variability in soil properties is a function of soil type, scale, nature of landuse and subsisting climatic factors among other things. Karageorgis (1980) already noted that soils on alluvial materials are often highly heterogeneous due to marked textural variation of the parent rock. The vertisol spatial structure according to Trangmar et al., 1985), could help to better understand soil distribution to help develop more robust soil-landscape models, notably on a particularly flat alluvial system like the Benue floodplain where soil inherent spatial variability is not easy to predict from soil-landscape relationships.

The goodness-of-prediction (*G*) revealed a good fit for most of the variables suggesting that the spatial prediction using variogram parameters is better than assuming mean of observed value as the value for any unsampled location for the given variable (Davis, 1987). This also implies that variogram parameters obtained from fitting of experimental variograms were reliable to describe the spatial structure of the vertisols and that the spatial maps obtained have a great potential for farm-level or planning of crop selection at different blocks of the farm or regional-scale application.

Conversely, goodness-of-prediction for TAP, TN, TOC and Ca/Mg in Garoua as well as EK, ENa, EMg, Clay and pH in Badoudi did not show a good fit. Nevertheless, a larger number of samples and the narrower sampling grid could have led to proper fitting of variograms and consequently to a better description of the spatial structure

on these variables (Liebhold and sharov 1998; Santra et al., 2008; Carmacho-Tamayo et al., 2008).

Implication for quality appraisal of the studied soils

Under savannah, it appears, as revealed by its good geographical distribution with a "pure nugget effect" model that the basic fertility parameter of the studied vertisols is clay content. Its value remained everywhere in the plots above the highest value (35%) necessary to maintain optimum soil nutrient assimilation by plants (Latham, 1971; Baishyia et al., 2017). The other favourable agricultural parameters that could be identified are pH-H_2O, TOC, TN, TAP, ECa, EMg and EK. However, their critical limits for crop cultivation, as defined by Sanchez et al. (1982), include: pH.H_2O 5.5 (lower limit) and 8.5 (upper limit), TOC 1 %, TN 1 %, TAP 15 %, ECa 5 me/100g, EMg 2 me/100g, EK 0.1 me/100g, Ca/Mg 2-5 and Mg:K 3-20. When compared with data collected in the savannah plot, one notes that only TN was below the predefined critical level. The other fertility parameters were either partially a function of position in the plot (pH.H2O, TOC and TAP) or not for ECa, EMg and EK which were everywhere above the critical limit. The most interesting combinations in the plot were ECa, EMg and EK. However, these elements must be in the ratio of 76% Ca, 18 % Mg and 6% K for optimum plant assimilation (Michel, 1979). According to Kabir et al. (1994) and Chevallier (1999), pure nugget effect with periodicity of the TOC might be attributed either to the presence of cracks or to the presence of successive protective vegetation tuffs separating intertuff spaces which are vulnerable to erosion. This observation could be applied to clay in the present study, mainly concerning the presence of successive protective vegetation tuffs, well recognisable in the field, which represent the main points of maximum fertility. Shlesinger et al.(1990) suggested that nutrients accumulation under vegetation tuffs is an autogenic process that leads to the development of "islands of fertility" in the field. Once the plot is subjected to cultivation (as in Garoua), most of the fertility parameters, notably TOC, TN, TAP, ECa, Ca/Mg ratio, Mg/K ratio and ENa, are now fitted by a "pure nugget effect". This change of spatial structure of vertisols enhanced by erosion at plot scale has already been reported by Mainam et al. (2003) in the semi-arid region of North Cameroon. The fundamental transformation of spatial pattern of soil variables, from linear model under fallow grassed savannah to "pure nugget effect" model in the cultivated sorghum plot is unquestionably related to a regular homogenisation of the plot by farming activities and removal of natural vegetation (Chan et al. 1995; Nael et al., 2004). When the values of those parameters were compared with predefined literature critical limits published by Sanchez et al. (1982) , it was observed that TN remained below the critical limit, while the other parameters (TOC, TAP, ECa, Ca/Mg ratio and Mg/K) were below or above based on their position in the field. The mean TOC contents in the cropland were higher than those of the savannah due to continuous addition of post-harvest crop residues to the farm. Other interesting parameters in the cropland were clay, pH.H_2O, EK, CEC and EMg. They were characterized by a spherical (clay, pH, EK, CEC) and a linear (CEC) variogram model revealing a heterogeneous distribution in the plot (Webster, 1990). This spatial pattern could also be the consequence of human-induced soil erosion (Chan et al., 1995). The EK, CEC and EMg were above the lower limits for crop cultivation (Sanchez et al., 1982). The high clay content (>35 %) is a limiting factor to the uptake of nutrients in the cropland (Latham, 1971; Barber, 1979; Blackmore, 1994; Abunyewa et al., 2004). The pH.H_2O is either above or below critical levels depending on the position in the cropland. The most interesting combinations of nutrients are ECa, EMg and EK; nevertheless, they do not respect the 76 % Ca, 18 % Mg and 6 % K equilibrium for optimum plant assimilation (Martin, 1979). Although TAP is high, the TN deficiency could be limiting its assimilation by plants caused by an unbalanced equilibrium between the two elements (Mémento de l'Agronome, 1993). Some environmental conditions like the high temperature and the seasonal waterlogging could be responsible for the low TN contents in the two plots (Prusty et al., 2009). It has been documented that those factors increase the activity of denitrifying bacteria which convert available soil nitrates into gaseous nitrogen making the soil deficient in nitrogen (Albrecht et al., 1992; Geeta et al., 2016). Management strategies to improve drainage could help to cub anaerobic respiration, thereby increasing nitrogen level.

Overall, although subjected to cultivation, the vertisols of the Benue floodplain remained fertile with a better distribution of the fertility parameters compared to those under fallow (savannah), although their general fertility level appeared lower when cultivated.

CONCLUSION

The main objective of this paper was to perform statistical and geostatistical analyses of vertisol properties in order to enhance a maximum agricultural exploitability of those soils. The main results revealed that, statistically, most of the vertisol properties did not vary significantly among the two studied plots under two land use systems ($P>0.05$). The PCA led to a reduction of fifteen original variables to four principal components explaining more than 70 % of the total variance. Geostatistically, most of the vertisol characteristics in the cropland were best-fitted by a pure nugget effect model, sometimes with cyclic periodicity indicative of "islands of fertility" within the plot. Continuous cultivation could be enhancing homogenization of fertility parameters despite a global reduction in fertility. Soil

characteristics under grassland were best-fitted by a linear model portraying a strong grade of spatial dependence. Contour maps obtained by kriging could have great potential for designing strategies for site-specific management.

ACKNOWLEDGEMENTS

The authors sincerely express gratitude to the International Institute for Tropical Agriculture (IITA of Nkol Bison (Yaounde, Cameroon), the Laboratory of Soil analysis and Environmental Chemsitry (LABASCE) of the Faculty of Agronomy and Agricultural Sciences (University of Dschang, Cameroon) and the Laboratory of Physico-chemistry of Mineral Materials of the Faculty of Science (University of Yaounde 1, Cameroon) for the realisation of the soil analyses.

The authors also express gratitude to Pierre Goovaerts (BioMedware Inc., Ann Arbor, MI 48106, USA) for his technological support in the realisation of the Geostatisitcal analysis.

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