Characterisation, classification and suitability assessment of soils formed in granite and gneiss in humid area of southwestern Nigeria for cacao (*Theobroma cacao*) production

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The study characterised and classified soils derived from coarse-grained granite and gneiss and assessed their suitability for cacao production. Four soil profile pits were established along a toposequence underlain by coarse-grained granite and gneiss and described following the FAO/UNESCO guidelines for soil profile description. Soil samples were collected from 18 identified genetic horizons of the profile pits and were subjected to routine physical and chemical characteristics determination. Land characteristics recognised on the field were combined with those determined in the laboratory to provide the land qualities in the study area. The land qualities obtained were matched with cacao requirements to obtain the soils' suitability classes. Suitability classes obtained were combined to produce aggregate soil suitability classes using the parametric approach. Results indicated that the soils are deep, well-drained, dark brown to reddish yellow in colour, varying from sandy-clay-loam to clay. The silt/clay ratio of the soils was > 0.15 indicative of young soils with high degree of weathering potential. The soils were strongly acidic, highly leached with low to moderate nutrients content. Soil organic carbon content and total nitrogen varied from low to high, ranging from 0.08 – 1.64% and 0.01 – 0.14%, respectively with low to medium available phosphorus. The high base saturation of greater than 50% by NH_4OAc placed all the pedons in the order Alfisols (USDA Soil Taxonomy) and correlate as Lixisol (FAO/UNESCO). All the pedons had kandic subsoil with ustic moisture regime and isohyperthermic temperature. The soils were presently marginally suitable (S3) but potentially highly suitable (S1) for cacao production. Their major limitation to cacao production was low fertility (high soil acidity, low organic matter, Ca and Mg contents). The productive potential of the soil for cacao production could be enhanced through the application of appropriate fertilisers.

Keywords: Suitability assessment, granite and gneiss, cacao production

Cacao (*Theobroma cacao*) is a major economic crop in Nigeria; however, inadequate knowledge of the soils is a limitation to its optimum production. In central southwestern Nigeria, cacao makes the most significant contribution to exports amidst the grown cash crops. It contributes extensively to the national economy in terms of employment and foreign exchange earnings. Akinwale (2006) reported that Nigeria was a leading exporter of cocoa and the second largest producer in the world, earning over US$20 million annually as foreign exchange from the export of cacao beans, besides revenue from cocoa by-products such as butter, cake, liquor and powder. The country has, however, lost its status as chief exporter of cocoa to Cote D'Ivoire and Ghana (IITA 2008). Lack of detailed information on soils and land characteristics of cacao growing areas is one of the key factors restraining optimal cacao production in Nigeria (Fasina et al. 2007). This is especially true of soils formed on granite and related parent materials in southwestern Nigeria. Soil characterisation provides facts for the understanding of the physical, chemical, mineralogical and microbiological properties of the soils to produce crops, support forests and grasslands as well as sustain homes and society structures (Ogunkunle 2004). Contemporary agriculture necessitates that farmers have some information on the potential and nutrients status of soils they intend to use. This has given rise to the need for land suitability assessment (LSA) prior to crop cultivation and other agricultural land uses. Basically, LSA encompasses accounting for the features of the

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land and matching them with the crop requirements in order to develop the land - crop production suitability index in a spatially explicit manner.

Cacao is important to Nigeria's economy, however, there is presently lack of a land evaluation system that provides information on the potential of land resources of different areas for the crop. Therefore, information on land suitability for cacao production is necessary to enhance the current yield of the crop and reinstate the country to its earlier position. The information will also be useful to areas with similar soils and geography. Information on soil suitability evaluation for cacao production is lacking at the Teaching and Research Farm of the Obafemi Awolowo University. The objectives of this study were to characterise and classify soils derived from coarse-grained granite and gneiss and assess their suitability for cacao production. The soils formed in coarse-grained granite and gneiss are widespread, account for about 40% of the total soil types found in humid area of southwestern Nigeria and are readily available to farmers for agricultural production.

Materials and methods

The study area

The study was carried out at the Teaching and Research Farm (T&RF), Obafemi Awolowo University, Ife Central Local Government Area of Osun State, Nigeria (Figure 1). The T&RF is situated within the humid tropical rain forest zone and lies between latitudes 7^o 32′ and 7^o 35′ N and longitudes 4^o 32′ and 4^o 40′ E, about 200 m above sea level (Ojetade et al. 2016). The area experiences about 8 months of annual rainfall (March – October) that is bimodal in distribution pattern with peaks in June/July and September/October (Fawole et al. 2016). Total annual rainfall is about 1500 mm (NASA 2019) and mean monthly air temperature is approximately 31^{o}C (Fawole et al. 2016).

