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Nature and Genesis of Vertisols and North Cameroon Management Experience: A Review

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Abstract Vertisols are tropical soils that occur world-wide (335 million ha) with high agricultural and other engineering potentials. However, they are underutilized as most of their physical characteristics make management techniques difficult and highly localized. This paper aims to highlight the characteristics, genesis and management strategies of Vertisols for sustainable use. Two main types of Vertisols can be distinguished: topomorphic Vertisols with $A(B)_gC$ or difficult $A(B)C_g$ profile and lithomorphic with A(B)C profile type. Vertisols generally show a dark colour, very high compacity, surficial desiccation cracks when dry, surface ponding when moist and large sub-surface slickensides. They contain at least 30% clay fraction, while smectite, cation exchange capacity and base saturation are very high. Lithomorphic Vertisols are developed on various parent rocks and topographic positions where weathering generates base-rich environments that promote smectite synthesis. The formation of topomorphic Vertisols is favoured by low landscape positions suitable for accumulation of basic cations. The latter cover very extensive surface areas of the globe mainly in tropical, semi-arid to (sub) humid and Mediterranean climates showing contrasting wet and dry seasons, while the former have limited geographical extensions and occur mainly in specific islands and volcanic regions. Swelling and shrinking upon wetting and drying is a major characteristic of Vertisols. Most of their properties and uses are dependent on shrink-swell behaviour. Micromorphologically, plasmic separations occur in all Vertisols especially in the middle part of the profile where shrink/swell is most pronounced. Most Vertisols fall under the A-7-5 and A-7-6 classes typical of inorganic clays of medium to very high plasticity designated as bad clays according to AASHTO. Vertisols present numerous interesting uses in the chemical industry, pharmaceutics, agronomy and environmental protection. Nevertheless, man-made structures on Vertisols are not advisable since large investments are needed to maintain and repair damaged infrastructure. In North Cameroon, vertisols cover about 1 200 000 hectares and agricultural management strategies are mainly tilted at moisture control, but also at fertility restoration.

Keywords: *vertisols, smectite, expansive clays, fabric, genesis, management, North Cameroon*

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1. Introduction

Vertisols constitute a group of soils that occur principally in hot environments with marked alternating wet and dry seasons [1-6]. They need for their formation the presence of a basic parent material or the presence of calcium and magnesium ions in case where the parent material is not basic [7,8,9]. They are generally formed on sedimentary plains, both on level land and in depressions; small areas of Vertisols are on hill slopes [10]. The natural vegetation is savannah and / or woodland [9,10]. These soils are characterised by high contents of expansive clays of smectitic type [10,11,12,13], a high cationic exchange capacity (30-80 cmol(+)/kg of soil) and a high base saturation (S/T > 80 %) [14,15]. Two main types of Vertisols can be distinguished: lithomorphic Vertisols which are formed on basic parent rocks and topomorphic ones that are localised mainly in lowest landscape positions [12,16]. Vertisols present numerous interesting economic potentials in ceramics, the chemical industry, pharmacology, agronomy and environmental protection [9,17,18,19]. These uses of Vertisols are mainly based on their smectite content [20]. Although large deposits of Vertisols are found all over the world, with high potentials for the production of different crops and other engineering use, they are generally underutilized. This is because of their high clay content, poor drainage and low hydraulic conductivity in the swollen state which makes management techniques to be highly localized. The aim of this paper was to highlight the nature, genesis, classification and management of Vertisols. The work is important mainly as it underscores soil data to use especially in agricultural purposes, farm planning and other engineering practices such as building, roads, etc.

2. Methodology

The present work was drawn from a vast wealth of literature on vertisols all over the world as well as information gleaned from many field expeditions in northern Cameroon and laboratory observations. Most of the data presented emerged over the past decade, having benefitted from a number of technological breakthroughs. Some of the less recent data, developed during the last couple of decades have also been included because they represent groundbreaking contributions to the knowledge of vertisols that undergo continuous improvement.

3. Concept and Historical Background

The term "Vertisol" was introduced by soil taxonomy [21], derived from a Latin word "vertere" meaning to "turn over". In effect, it was, observed that these soils were often subjected to internal "turn over" movements [7,22,23]. Later on, [7] emphasized that these vertic movements are due to two contrasting seasons, characterised by a well marked dry season. In effect, in Vertisols, moisture variations may provoke alternate shrink-swell cycles leading to mechanical brassage and homogenisation of profile [2,4,8,9,24]. For many users like farmers, these soils were particularly remarkable by their dark colour, the presence of cracks, although only during the dry season, and by their difficult workability due to surface ponding and stickiness when wet and extreme hardness when dry [5,24,25]. These reasons explain why Vertisols are one of the soil groups with the greatest number of vernacular names summarized by [1].

4. Ecology of Vertisols

The formation and conservation of Vertisols necessitate two alternating seasons within the year: a humid season and a sufficiently marked dry season to enhance formation of desiccation cracks [1,2,10,22]. These soils often occur in low landscapes whose slopes seldom go beyond 3% [10,26-31] since steeper slopes favour erosion and leaching of basic cations compromising smectitization [7]. Such low landscapes include dry lake bottoms, river floodplains, river terraces and other lowlands that are periodically wet [10]. Vertisols are commonly reported in areas of elevation less than 1000 m altitude and on relatively flat topography [32]. Nevertheless, [34,35,36] observed that some Ethiopian Vertisols occur above 2000 m altitude and on a wide range of slopes from <5 % to >15 % against the claims of [26,27]. Most Vertisols develop on young landscapes, but they may occur on old geomorphic surfaces with low gradients [10,16]. The parent material of Vertisols is preferably a basic parent rock like shale, limestone, dolomite and metamorphic rocks of basic origin [37,38,39,40]. If the parent material is not basic, then alkaline and alkali-earth elements must be added to the profile by seepage or floodwater [10,25]. Vertisols developed on alluvial deposits take a relatively shorter time (few hundreds to a few thousand years) than those developing on weathering products (tens of thousands of years) to attain maturity. This is because alluvial materials already have the necessary ingredients (basic cations and swelling clays) for the expression of vertic properties, while regolith requires a longer period for the minimum amount and type of clays to be present for the expression of vertic properties [10,25]. Because of their ecology and physical properties, the climax vegetation on vertisols is savanna, grassland and/or scanty forest [10,26,32].