Vegetation and land use/cropping history

The native vegetation of the area is rainforest characterised by tall trees and thick shrubs (Fawole et al. 2016). However, as a result of anthropogenic impacts, the native vegetation has given way to various forms of arable crop cultivation. At the time of field investigation, there was a mosaic of farmland growing water melon, maize and cassava as well as secondary forest regrowth. History had it that no form of soil amendment (fertiliser, manure or lime) had been used on the soils. The weed control was mainly through manual weeding with cutlasses and hoes.

Soil sampling and sample collection

A transect underlain by coarse-grained granite and gneiss was carefully identified and selected, using the existing soil information on central southwest Nigeria (Smyth and Montgomery 1962). Four soil profile pits were established along a transect underlaid by coarse-grained granite and gneiss. The profile pits (about 80 m spacing between pits) were described following the FAO (2006) guidelines for soil profile description. Soil samples were collected from 18 identified genetic horizons of the profile pits. A multiple subsampling method (Smeck and Wilding, 1980) was employed to ensure representativeness of the samples collected from a given horizon, starting from the lowest horizon to the uppermost, in order to prevent cross-contamination of soil samples. Soil samples collected were air-dried, crushed gently in ceramic mortal and passed through a 2 mm sieve to separate materials larger than 2 mm. The less than 2 mm fractions were retained for laboratory analyses.