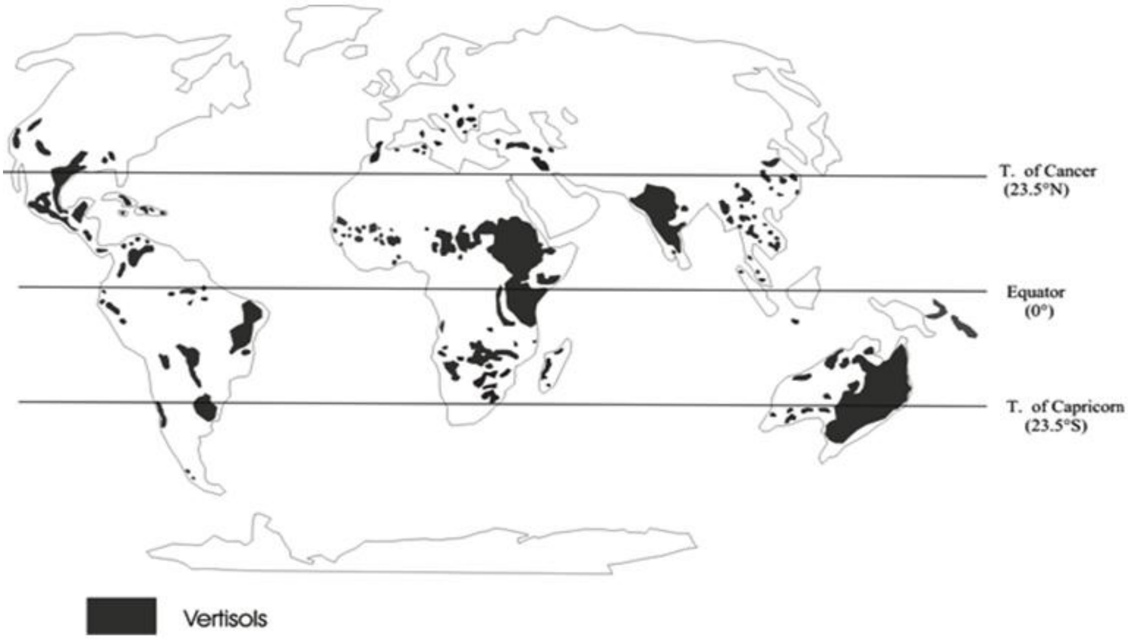


Figure 1. Vertisol distribution map of the world [2]

5. Global Distribution of Vertisols

Globally, Vertisols occupy about 335 million ha (2.42 % of ice-free land) of land on earth out of which 150 million ha (48%) is potential cropland (Figure 1) [2,41]. They occur mainly in the tropics covering about 200 million ha (4 %) of land. Globally, 177 million ha (56 %) of the 335 million ha have ustic soil moisture regime and 89 million ha (27 %) have aridic soil moisture regime, frequently occurring on desert fringes. The largest deposits (more than 75 %) of Vertisols in the world occur in the humid tropics mainly in the Deccan plateau of India (79 million ha or 24 %), the Murray Darling basin of South East Australia (70 million ha or 21 %), the Gezira plain of Sudan (50 million ha or 15 %), the Blacklands of Texas (18 million ha or 6%), the East African Rift Valley and the Ethiopian Plateau region (13 million ha or 4 %), China (13 million ha or 4 %) and in Rio Plasta Basin of North Argentina (6 million ha or ≈2%) [25,41,42]. Lithomorphic Vertisols formed directly on the weathering products of rocks are localised in areas affected by volcanism [35,41]. Nevertheless, according to [41], the uncertainty of this estimate remains high since many countries are yet to be included in the inventory and some areas under Vertisols are often too small to resolve at the scale of a map.

6. General Properties of Vertisols

6.1. Morphological Characteristics

The morphological properties of Vertisols are summarized in Table 1, Figure 2 and Figure 3. Vertisols profiles are generally of A(B)C type, with a B-cambic horizon [2,7]. Two main types of Vertisols can be distinguished: topomorphic Vertisols with $A(B)_gC$ or $A(B)C_g$ profile and lithomorphic with A(B)C profile type [14]. With an average depth between 1 and 4 m, Vertisols are generally dark in colour with a clayey texture. The A-horizon comprises both the surface crust and the underlying structured horizon that changes only gradually with depth. The subsurface soil with its distinct vertic structure conforms to the definition of a vertic horizon [14]. Important morphological characteristics such as soil colour, texture, chemical composition, etc are all uniform throughout the profile. A calcic horizon or a concentration of soft powdery lime may be present in and/or below the vertic horizon. Gypsum can occur either uniformly distributed over the matrix or in nests of gypsum crystals. Vertisols are plastic when wet, friable, and very hard when dry [11,30,43,44,45]. Structure is massive at the upper horizons with polygonal to prismatic blocks separated by deep surficial desiccation cracks and sub-surface frictional planes or slickensides, but becomes massive at depth [10,13,31,46]. Porosity is low and much infiltration of water for plants is through cracks [44,46,47]. Gilgaï microrelief "repeated mounts and depressions" are common, although not in all vertisols since they are often destroyed by farming [47,48,70].

6.2. Micromorphological Properties

Plasmic separations (or stress cutans) are common in Vertisols [27,28,48,49,50]. Some of these fabrics are vosepic (following voids) and skelsepic (related to skeletal material). Some sub-cutanic plasmic separations are masepic (striations in the plasma) whereas plasmic fabric along a closed void may appear as a non-cutanic plasmic separation [50]. Vertisol microstructure may also be described as asepic (no plasmic separations), argillasepic (clay-sized plasmic fabrics) and omnisepic (in many directions), Lattisepic (in two perpendicular directions). Insepic plasmic separations in Vertisols have been described by [49,51] while omnisepic and lattisepic plasmic fabrics have been reported by [27,28,39,49,50]. Vertisols of India show argillasepic, insepic, masepic and lattisepic plasmic fabric [52]. Surface related plasmic separations occur in all Vertisols, but are rare in surface horizons for two reasons: a generally higher organic matter contents that shades them and a lower vertic movements [25,28]. Intensity of plasmic fabrics generally increases with depth and attain maximum expression in the middle part of the profile corresponding to the zone of maximum pedoturbation and slickenside development [53]. In Carbonate-rich horizons, plasmic fabrics are poorly expressed or show crystic (crystal-sized) fabrics of carbonates [49]. In North Cameroon Vertisols, [27,28] reported isotic plasmas at the surface horizons and vosepic and locally lattisepic plasmic fabrics at the zone of slickensides (Figure 4).

6.3. Mineralogy

Vertisols are characterized by high amounts of smectite like montmorillonite, beidellite and nontronite [11,13,54]. Other minerals are illite, kaolinite, halloysite and/or short-ranged minerals like allophane. Iron oxides are very rare [25]. Minerals in sand and silt fractions include quartz, ilmenite and magnetite [9,13,17,19,27,28,38]. In the Deccan plateau of India, the Vertisols have beidellite as swelling clay since Vertisols form the lowest member of a catena, associated with red soils derived from similar parent material. In the Gezira and the Fung clay plains (Sudan), montmorillonite is dominant, accompanied by some kaolinite; but in Khashm el Girba, illite is present [36]. In the Athi plains of Kenya and the coastal area of Ghana, the clay is largely montmorillonitic in the Vertisols, whereas in Togo aluminous beidellite occurs. In Tanzania, the black cracking clays in the south, the Mbuga soil in the Ukiriguru catena, and the Vertisols of the West Lake region, all contain montmorillonite as the dominant mineral, with some kaolinite present, but in the Lubiri mbuga Vertisols (Tanzania), illite is dominant, with accessory kaolinite [56].

6.4. Chemical Composition

Vertisols are rich in silica and alumina (Table 1). Alkali-earths (Ca and Mg) and alkaline (Na and K) are also highly concentrated [44,57]. Titanium oxide occurs in very small concentrations. Also, silica-alumina ratio is very high (>>> 2) indicating the presence of low leaching mechanisms and the predominance of a 2/1 clay minerals (notably smectite) characteristic of a dominant bisiallitisation process [58,59]. Available indices of trace elements in Vertisols are sufficient for plant growth except Zn, which is inadequate [60]. Available heavy metal contents are below tolerable levels that can pose danger to man and livestock and generally decrease with profile depth associated with decreasing organic carbon contents and increasing pH and $CaCO_3$ [19,37,61]. Thus, trace elements contents published by [36] for Bale Mountain area of Ethiopia were 4800 to 12000 mg/kg Fe, 774 to 2947 mg/kg Mn, 55 to 143 mg/kg Zn, 5 to 65 mg/kg Cu, 19 to 119 mg/kg Co, 6 to 35 mg/kg Pb and 0 to 4 mg/kg Cd.

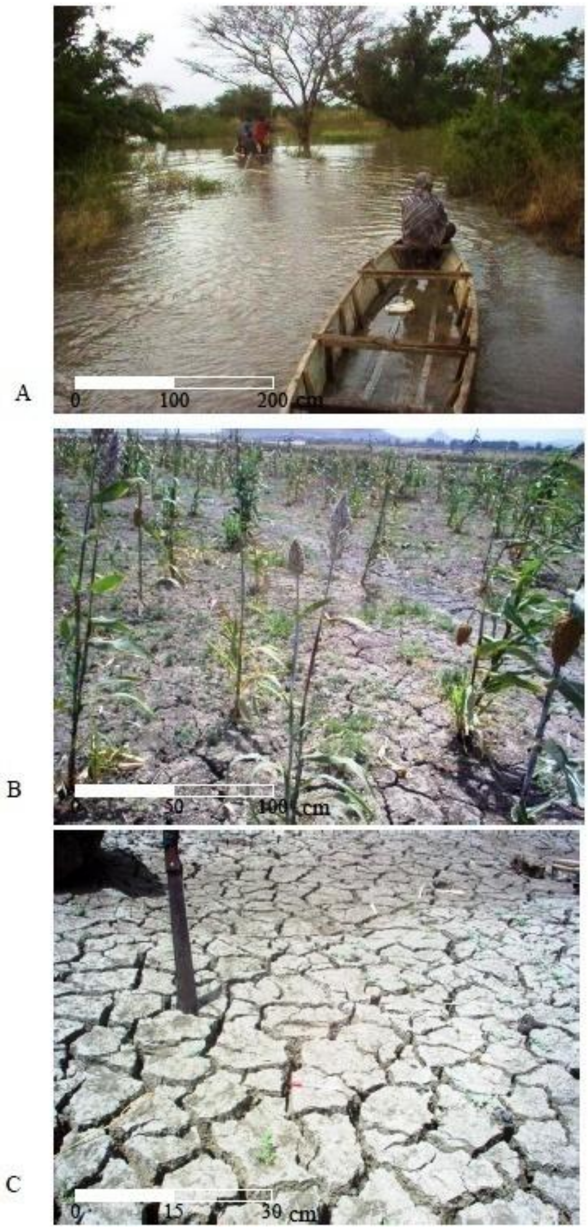


Figure 2. Surface view of a Vertisol field in Garoua (North Cameroon) at different periods of the year [29]. A: Flooded Vertisol field (end-August 2011); B: Sorghum crop on Vertisols (mid-February 2011); C: highest expression of desiccation cracks (mid-March 2011)

6.5. Physico-chemical Characteristics

Physically, the bulk density of Vertisols ranges between 1.6 and 2.1, although higher values have been reported [47,62,63]. Texture is generally heavy clayey but occasionally clayey or silty clayey with clay contents varying between 45 and 90 % (11,27,64). Low clay contents (22%) have been reported for some South African [37] and Tanzanian Vertisols [56]. Other works [32,62] show uniform clay distribution throughout depth caused by vertic movements that homogenise the whole profile. Nevertheless, in selected cases, there is a gradual increase in clay content with depth [1,13,19,47,65]. Vertisols can also have argillic horizons [66], which justify the subsoil horizon designation as 'B' [67] instead of 'A' in earlier concept on Vertisols with no horizonation [68]. Although, the slight increase in clay content with depth in Vertisols has been attributed to inheritance from parent material [32], clay illuviation is also common [66].

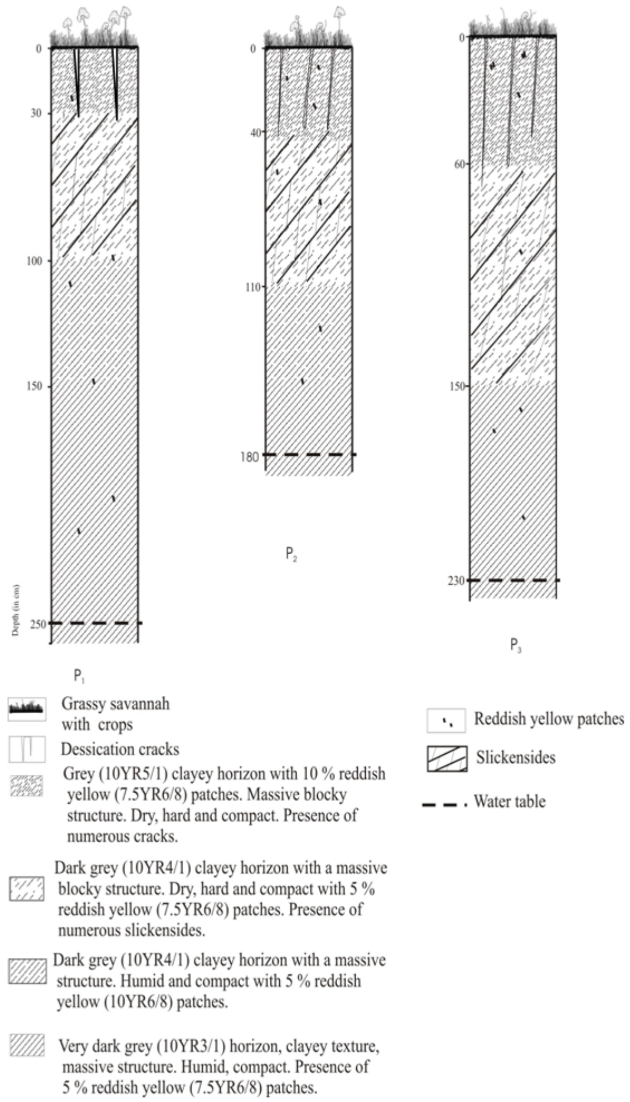


Figure 3. Vertisol profiles in the Benue floodplain of North Cameroon

Pedoturbation was much considered as an important pedogenic process in Vertisols until early nineties that would obliterate all evidence of illuviation, except in the lower horizons [11]. Gravel-sized particles are rare and when present, they make up less than 10% of the bulk volume of material [69]. Sand content varies between 2 and 50 % and silt 10 to 60%. Porosity is low (15 and 30 %) according to [27,70]. Water reserves are very important in the rainy season but the water retention capacity is high due to the presence of smectite [47,71]. The natural moisture content of Vertisols is variable. The mean available water content of Vertisols has been reported as 110 mm in Australia [72], 125 mm in the Sudan [73] and 230 mm in India [74] for the upper metre depth of the soil profile. Virgo and Munro [75] observed that the moisture content in deeper layers of the soil profile decreases, apparently due to compression effect on matric potential. A typical deep Vertisol may be able to hold as much as 250 mm of available water once the profile is fully charged. Recent work in North Cameroon [45] reveal available water capacity of 134-407 mm/m, readily available water content of 89-271 mm/m and water holding capacity of 268-814 mm/m. Also in North Cameroon, Vertisols may be acidic, neutral or alkaline [10,25,77]. The organic matter content is low (about 2 %) and homogenously distributed throughout the profile [2]. Its presence is believed to give Vertisols the characteristic black colour suggesting poor drainage imposed by the heavy clayey texture, slow transformation and strong maturation [2]. The C/N ratio values are often high (>12) and this is related to low mineralisation rate of organic matter [7,47]. The CEC generally varies between 30 and 80 cmol(+)/kg and the CEC of the clay fraction ranges between 50 and 100 cmol(+)/kg clay [10]. The base saturation is very high (S/T>80%) with Ca^{2+} and Mg^{2+} often occupying more than 90 % of the exchangeable sites [28,78]. The Ca/Mg and Mg/K ratios normally show between 1- 3 and 5-20, respectively [1,43,60].