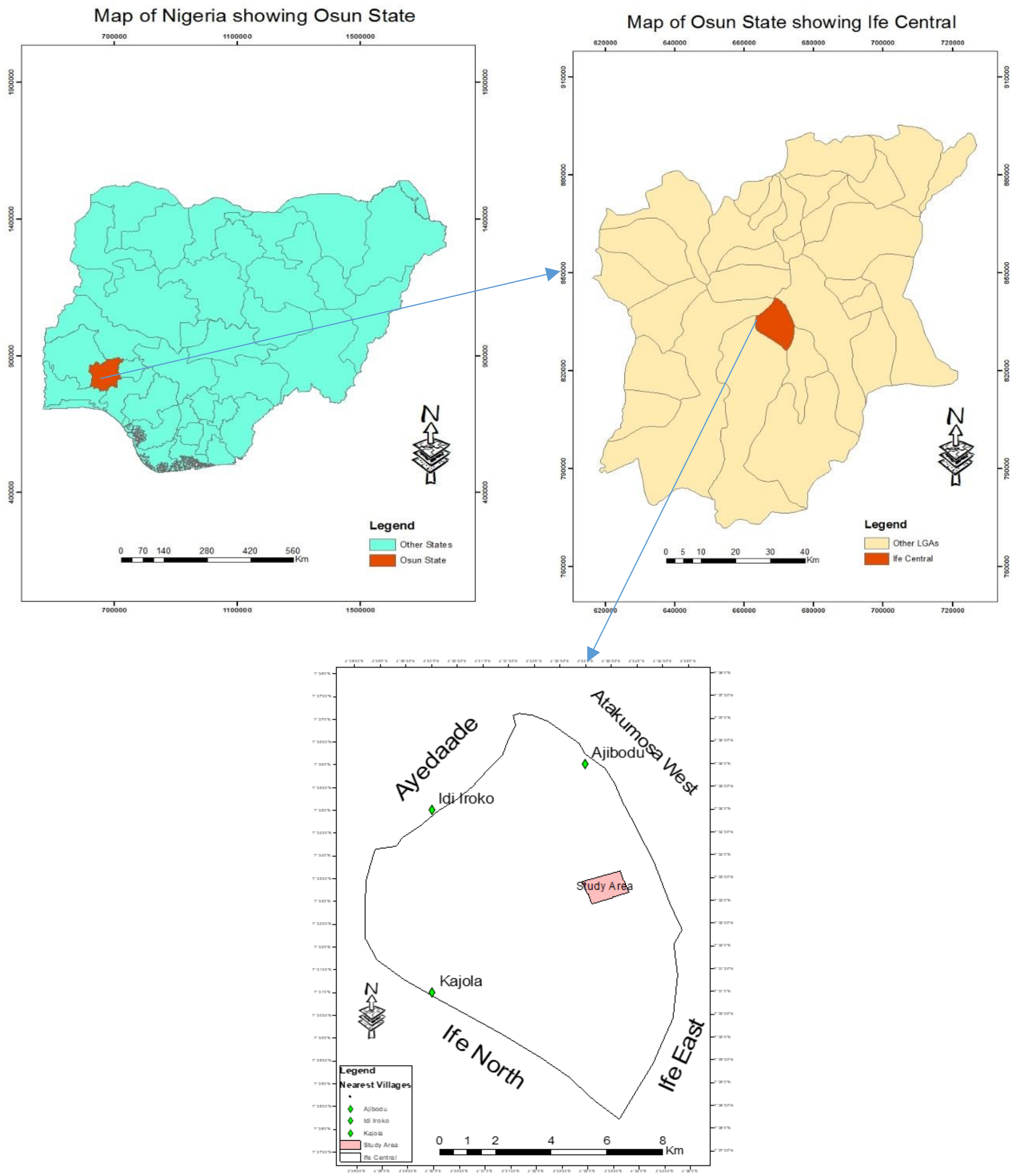

Figure 1: Location map of the study area

Soil sample and statistical analyses

Particle size distribution analysis was carried out using the hydrometer method (Gee and Or 2002), while the soil pH was determined in distilled water and 1.0 M KCl (Thomas 1996). Organic carbon was determined by chromic acid digestion (Darrell et al. 1994), available phosphorus by the Bray-1 method (Kuo 1996) and total nitrogen using the micro-Kjeldahl digestion method (Bremner 1996). Exchangeable cations were extracted with 1.0 M NH_4OAc solution at pH 7. Magnesium and Ca were determined by atomic absorption spectroscopy, K and Na by a flame photometer (Thomas 1982; Jones 1998). Cation exchange capacity was determined by 1.0 M ammonium acetate (NH_4OAc) at pH 7 (Sumner and Miller 1996). Exchangeable acidity was also determined (McLean 1965). Suitability of the soils for cacao production was assessed using the parametric method (Sys et al. 1993; FAO 2006). Land characteristics recognised on the field were combined with those determined in the laboratory to make the preferred land qualities which were used as basis for the land assessment. A numerical rating of the land characteristics in a normal scale from a maximum (normally 100) to a minimum value (20) was employed. If a land characteristic was optimal for the considered land utilisation type, the maximal rating of 100 was attributed; if the land characteristic was unfavourable, a minimal rating of 20 was applied (Sys et al. 1993). A land index was calculated from the individual ratings using the square root method:

$$I = A \times \sqrt{\frac{B}{100} \times \frac{C}{100} \times \cdots \times \frac{F}{100}}$$

where:

I = land index
A = overall lowest characteristic rating
B, C…F = lowest characteristic ratings for each land quality group (Udoh et al. 2006).

Soil classification was carried out using the morphological, physical and chemical properties of the pedons, following the guidelines in USDA Soil Taxonomy (Soil Survey Staff 2014) and IUSS Working Group WRB (2015) systems of soil classification.

Results and discussion

Characteristics of the soils

The summary of the morphological characteristics of the soils identified at different positions along the toposequence is presented in Table 1. The soils are underlain by coarse-grained granite and gneiss rocks and are indispensable to farmers in central southwestern Nigeria (Elueze 1982; Smyth and Montgomery 1962). These rock types are widespread, and soils formed in them are readily accessible for cultivation in the region. The colour of the soils changed in response to changes in slope position and drainage conditions. According to Gerrard (1981), the change in soil colour could be ascribed to variation in the physiographic positions of the soil profile pits and drainage condition of the soils. The colour of the soils varied from 10YR 5/3 to 7.5YR 3/2 at the upper soil layer (surface horizons) to reddish yellow (5YR 6/8) in the subsoil. The colour of the soils became lighter with soil depth. The bright sub-surface soil colour is indicative of good internal drainage (Amusan 1991), while Olayinka (2009) noted that the dark colour of the surface horizons compared to the sub-soil could be attributed to decomposition and mineralisation of organic material deposits from litter.

The structure of the soils ranged from weak fine crumb in the surface soils to strong angular blocky in the sub subsoil. There were some few patchy cutans within 54 – 186 cm soil depth. There were some common red (2.5 YR 5/8) mottles within 85 – 127 cm soil depth at the lower slope position. Roots concentration was common in the surface horizons of all the pedons examined and decreased with soil depth. Boundaries between A and B horizons were clear as a result of the dark colour impacted on the surface horizons by the soil organic matter (Driessen et al. 2001). The soil consistence (wet) varied from slightly sticky to sticky and slightly plastic to plastic in the surface and sub-surface horizons, respectively.

Table 1: Morphological characteristics of the soils

Horizon	Depth (cm)	Colour (moist)	Texture[a]	Structure[b]	Consistence[c] (moist/wet)	Boundary[d]	Other features
Pedon 1 (Mid slope): typic isohyperthermic kandiustalf (*Iwo Series*)							
A	0-22	10YR 5/3	ngsl	2fcr	mvfrwnstspl	cw	few coarse, few fine roots and frequent gravel angular nodules
AB	22-41	7.5YR 4/6	grscl	2mcr	mfrwsstspl	cs	very few coarse, very few very fine roots
B2	41-68	2.5YR 5/8	grscl	2mcr	mfrwsstspl	cw	very few, very fine, very few coarse roots
BC1	68-97	7.5YR 6/8	grcl	2msbk	mfmwstpl	dw	very few coarse roots
BC2	97-148	5YR 6/8	ngscl	2msbk	mfmstpl	ND	-
Pedon 2 (Mid slope): typic isohyperthermic kandiustalf (*Iwo Series*)							
A	0-12	7.5YR 3/2	ngsl	2vfcr	ml wnstnpl	sw	common fine, very fine and very few coarse roots
AB	12-37	7.5YR 4/3	ngsl	2mcr	mvfrwsstspl	ad	common fine, few very fine and coarse roots
Bt1	37-76	7.5YR 4/6	sgrscl	2fcr	mvfrwsstpl	cs	very few very fine, common fine and frequent coarse roots
Bt2	76-143	2.5YR 5/8	ngcl	2fcr	mfrwsstpl	cs	very few fine and few coarse roots
BC	143-200	7.5YR 6/8	ngcl	2mcr	mfrwstpl	ND	devoid of roots
Pedon 3 (Mid slope): typic isohyperthermic kandiustalf (*Iwo Series*)							
A	0-22	7.5 YR 3/1	grsl	1fcr	mvfrwnstnpl	aw	common very fine, fine, medium and coarse root
AB	22-54	5YR 5/6	grscl	2msbk	mfrwsplsst	cw	very few very fine and coarse roots
B2	54-88	2.5YR 4/6	sgrscl	2msbk	mfrwstpl	cw	few patchy cutans, very few fine, very fine and coarse roots
BC	88-186	2.5YR 5/6	sgrc	2msbk	mfmwvstpl	ND	few patchy cutans, very few coarse roots
Pedon 4 (lower slope): typic isohyperthermic kandiustalf (*Oba Series*)							
A	0-20	7.5YR 3/2	ngsl	1fcr	mfrwsstspl	aw	common very fine, medium and coarse roots
AB	20-30	5YR 4/4	grsc	2mcr	mfrwnstnpl	cw	few fine, very fine, coarse roots and common medium roots
B2	30-85	7.5YR 5/8	grsc	2mcr	mfrwstnpl	cw	few medium roots
BC	85-127	2.5YR 5/8	sgrc	3mabk	mvfmwstnpl	ND	common mottles

[a]Texture: ng = non gravelly, sgr = slightly gravelly, gr = gravelly, c = clay, sc = sandy clay, cl = clay loam, sl = sandy loam, scl = sandy clay loam;
[b]Structure: 1 = weak, 2 = moderate, 3 = strong, cr = crumb, sbk = subangular blocky, abk = angular blocky, vf = very fine, f = fine, m = medium;
[c]Consistence: m = moist, w = wet, vfr = very friable, fr = friable, fm = firm, vfm = very firm, nst = non sticky, sst = slightly sticky, vst = very sticky, st = sticky, npl = non plastic, spl = slightly plastic, pl = plastic, l = loose;
[d]Boundary: a = abrupt, c = clear, g = gradual, d = diffuse, s = smooth, w = wavy, ND = not determined.

Sand content ranged from 32 – 81% and decreased with soil depth. Surface horizons had more sand fraction than the subsurface horizons. Sand particles was the dominant fraction while silt content was least in all the horizons examined (Table 2). Amusan (1991) ascribed greater sand content in the surface horizons to the translocation of colloidal clay particles deep into the profile with percolating water, and selective erosion and transport of fine particles to the lower slope positions during heavy downpours. Sub-surface horizons had more clay fraction than the surface horizons. Texture varied from sandy-loam through sandy-clay-loam in the surface horizons to clay in the sub-surface horizons. Clay content increased with soil depth and ranged from 12 – 58%. Higher clay content noticed in the subsurface horizons in the pedons could be attributed to illuviation (Ojanuga 1975; Malagwi et al. 2000). Silt content was generally low ranging from 6 – 18%; there was no consistent pattern of distribution of silt content across the studied area. This was in agreement with the work of Okusami and Oyediran (1985) and Ojetade et al. (2014) who worked in similar environments in the Basement Complex area of southwestern Nigeria.