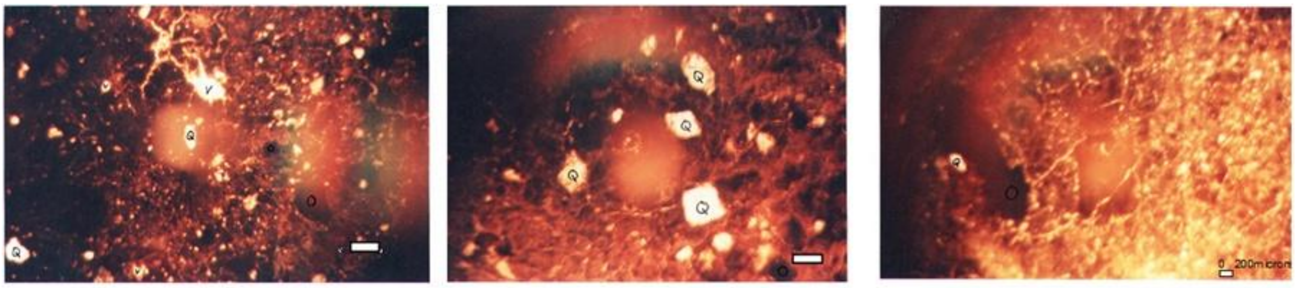
Table 1. Morphological and physical properties of some Vertisols in North Cameroon [60] and Turkey [12,15]

Horizon	Depth above water table (cm)	Munsell Colour		Structure	Consistency		Rock fragments	Boundary	Roots	Clay	Sand	Silt	Textural class (USDA)
		Code	Colour		Dry	Wet							
North Cameroon (on recent alluvium)													
Ap	0-30	10YR5/1	G	3c, abk	h, f	s, p	n	g	c, f	62.50	10.8	26.66	Heavy clay
Bv	30-100	10YR4/1	DG	3m, abk	h, f	s, p	v	g	f, f	70.00	6.3	25.00	Heavy clay
B_{t1}	100-150	10YR4/1	DG	3c, abk	h, f	s, p	v	g	-	72.50	6.5	17.00	Heavy clay
B_{t2}	150-250	10YR3/1	VDG	3c, abk	h, f	s, p	c	-	-	75.00	7.5	18.86	Heavy clay
North Cameroon (on recent alluvium)													
Ap	0-40	10YR5/1	G	3c, abk	h, f	s, p	v	g	c, f	68.00	10.7	22.50	Heavy clay
Bw	40-110	10YR4/1	DG	3m, abk	h, f	s, p	v	g	f, f	72.00	11.95	16.03	Heavy clay
B_{t1}	110-210	10YR4/1	DG	3c, abk	h, f	s, p	c	-	-	75.00	6.4	20.0	Heavy clay
Northeastern Turkey (Marn)													
Ap	0-20	5YR3/4	DRB	3f, sbk	h, f	s, p	n	g	c, m	45.3	10.4	43.8	Clay
Bw	20-80	5YR3/4	DRB	3m, abk	h, f	s, p	n	w	c, f	48.1	6.6	45	Clay
C	80-110	5YR3/4	DRB	3m, abk	h, f	s, p	c	w	-	45.5	11.5	42.7	Clay
Northeastern Turkey (Marn)													
Ap	0-20	5YR3/2	DRB	2m, sbk	h, f	s, p	n	w	c, f	43.7	14.3	41.3	Clay
Bw	20-70	5YR3/2	DRB	3c, abk	h, f	s, p	n	s	c, f	46	10.5	43	Clay
C	70-115	5YR3/4	DRB	2c, abk	h, f		v	s	-	42.1	17.3	40.1	Clay
Northeastern Turkey (limestone)													
Ap	0-25	5YR3/4	DRB	2f, sbk	h, f	s, p	n	g	c, m	37	27.4	35.6	Clayey loam
Bw	25-75	5YR3/4	DRB	3m, abk	h, f	s, p	n	w	c, m	39.7	23.6	36.3	Clayey loam
C	75-115	5YR4/6	YR	2c, abk	h, f	s, p	v	w	-	37.9	26.5	37.9	Clayey loam
Northeastern Turkey (limestone)													
Ap	0-15	5YR3/4	DRB	2f, sbk	h, f	s, p	n	g	c, f	35.4	32.7	31.9	Clayey loam
Bw	15-70	5YR3/4	DRB	3m, abk	h, f	s, p	n	g	f, f	37.8	28.1	34.1	Clayey loam
C	70-120	5YR4/4	RB	2m, sbk	h, f	s, p	v	w	-	33.1	38.8	28.1	Clayey loam

Key of soil properties.

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

G: grey; DG: dark grey; VDG: very dark grey; DRB: dark reddish brown; YR: yellowish red; RB: reddish brown.



Vertisol surface horizon (0-30 cm) showing dense, abundant and isotic plasma, with fissures (V) and angular quartz grains (Q).

Zone of slickensides (30-100 cm): very dense and birefringent (vosepic) plasma with tiny quartz grains (Q) and tiny fissures

Dark grey horizon (100-150 cm): very dense and abundant (vosepic) plasma with quartz grains (Q) and tiny fissures.

Figure 4. Microphotographs of plasmic fabrics in some North Cameroon Vertisols under cross polarized light

Table 2. Chemical compostion of some Vertisols in the world [28,65]

Horizon \ Oxide	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_3	SiO_2/Al_2O_3	LOI
North Cameroon	53.46	18.88	6.72	0.08	1.06	1.16	0.87	1.85	1.02	0.09	2.83	14.64
	53.29	18.79	6.60	0.06	1.34	1.00	0.88	2.18	1.01	0.16	2.84	14.61
	53.40	19.07	6.89	0.09	1.38	1.38	0.92	2.11	1.11	0.19	2.80	14.03
	53.15	20.66	7.20	0.06	1.20	1.20	0.53	1.77	1.08	0.21	2.57	13.07
India	49.3	13.7	14.8	-	4.8	6.9	-	-	1.9	-	3.60	-
Ghana	54.26	20.29	10.22	0.29	2.78	1.6	1.12	0.05	1.41	0.004	2.67	-
	62.18	18.23	6.7	0.07	2.45	0.7	2.07	0.11	1.09	0.05	3.41	-
Indonesia	42.80	19.03	8.68	0.05	1.81	1.73	0.75	0.08	0.02	0.06	2.25	-

6.6. Engineering Properties

Some engineering characteristics of Vertisols are shown in Table 2 [28,65]. The specific gravity of Vertisols varies between 2.3 and 2.9 (Table 3). The liquid limits of Vertisols are variable but globally range between 30 and 190%, whereas the plasticity index varies between 15 and 145% [65,79,80]. Free swell varies between 50 and 220%. Na-clays have greater tensile moisture contents range from 1000 to 3000 kg m^{-3} and 10 to 50%, respectively. The Californian bearing ratio (CBR) values of unsoaked samples are relatively high (35-40 %) but soaking reduces the value drastically (0-2 %) indicating low resistance to tangential stress and high compressivity. The compression limit values (Table 3) of Vertisols are typical of stiff clays [80]. Apart from a few exceptions, the natural water contents of Vertisols range between 20 and 30%, and these values are always between the liquid limit and the plastic limit. The correlations coefficients between the different mechanical properties are shown in Table 4. Based on the AASHTO Classification System, Vertisols fall under the A-7-5 and A-7-6 classes with group index values varying from 13 to 20 and they classify as bad clays [81]. They are inorganic clays of low to very high plasticity [27,31,65,82]. Their permeability varies from <0.02 to 0.2 cm/hour (slow to very slow) [47].

Table 3. Geotechnical properties of some Vertisols in the world [28,65].

Country	Particle size grading			SG	Atterberg limits			A	SL	GI	Cc	Wn	Ic (dry)	CBR	Class	MDD ($kg\ m^{-2}$)	OMC (%)	Free
	Sand	silt	clay		LL	PL	PI								(AASHTO)			swell
Cameroon	10.84	26.66	62.5	2.5	37	13	24	0.38	10	14	0.098	20.44	0.69	4.79	A-7-5	2350	11.9	60
	6.3	25	70	2.6	36	11	25	0.36	9	15	0.105	20.94	0.6	4.72	A-7-5	1990	10.1	65
	6.5	17	72.5	2.6	42	16	26	0.36	11	15	0.112	21.44	0.79	3.89	A-7-5	2910	14.7	75
	7.5	18.86	75	2.6	39	10	29	0.39	8	16	0.133	22.93	0.55	3.76	A-7-5	1810	9.2	80
	10.7	22.5	68	2.5	39	16	23	0.34	12	10	0.091	19.94	0.83	4.74	A-7-5	2910	14.7	70
	11.95	16.03	72	2.6	43	15	28	0.39	9	11	0.126	22.44	0.73	3.53	A-7-5	2730	13.8	75
	6.4	20	75	2.6	46	13	33	0.44	9	11	0.161	24.93	0.64	2.8	A-7-5	2370	12	85
India	6	54	40	2.6	82	35	47	1.2	10	16	0.259	31.91	1.07	1.1	A-7-6	1290	35	73
	2	37	61	2.6	86	32	54	0.88	ud	16	0.308	35.4	0.94	0.92	A-7-6	1400	36.3	132
	11	28	61	2.7	77	31	46	0.75	10	18	0.252	31.41	0.99	1.2	A-7-6	1410	30	80
Honduras	2	23	75	2.64	126	58	68	0.9	25	16	0.406	42.38	1.23	0.5	A-7-5	1478	53.4	ud
Rhodesia	34	11	55	2.6	72	24	48	0.66	11	15	0.266	32.41	0.82	1.23	A-7-6	1570	22.1	ud
Ghana	20	18	62	2.4	92	30	62	1	ud	16	0.364	39.39	0.85	0.75	A-7-6	1680	19.48	140
	38.3	15.2	46.5	2.3	75	26.5	48.5	1.04	ud	17	0.2695	32.66	0.87	1.17	A-7-6	1820	17.54	73
Nigeria	13	15	73	2.34	62.3	24.2	38.1	0.53	18.6	19	0.1967	27.47	0.91	1.79	A-7-6	1710	18	76.25
	20	5	75	2.66	65	19	46	0.61	13	18	0.252	31.41	0.73	1.42	A-7-6	1630	19.2	70
Chad basin	10	20	70	ud	58	16	42	0.6	12	19	0.224	29.42	0.68	1.74	A-7-6	2970	20.2	70
	14	34	52	ud	56	30	26	0.5	15	22	0.112	21.44	1.33	2.92	A-7-6	2162	13	55
Tanzania	19	31	48	ud	60	30	30	0.63	ud	21	0.14	23.43	1.22	2.36	A-7-6	1730	18.7	65
	6	34	60	ud	80	35	45	0.75	ud	18	0.245	30.91	1.09	1.18	A-7-5	1400	28.5	220
Australia	11	22	67	2.83	88	34	54	0.81	22	16	0.308	35.4	0.97	0.89	A-7-6	1538	21	ud
	1	29	70	2.87	100	27	73	1.04	23	16	0.441	44.87	0.76	0.58	A-7-6	1514	29	ud
Ethiopia	4	38	56	ud	109	28	81	1.45	14	16	0.497	48.86	0.74	0.48	A-7-6	1485	28	88
Zambia	14	35	51	2.58	49	16	33	0.65	16	21	0.161	24.93	0.73	2.63	A-7-5	1802	16	57
	30	20	50	2.61	50	17	33	0.66	15	21	0.161	24.93	0.76	2.58	A-7-6	2120	15.6	58

SG: specific gravity; LL: Liquid limit; PL: plastic limit; PI: plasticity index; A: activity; SL: shrinkage limit; GI: group index; A: activity; SL: shrinkage limit; GI: group index; Cc: compression index; MDD: maximum dry density; optimum moisture content; ASTM: American Society for Testing Minerals; AASHTO: American Association for Highway and Transport Officials; Wn: natural water content; Ic: consistency index; uf: unfound data.

Table 4. Correlation coefficients (r) amongst different mechanical properties of Vertisols [28,29,65] (n=25)

	Sand	silt	clay	SG	LL	PL	PI	A	SL	GI	Cc	Wn	Ic(dry)	CBR	MDD	OMC	FS
sand	1.00																
Silt	-0.48**	1.00															
clay	-0.45*	-0.56**	1.00														
SG	-0.44*	0.12	0.28*	1.00													
LL	-0.17	0.26*	-0.13	0.32*	1.00												
PL	-0.15	0.34*	-0.22	0.11	0.86**	1.00											
PI	-0.15	0.17	-0.04	0.42*	0.94**	0.64**	1.00										
A	-0.02	0.46**	-0.46**	0.23	0.85**	0.62**	0.88**	1.00									
SL	0.04	-0.01	0.00	0.16	0.59**	0.61**	0.50**	0.38*	1.00								
GI	0.27*	0.19	-0.46**	-0.28*	0.13	0.23	0.05	0.19	0.33*	1.00							
Cc	-0.15	0.17	-0.04	0.42*	0.94**	0.64**	0.99**	0.88**	0.99**	0.05	1.00						
Wn	-0.15	0.17	-0.04	0.42*	0.94**	0.64**	0.99**	0.88**	0.50**	0.40*	0.99**	1.00					
Ic(dry)	-0.01	0.40*	-0.41*	-0.23	0.46**	0.80**	0.16	0.27*	0.43*	0.06	0.16	0.16	1.00				
CBR	-0.06	-0.16	0.22	-0.24	-0.89**	-0.72**	-0.87**	-0.87**	-0.50**	-0.31	-0.87**	-0.87**	-0.39*	1.00			
MDD	0.01	-0.35*	0.33*	-0.32*	-0.69**	-0.62**	-0.63**	-0.66**	-0.34*	-0.64**	-0.63**	-0.63**	-0.37*	0.71**	1.00		
OMC	-0.33*	0.38*	-0.09	0.34*	0.86**	0.87**	0.72**	0.65**	0.45*	0.07	0.72**	0.72**	0.53**	-0.72**	-0.58**	1.00	
FS	-0.17	0.08	0.08	0.39*	0.43*	0.39*	0.40*	0.28*	0.22	-0.09	0.40*	0.40*	0.21	-0.45*	-0.40*	0.28*	1.00

G: specific gravity; LL: Liquid limit; PL: plastic limit; PI: plasticity index; A: activity; SL: shrinkage limit; GI: group index; A: activity; SL: shrinkage limit; GI: group index; Cc: compression index; MDD: maximum dry density; optimum moisture content; ASTM: American Society for Testing Minerals; AASHTO: American Agency for Highway and Transport Officials; Wn: natural water content; Ic: consistency index; FS: free swell; **Significant at the 0.01 level; *Significant at the 0.05 level.