Though the water holding capacity of the soil was not assessed, soil texture and structure are good indices of water holding capacity of soils. Soil available water is the range between the field capacity and the permanent wilting point which is mainly influenced by the soil texture. Clayey soils retain more water, and longer, than sandy soils. The finer the texture is, the higher is the available water for plants use (Hillel 1971). The surface horizons of the soils are mainly sandy-clay-loam while the sub-surface horizons are clay. This is, potentially, an indication that the soils have reasonably good water holding capacity which will serve as an insurance against drought or moisture stress. The silt-clay ratio of the soils along the toposequence ranged from 0.10 - 0.70. Mbagwu et al. (1985) reported that the silt-clay ratio reflects the weathering stage of soil parent materials and also shows the erodibility potential of soils. According to Van Wambeke (1962), old parent materials generally have silt/clay ratios below 0.15 while silt/clay ratios above 0.15 are indicative of young parent materials. The result of this study showed that the greater part of the soils has a silt/clay ratio above 0.15 signifying that the soils are relatively young with a high degree of weathering potential. The silt/clay ratios were higher in the surface horizons and decreased with depth until the BC horizon, where they increased. The decrease of silt/clay ratio values with depth indicated that the subsoils were more weathered than surface horizons. This is in line with the findings of Fasina et al. (2015). The second weathering index, silt/(silt + clay) ratio ranged between 0.92 and 0.98. According to Stewart et al. (1970) and Azeez (1998), a silt/(silt + clay) ratio of 0.7 indicates moderate weathering, < 0.7 severe weathering and > 0.7 incipient weathering. Therefore, since the values were greater than 0.7, the soils have high degree of weathering potential.

The bulk density values ranged from 1.13 – 1.58 gcm^{-3} in the surface horizons and 1.33 – 1.75 gcm^{-3} in the sub-surface layers. Generally, the bulk density value increased with depth. The exemption to this trend was noticed in pedon 01 where the values fluctuated irregularly. Miller and Donahue (1990) reported that plants perform optimally in soils with bulk densities below 1.4 and 1.6 gcm^{-3} for clayey and sandy soils, respectively. Results of this study show that bulk density values of surface horizons were less than 1.6 gcm^{-3} which implied that the soils were not compacted. Therefore, there would be very little or no impedance to plant roots penetration and seedling emergence.

Table 2: Physical properties of the soils

Horizon	Depth (cm)	Sand	Silt (%)	Clay	Silt/Clay	Silt/(Silt +Clay)	BD* (g/cm^3)	TC*
Pedon 1 (Mid slope): typic isohyperthermic kandiustalf (*Iwo Series*)								
A	0-22	66	14	20	0.70	0.95	1.31	Sandy clay loam
AB	22-41	68	12	20	0.60	0.95	1.33	Sandy clay loam
B2	41-68	60	8	32	0.25	0.97	1.71	Sandy clay loam
BC1	68-97	36	10	54	0.19	0.98	1.33	clay
BC2	97-148	54	16	30	0.53	0.97	1.48	Sandy clay loam
Pedon 2 (Mid slope): typic isohyperthermic kandiustalf (*Iwo Series*)								
A	0-12	74	10	16	0.63	0.94	1.13	Sandy loam
AB	12-37	64	10	26	0.38	0.96	1.48	Sandy clay loam
Bt1	37-76	36	6	58	0.10	0.98	1.35	Cay
Bt2	76-143	40	8	52	0.15	0.98	1.56	Clay
BC	143-200	32	18	50	0.36	0.98	1.62	Clay
Pedon 3 (Mid slope): typic isohyperthermic kandiustalf (*Iwo Series*)								
A	0-22	81	7	12	0.58	0.92	1.58	Sandy loam
AB	22-54	48	8	44	0.18	0.98	1.61	Sandy clay
B2	54-88	37	9	54	0.17	0.98	1.46	Clay
BC	88-186	36	12	52	0.23	0.98	1.75	Clay
Pedon 4 (Lower slope): typic isohyperthermic kandiustalf (*Oba Series*)								
A	0-20	74	10	16	0.63	0.94	1.43	Sandy loam
AB	20-30	76	8	16	0.50	0.94	1.46	Sandy loam
B2	30-85	44	10	46	0.22	0.98	1.39	Clay
BC	85-127	68	8	24	0.33	0.96	1.61	Sandy clay loam

*BD = Bulk density; TC = Textural class

The chemical properties of the soils are shown in Table 3. Generally, the pH of the soils was low ranging from 4.4 – 5.6 and 3.6 – 5.1 in water and 1 M KCl solution, respectively. In the surface horizons specifically, the pH ranged from strong to very strong acid (4.4 – 5.4) and (3.9 – 4.8) in water and 1 M KCl solution, respectively. The pH values in all the pedons did not follow any particular pattern. Wood (1989) reported that cacao could thrive in soils with variable pH (H_2O) which may range from very acid (pH 5) to very alkaline (pH 8). The acidic nature of the soils may be attributed to leaching of exchangeable bases from the soils, continuous removal of crop residues and nature of the parent rock (granite and gneiss). According to Amusan (1991), phytocycling and upward movement of bases due to intense evaporation during the dry season in the humid tropics could have accounted for the relatively higher pH of the surface horizons.