6.7. Spatial Variability of Vertisols properties

Understanding Vertisols spatial variability is necessary for the adoption of right soil management practices and soil quality monitoring [34]. This situation is complicated in Vertisols due to the changes in soil properties (morphology, physico-chemistry, hydrology, mechanics and mineralogy) in different parts of the soil as a function of depth and surface microvariability (Table 5). The spatial variability of Vertisols has been addressed by many authors such as [28,41,44,70,72,83,84,85,86,87,88,89,90]. The understanding of the pedogenic behaviour of Vertisols demonstrates the importance of verifying spatial variability in physical, chemical and biological properties over short lateral distances. If a pedon is defined as a short constant area sampling unit, then Vertisol mapping and classification will be based on distribution and composition of contrasting soils within the gilgai cycle [91,92]. In many cases, a complex of two or three soils of different taxa would correspond to different gilgai elements such as microhighs, intermediate (or slope) and microlow. The spatial variability of Vertisols properties in small farm holdings occurs at small scale less than a hectare [27,44,89,90]. Variogram models plotted for Vertisols show various patterns: Spherical and the Gaussian models in some northern Nigerian [93]. In Garoua (north Cameroon), most Vertisol characteristics on sorghum are best fitted by a "pure nugget effect" model, while those under natural savannah in the same zone are linear and spherical with strong grade of spatial dependence [45].

Table 5. Relationship between microlows and microhighs of gilgai microrelief [91]

No	Property	Microlow	Trend	Microhigh
1	Surface thickness	thicker	+	thinner
2	Solumn thickness	thicker		Thinner
3	colour	darker		Lighter
4	Structure A	Finer size		Coarse size
5	Structure Bss	Stronger grade		Weaker grade
6	Consistency	Very firm		Extremely firm
7	Slickenside expression	Greater	++	fewer
8	Slickenside orientation	Anticlinal		Synclinal
9	Carbonate leaching depth	Greater		Lower
10	Hard nodules and concretions	Greater		Fewer
11	Soft masses	Fewer		Greater
12	Cracking expression (width and depth)	Higher/last to open	+	Lower/fewer to open
13	External water movement	Run on	++	Run off
14	Internal water movement	Lower		higher
15	Moisture content	Higher		Lower
16	Clay content	Higher	++	Lower
17	Specific surface area (m^2/g)	Higher	++	lower
18	COLE ($cm\ cm^{-1}$)	Higher		Lower
19	Cohesive strength	Lower		Higher
20	Plasticity index	Higher		Lower
21	Shrinkage limit	Higher		Lower
22	Organic carbon (%)	Higher	+	Lower
23	Total nitrogen (%)	higher	++	Lower
24	pH	Lower	++	Higher
25	Exchangeable bases (me/100g)	Lower		Higher
26	Carbonates (%)	Lower		Higher
27	Available K, Fe and Zn	Higher		lower
28	Electrical conductivity ($\mu S/m^{-1}$)	Higher	++	Lower
29	Exchangeable sodium percentage (%)	Higher	++	Lower

+: common trend reported in literature; ++: reverse trends have also been reported.

6.8. Genesis of Vertisols

The genesis of Vertisols involves two stages [10,37,49,62]: formation of smectite-rich parent material and the formation of a vertic horizon. The basics for smectite formation are enough rainfall to enable weathering, a well marked dry season to allow crystallization of clay minerals that form upon weathering, low drainage to avoid leaching of weathering products and finally high temperatures to speed up chemical weathering. Under such conditions smectite clays can be formed in the presence of Si and basic cations, if soil pH is above neutral. The formation of a vertic horizon, principal genetic process in Vertisols, has been expressed by two common models: the shear failure model proposed by [91] and the self-swallowing model as described by [92]. A Schematic representation of the mode of formation of slickensides and gilgai microrelief (Figure 5) was documented by [94]. Figure 6 summarizes the environmental conditions and characteristics of Vertisols as slightly modified by [28] from [95].

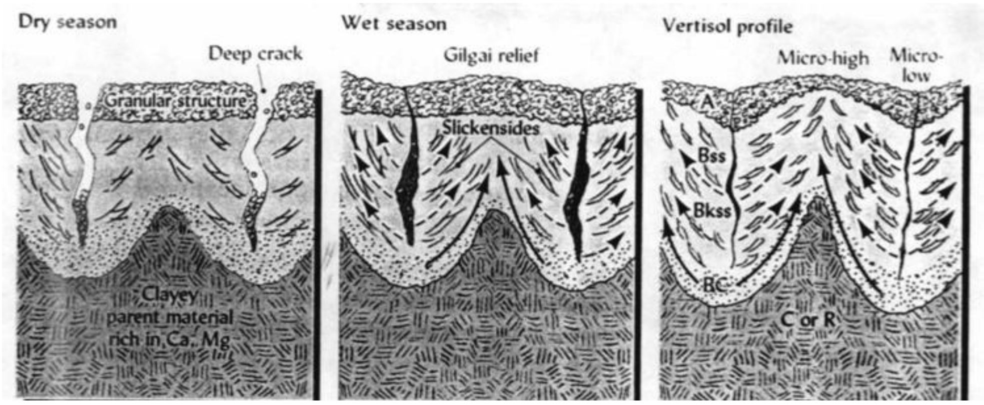


Figure 5. Schematic model of slickensides and gilgai microrelief based on [94]