The differences in soil pH values (ΔpH = pH (KCl) – pH(H_2O)) were all negative ranging from -2.12 to -0.27. Negative delta (-Δ) pH indicates the presence of excess negative charges at the exchange complex. It also suggests the dominance of silicate clay minerals over oxides (Van Raij and Peech 1972; Gallez et al. 1976).

The soil Ca^{2+} values were below the critical value of 5.0 $cmol_+$/kg soil for cacao (Ipinmoroti and Ogeh 2014). Therefore, based on the range of exchangeable Ca^{2+} values, application of Ca^{2+} containing fertiliser would be required to achieve ideal cacao yields. The calcium content fluctuated irregularly with soil depth and across the slope. The exchangeable magnesium (Mg^{2+}) content ranged from 0.37 to 1.04 $cmol_+$/kg soil. The exchangeable Mg content are lower than 0.8

$cmol_+$/kg soil which is the critical value for Mg for optimal cacao production (Ipinmoroti et al. 2009). Exchangeable potassium (K) contents ranged between 0.06 and 0.15 $cmol_+$/kg soil. Msanya et al. (2001) rated K^+ levels as low (< 0.2 $cmol_+$/kg soil) and medium (0.2 – 0.4 $cmol_+$/kg soil). Potassium content of the soils is above the critical level of 0.03 $cmol_+$/kg soil for optimal cacao production (Aikpokpodion 2010). Hence, K^+ fertiliser supplement would not be necessary to attain optimal cacao yields. The exchangeable sodium (Na^+) ranged from 0.03 – 0.05 and was almost uniform, irrespective of soil depth and topographic position. The values of Na^+ in the soils were less than 1 cmol/kg beyond which it becomes harmful to plant roots (Uwitonze et al. 2016). This implies that there is no sodicity problem in the studied soils (EUROCONSULT 1989). The low values of exchangeable bases of the soils may be attributed to pronounced leaching which characterises most tropical soils (Onweremadu 2006). Exchangeable acidity values ranged from 0.5 – 3.1 $cmol_+$/kg soil. Exchangeable Al^{3+} accounted for a greater percentage of the total acidity. The percent aluminium saturation of the soils ranged from 9 – 58%. Production of cacao on acidic and low fertility soils is mostly determined by the level of aluminium toxicity and adequate supply of essential nutrients. In tropical soils, increasing soil Al saturation decreases cacao growth significantly and soil Al saturation more than 30% has been reported to be toxic to cacao (Sónia 2012).

The cation exchange capacity (CEC) values were generally low ranging from 3.22 – 6.06 $cmol_+$/kg soil. The low CEC may be related to low organic matter content. Lal and Kang (1982) reported that the higher the organic matter content of the soil, the higher the CEC. Nnaji et al. (2002) stated that low CEC could be as a result of high rainfall, clay type and content as well as previous land-use. The study area has been cultivated continuously over time without the addition of any form of soil amendments. A CEC range of 15 – 25 $cmol_+$/kg is said to be suitable for growth of most plants (Landon 1991). Percentage base saturation (PBS) of the soils ranged from 43.50 – 97.80%. Low base saturation levels may result in very acid soils and concentration of potentially toxic cations such as aluminium and manganese (Hodges 2007).

Effective cations exchange capacity (ECEC) values fluctuated with soil depth and were generally low with values ranging from 2.39 – 5.38 $cmol_+$/kg soil. These low values are similar to the findings of Agboola and Unamma (1991) who asserted that soils in the tropics were subjected to intensive weathering which had resulted in a high proportion of kaolinitic clays with low cation exchange capacity. The low ECEC of these soils indicates their low capacity to retain nutrients, hence the need for proper soil management. The soil organic carbon content ranged from 0.08 – 1.64% corresponding to 0.13 – 2.82% soil organic matter (SOM) which was rated as low to high. The values generally decreased with soil depth. These values were below the critical value of 3% ideal for cacao production in Nigeria (Omotoso 1975). Adepetu (1986) classified percent SOM into low (0 – 1.5%), medium (1.5 – 2.5%) and high (> 2.5%). The low SOM obtained might be due to the effect of high temperatures which favour rapid decomposition and mineralisation of organic materials (Fasina et al. 2005). Total nitrogen content of the soils varied from 0.01 to 0.14%. The values are within the low to medium soil nitrogen fertility class range of < 0.1% (low), 0.1 – 0.2% (medium) and > 0.2% (high) (Sobulo and Adepetu 1987). Nitrogen content of the soils was adequate for cacao production since most of the values were higher than the critical level (0.09%) for cacao production (Egbe et al. 1989). The available phosphorus (P) ranged from 12.34 – 34.50 $\mu g\ g^{-1}$. The values were within medium to high level class. Sobulo and Adepetu (1987) and Adepetu (1990) ranked available P content of Nigerian soils into low (< 8 $\mu g\ g^{-1}$), medium (8 – 20 $\mu g\ g^{-1}$) and high (> 20 $\mu g\ g^{-1}$). The available P content was generally adequate for cacao production since the values obtained were above the critical value. Ibiremo et al. (2011) reported that 10 ppm of available P was required for optimum cacao production. Thus, addition of P fertiliser would not be necessary on the soil for optimal production. The exchangeable calcium for the soil varied from 1.21 – 3.17 cmol+/kg soil.

Table 3: Chemical properties of the soils

Horizon	Depth (cm)	pH			Exchangeable bases				Exch. Acidity		Total Acidity	CEC	ECEC	Base Saturation	Organic Carbon	Total Nitrogen	Avail. P ($\mu g\ g^{-1}$)
					Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	Al^{3+}	H^{+}							
		H_2O	KCl	ΔpH	<------------------------------ (cmol(+) kg^{-1} Soil)------------------------------>									<---------------(%)--------------->			
Pedon 1 (Mid slope): typic isohyperthermic kandiustalf (*Iwo Series*)																	
A	0-22	5.4	4.8	-0.6	3.17	1.02	0.13	0.03	1.00	0.90	1.90	4.45	5.35	97.8	1.48	0.13	21.31
AB	22-41	5.4	4.2	-1.18	1.94	0.61	0.08	0.08	0.50	0.60	1.10	6.06	3.16	43.94	0.86	0.08	27.64
B2	41-68	5.4	4.4	-1.01	2.09	0.67	0.12	0.12	0.70	0.30	1.00	3.60	3.60	80.64	0.19	0.02	13.93
BC1	68-97	5.4	4.8	-0.55	2.68	1.04	0.12	0.12	0.70	0.30	1.10	4.17	4.57	92.92	0.55	0.05	27.11
BC2	97-148	5.6	5.1	-0.56	2.13	0.8	0.12	0.12	0.60	0.40	1.00	4.45	3.67	69.08	0.12	0.01	23.10
Pedon 2 (Mid slope): typic isohyperthermic kandiustalf (*Iwo Series*)																	
A	0-12	4.9	4.1	-0.77	1.22	0.37	0.06	0.03	0.70	0.00	0.70	3.88	2.39	43.5	1.01	0.09	34.50
AB	12-37	4.9	4.0	-0.88	1.48	0.41	0.06	0.03	0.90	0.10	1.00	3.50	2.89	56.77	0.27	0.02	20.89
Bt1	37-76	5.3	4.4	-0.89	2.44	0.98	0.12	0.04	0.90	0.00	0.90	3.88	4.47	92.02	1.21	0.10	25.85
Bt2	76-143	5.2	4.0	-1.23	1.87	0.93	0.12	0.04	1.30	0.10	1.40	5.40	4.26	54.84	0.08	0.01	19.20
BC	143-200	5.1	3.9	-1.2	1.59	0.79	0.13	0.05	1.80	1.20	3.00	3.22	4.36	79.62	0.08	0.01	24.27
Pedon 3 (Mid slope): typic isohyperthermic kandiustalf (*Iwo Series*)																	
A	0-22	5.2	4.4	-0.86	1.37	0.5	0.10	0.04	1.20	0.40	1.60	3.41	3.21	58.85	0.66	0.06	15.51
AB	22-54	5.0	4.1	-0.93	2.09	0.49	0.22	0.04	1.00	0.20	1.20	3.98	3.82	70.82	0.23	0.02	25.11
B2	54-88	5.0	3.9	-1.12	1.68	0.55	0.15	0.04	2.30	0.70	3.00	4.45	4.72	54.31	0.12	0.01	21.42
BC	88-186	5.0	3.7	-1.27	1.3	0.78	0.16	0.04	3.10	0.30	3.40	3.79	5.38	60.16	1.40	0.12	21.31
Pedon 4 (Lower slope): typic isohyperthermic kandiustalf (*Oba Series*)																	
A	0-20	4.4	3.9	-0.47	2.18	0.83	0.14	0.04	1.20	0.20	1.40	3.31	4.39	96.3	1.64	0.14	14.56
AB	20-30	4.4	4.1	-0.27	1.39	0.37	0.13	0.04	0.60	0.30	0.90	3.22	2.53	60.09	0.82	0.07	29.12
B2	30-85	4.8	4.0	-0.79	2.34	0.65	0.15	0.04	0.30	0.30	0.60	4.07	3.49	78.3	0.47	0.04	23.84
BC	85-127	5.0	3.6	-1.35	1.21	0.61	0.13	0.04	1.00	0.10	1.10	4.45	2.99	44.7	0.08	0.01	12.34