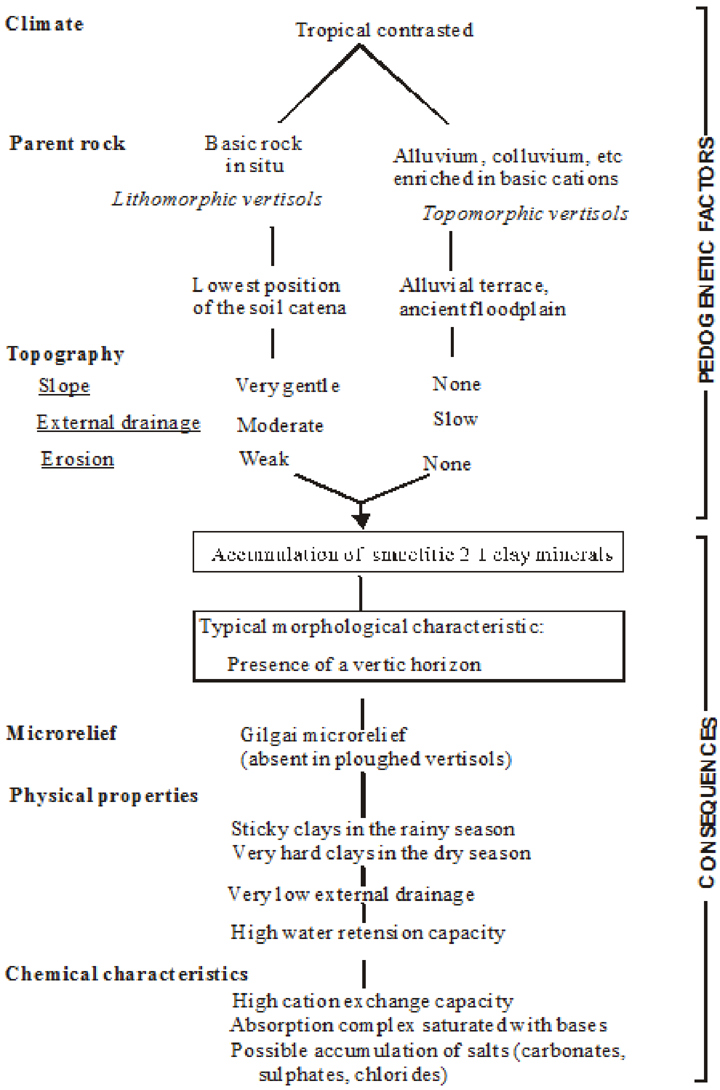


Figure 6. Environmental factors and properties of Vertisols as modified from [95]

7. Management of Vertisols

Vertisols form a great agricultural potential but adapted management is a necessity for sustained production [34,70]. The comparatively good chemical fertility and occurrence in extensive plains where reclamation and mechanical cultivation can be envisaged are assets of Vertisols [34,96]. Their physical characteristics and notably their difficult water management constitute a limitation to agricultural activities. The susceptibility of Vertisols to waterlogging is the single most important factor that reduces the actual growing period. The agricultural use of Vertisols ranges from very extensive (grazing, collection of fire wood, charcoal burning) through smallholder post-rainy season crop production (millet, sorghum, cotton, chick peas) to small-scale (rice) and large-scale irrigated agriculture (cotton, wheat, barley, sorghum, chickpeas and sugar cane) [26]. Cotton is known to perform well on Vertisols because cotton has a vertical root system that is not severely damaged by cracking of the soil Tree crops are generally less successful because tree roots find it difficult to establish themselves in the subsoil and are damaged as the soil shrinks and swells. Management practices for crop production are primarily directed at water control in combination with conservation or improvement of the soil's fertility level notably cationic balance [97]. Tillage is hindered by stickiness when the soil is wet and hardness when it is dry. Excess water during the rainy season must be stored for post-rainy season use ('water harvesting') on Vertisols with very slow infiltration rates. Thus, several management practises have been devised to improve the water regime. Some of these techniques include the evacuation of excess surface water [32], Gully control [11], storage of excess water within the watershed [71] and water harvesting in areas with Vertisols [27,98]. One of the traditional methods practiced for overcoming the waterlogging problem is planting crops late in the season after the excess water has naturally drained away to grow on the residual moisture. The varieties of these crops like wheat, chickpea, rough pea etc have a short growing period of not more than three months. Salinity in Vertisols may be inherited from the parent material or may be caused by irrigation. Leaching of excess salt is hardly possible. It is, however, possible to flush salts that have precipitated on the walls of cracks. Surface leaching of salts from rice paddies in India was achieved by evacuating the standing water at regular intervals. The fallow year observed in rotations in the Gezira/Manaqil (Sudan) irrigation scheme, is crucial for maintaining low salinity level in the Vertisols. Other techniques exist to improve rooting conditions and to maintain the nutrient status of Vertisols [34]. On the engineering point of view, man-made structures as houses, roads, electric poles and others on Vertisols are not advisable since large investments could be needed for maintenance and repair of damaged infrastructure [25]. The changes in the environment around the constructed structure result to negative pore water pressure which in turn produce volume changes in the soil. Krohn and Slossen [99] estimated that 7 billion US Dollars are spent each year in the USA due to damage to structures built on swelling clays. More than twice as much money is spent on damage due to swelling soils than on damage from floods, hurricanes, tornadoes and earthquakes [100,101].

8. Vertisol Management Experience in North Cameroon

In Cameroon, Vertisols occur in the North precisely in the sudano-sahelian zone [12,13,27,28, 33,43,71,102-106]. The detailed characteristics are reported by these authors. The vertisols here include the topomorphic and lithorphic Vertisols. Both cover a total surface area of 1200 000 ha, specifically in the the Diamare, Kaele, Logone and Shari plains and the Benue plains [43,102,108]. However, the lithomorphic Vertisols are more localized and form on calco-alkaline granites, embrechites and upland schists in north Cameroon [13,109].

8.1. Indigenous Knowledge on Vertisol Management in North Cameroon

In North Cameroon, indigenous knowledge about the physical environment is often very wide and many farmers have developed traditional calendars for scheduling of agricultural activities [110]. Many farmers sow according to the phases of the moon, believing that there are lunar phases of rainfall. They also cope with climatic seasonality using weather indicators based on the phenology of the local vegetation [111]. Soil types, degrees of soil fertility and land-use categories are discriminated in detail, usually by colour, texture, smell and sometimes by taste. For instance, farmers in north Cameroon distinguish different types of Vertisols (harde, karal, yaeres,...) according to [112]. The soils are mainly ranked according to agricultural potential and used in both land-value evaluations and rural census. Confronted with specific problems (slope, flooding, drought, pests, diseases, soil fertility decline, etc.), small farmers have developed numerous indigenous management systems aimed at overcoming these constraints. The strength of rural people's knowledge is based on acute observations, trial and error and experimental learning. The experimental approach is very apparent in the selection of seed varieties for specific environments, but it is also implicit in testing of new farming methods to overcome specific biological or socioeconomic constraints.

Traditionally, some tree species are preserved when savannas or forests are cleared up, resulting in park savannas, agro-forests or home garden. Living hedges are locally used to border farmsteads, protect gardens from livestock, and produce forage and fire-wood. On the Mandara Mountains, where the population density is high, agro-forests and multi-story gardens are numerous around the dwellings.

The traditional long fallow is very efficient in restoring biological, chemical and physical properties of the topsoil, but it is often no longer possible to wait 10–50 years between two cropping cycles, due to population pressure. Expanding cropped areas is difficult in many parts of north Cameroon, where often less than 30 % of the land surface is suitable for cropping [107]. Contour ploughing is a common practise to slow the speed of rainwater and to check soil erosion.

Walls are usually constructed at the upper course of the streams and the aim is to slow the speed of water before it reaches the lowlands so as to reduce its erosive power.

In some areas farmers construct microcatchments to collect and store water as well as to increase infiltration rate.

The modification of the planting calendar and the adaptation of sorghum to dry-season (Muskwari) is aimed at overcoming the prolong drought. Farming activities are organised based on the two seasons of the year: rain-fed agriculture from July to September, and irrigated farming from October to Match.

8.2. Innovations in Farming Techniques

Vertisols are found in the third agro-ecological zone of Cameroon [113]. The annual rainfall of varies between 600 and 1400 mm; a continuous dry season lasting 6 to 9 months alternates with a rainy season that fluctuates from year to year. Cameroon has a total surface area of 475.000 km^2. Vertisols cover 1200000 ha (2.5% of the total country and 12% of North Cameroon). The changes in cropping systems reveal both intensification to increase Vertisol productivity and extensive practices. The fight against bushfires, improvement of burning, resort to other sources of fuel (cow dung, farm residues, etc) and even the use of herbicide are aimed firstly at improving productivity [112]. With the twin objective of increasing areas and reducing risks, farmers use the heterogeneity of the environments farmed by seeking to use different types of vertisols (karal, hardes, yaeres, etc). However, landholding distribution is very unequal from one farmer to another. The land is closed to livestock from the end of July onwards to limit soil compaction soil moisture absorption. Livestock benefits only from the first herbaceous regrowth at the beginning of the rainy season. Sorghum stems are often stored after the harvest and form an important dry-season forage resource, partially making up for the decrease in grazing land and ligneous forage. The typical Vertisols are now used to a great extent and new vertisol lands mainly consist of more or less vertic land, requiring the adaptation of cultural techniques. Use of harde requires development for muskwari. Farmers build and maintain a close network of small ridges forming enclosures so that rainwater is retained and infiltration increased. After three or four years, the karal/harde recovers Vertisol characteristics (shrinkage cracks, microrelief, etc.) and production is comparable to that on the other Vertisols. The technique improves the water balance and has strongly contributed to improving the productivity of vertisols.

Manual weeding is performed immediately after the first rains to control ligneous plants and certain weeds that hinder soil moisture absorption. The farmers encourage the growth of annual gramineae that are easily scythe and burn fiercely, limiting regrowth of tough plants during the cropping cycle [112]. The recent introduction of herbicides in crop management has fostered weed control and reduced karal preparation time [106]. Herbicide is already enabling the use of kare infested by perennial weeds (wild rice with rhizomes, *Cyperus*, etc.).

The dissemination of innovations has been by the circulation of information and collective learning in a rural society over a period of several decades. However, the process is not homogeneous among communities. In the foothills zones where muskwari is fairly recent, farmers are still learning and seem more innovative than in traditional replanted sorghum zones. They are more open to accepting new techniques and local varieties from other regions.

Terracing is one of the best soil conservation methods, where cultivation is done on a terrace levelled section of land. Here, farming is done in a unique step-like structure and the possibility of surface runoff is stalled.

Burning is often the only way for poor farmers to clear the land, decrease the pressure of pests, and increase available phosphorus and exchangeable cations [107]. It is a common traditional strategy for clearing large areas for grazing and cropping. Generally, burning the hill slopes permits to transfer nutrients to lowlands for irrigated rice.

Crop residue management involves sorghum stalk and sometimes bean and groundnut residues which are the common crop residues found in most farms in North Cameroon. The amount of sorghum stalk available on the farm after crop harvest is high but the quality is low both in terms of nutrient content and decomposition rates. For example, one ton of sorghum stalk contains about 7 kg of nitrogen, 1 kg of phosphorus and 8 kg of potassium and not all these nutrients are available to the crop due to low decomposition. Besides sorghum stalk has other competing uses like house thatching, firewood and feed for animals. Bean residues are usually carried to homesteads together with the pods in the harvesting process, but the quantities are very small to meet crop nutrient demands among other uses like animal feed.

The manure from livestock is spread on the fields or concentrated in home-gardens in addition to compost. Compost is ‘the manure of poor farmers’ who possess no livestock. Correctly applied, compost can improve locally soil organic matter and fertility. Moreover, manure and compost are often sold for high-value vegetable production in the lowlands during the dry season. Compost may thus maintain soil fertility, but is difficult to obtain in sufficient amount.

8.3. Support Services Managed by Farmers' Organisations

A land management programme initiated by the DPGT (Développement Paysannal et Gestion des Terroirs) project designed responses to weed problems. The references assembled on these technical problems are disseminated within the framework of advisory systems managed by farmers' organisations. The interventions of APROSTOCs (Associations de Producteurs et de Stockeurs de Céréales) are gradually acquiring a network of farmer advisers who support the improvement of muskwari sorghum growing. These services are based on informal networks for the dissemination of information in order to make the best use of farmers' know-how and to achieve greater effectiveness in technology transfers. The farmer advisers are members of the rural communities in which they operate. They call upon farmers who are recognised and influential in village societies to help with training workshops and test technical improvements.

8.4. Land Use Patterns in north Cameroon

A number of activities often converge on Vertisol farmlands in North Cameroon (agriculture, cattle-rearing, fishing, etc) [28,43]). However, exploited land surfaces have strict time delimitation, but very little spatial delimitation and cattle move freely into farmland at post-harvest, even though there is no formal association between farmers and grazers often leading to farmer-grazer conflicts [106,115,116]. The impact of large cattle herds is harmful to soils since animals destroy soil structure and the vegetation cover. The low yields are often not a direct reflection of the soil quality, but rather that of the farming techniques such as the use of simple tools, manual labour and zero-irrigation. The principal crop grown on vertisols is dry season sorghum (muskwari), whose planting date is around mid-December. Specifically in the Benue valley, the early sorghum is frequent on the raised sandy beaches where its survival depends solely on soil moisture and infiltration from the Benue river channel. Sorghum is also cultivated using rainwater trapped by man-made catchments as in Garoua, Pitoa, Guebake, Langui Be, Yagoua, etc. Rice cultivation is mainly irrigated on Vertisols. Fluvial rice cultivation is limited to the border of the main river channels on leached vertic glei soils where the plant water supply is derived from perched water table. Corn, sweet potatoes and groundnuts are rare in the floodplain and grow on glei soils of the well-drained slopes of the sandstone inselbergs. Groundnut is mildly cultivated on leached vertic gley soils of the ancient terrace. Cotton is cultivated under the same conditions as corn. Small quantities of beans, tomatoes and diverse fruits are cultivated on the sandy beaches. In North Cameroon, there is an underexploitation of land resources mainly due to the small size nature of most farms cultivated and the relatively limited types of crops cultivated on Vertisols. Moreover, the simple nature of farm techniques limits the expansion of cultivated surfaces, but locally high yields with more elaborated farming habits is clear evidence of the possibility of increasing yields by increasing surface areas and types of crops, even with traditional farm techniques.

9. Conclusions

The aim of this paper was to highlight the characteristics, genesis and best management strategies of Vertisols. Two main types of Vertisols can be distinguished: lithomorphic Vertisols and topomorphic Vertisols. Lithomorphic Vertisols are developed on various parent rocks whose weathering generates base-rich environments favourable for smectite synthesis, while topomorphic Vertisols formation is favoured by low landscape positions favourable for accumulation of basic cations, mainly in tropical, semi-arid to (sub) humid and Mediterranean climates with an alternation of distinct wet and dry seasons. The latter cover very extensive surface areas of the globe, while the former have limited geographical extensions and occur mainly in specific islands and volcanic regions. Vertisols are characterized by at least 30 % clay fraction, abundance of smectitic swelling clay minerals, a high cation exchange capacity and a high base saturation (>80%). Swelling and shrinking upon wetting and drying is the major characteristic of these soils on which depend most of the other properties. Based on their smectite content, these soils present numerous interesting uses in many industrial domains including agriculture, ceramics and other engineering purposes. Nevertheless, man-made structures on Vertisols are not advisable since large investments are needed to maintain and repair damaged infrastructure. In North Cameroon, Vertisols occur in the sudano-sahelian zone covering a surface area of about 1200 000 hectares. Specific constraints (slope, flooding, drought, pests, diseases, soil fertility decline, etc) have led to several innovative management strategies (water control, terracing, contour ploughing, composting, etc).

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Conflict of Interests

The Authors declare that this article content has no conflict of interests.

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