Classification of the soils

Clay movement and/or accumulation has been established by the particle size data and the presence of clay coatings in horizons of the pedons (Tables 1 and 2). This signifies the presence of argillic or kandic horizons. The presence of kandic horizons is established in the pedons because they meet the following requirements: coarse textured surface horizon over vertically continuous sub-surface horizons; ECEC values within the sub-surface B-horizons that are less than 12 $cmol_+$/kg soil; a regular decrease in organic carbon content with increasing soil depth (Table 3) (Soil Survey Staff 2014). The high base saturation of greater than 50% by NH_4OAc – pH 7 at a depth of 125 cm below the upper boundary of the kandic horizon (Soil Survey Staff 2014), placed all the pedons into the order Alfisol in the USDA Soil Taxonomy. They belong to the suborder Ustalf due to their ustic moisture regime (Okusami and Oyediran 1985) and also fit into the Kandiustalf great group, because the soils are dry for more than 90 cumulative days but less than 180 days. The soil temperature regime in southwestern Nigeria is isohyperthermic (Amusan and Ashaye 1991). All the pedons were therefore classified as Typic Isohyperthermic Kandiustalf at subgroup level due to low activity clay (Soil Survey Staff 2014). However, in the FAO/UNESCO system of soil classification, they are classified as Chromic Lixisol, in view of the reddish hue.

Suitability evaluation of the soils for cacao production

Table 4 shows land-use requirements for cacao production. The factor rating of land use requirements for cacao were matched with the properties of the soils (Table 5) to obtain the actual (A) suitability class scores of each land unit for cacao (Table 6). Numerical rating of the land characteristics in a normal scale from a maximum (100) to a minimum value of 20 was used. Maximal rating of 100 was attributed if a land characteristic was optimal for cacao production and if unfavourable, the least rating was applied. The potential (B) suitability class scores were obtained after soil fertility had been corrected and attributed 100. Aggregate suitability class score (land index) for each land unit was calculated using the square root equation method.

The results for the actual suitability rating (A) showed that the pedons classified as marginally suitable (S3) for cacao production (Table 6). Nevertheless, after the fertility constrains would have been removed with adequate and proper fertiliser application, the soils are highly suitable (S1) for cacao production. The potential suitability (B) reflects what is expected after limiting constrains have been removed. The major limitation of the soils was poor fertility.

Table 4: Climatic, soil and land requirements for cocoa production

Land, soil and climatic characteristics	S1 (100%)	S2 (85%)	S3 (60%)	N1 (40%)	N2 (20%)
Climatic					
Annual rainfall (mm)	1,600 - 2,500	1,400 - 1,600	1,200 - 1,400	-	<1,200
Length of dry season (months)	1-2	2-3	3-4	>4	any
Mean annual temperature (°C)	23-28	28-35	20-25	35-38	>38
Relative humidity (Driest month,%)	40-65	35-65	30-75	any	-
Topography (t)					
Slope (%)	<8	<16	<30	-	any
Wetness (w)					
Flooding	No	No	F1	F1	any
Drainage	Well drained	Moderate	Imperfect	Poor	Very poor
Physical soil characteristics (s)					
Texture/structure	C-60s to SC	C+60s to SCL	C+60s to LFS	C+60s to LFS	Cm to Cs
Coarse fragments (Vol.%)	<15	15-35	35-55	>55	any
Soil depth (cm)	>150	>100	>50	>50	any
Fertility characteristic (f)					
Apparent CEC (cmol+/kg soil)	>16	12-16	8-12	<8	-
Base saturation (%)	>60	50-35	<20	-	-
Organic matter (% C, 0-15cm)	>3	2.5-1.5	1.5-0.8	0.6-0.8	<0.6
Soil pH (in water)	6.0 -7.0	7.0 – 7.6	5.5 – 6.0	5.5 – 4.0	>7.6

F1 = Slight, C+60s to SCL = Very fine clay blocky structure to sandy clay loam, C-60V to L = Clay vertisol structure to loam, C+60s to fs = Very fine clay blocky structure to fine sand, C+60v to fs = Very fine clay vertisol to fine sand, C+60s to s = Very fine clay, vertisol structure to sandy soil, CM to SC =Massive clay to sandy clay
S1 = highly suitable, S2 = moderately suitable, S3 = marginally suitable, N1 = presently not suitable,
N2 = permanently not suitable
Source: Modified from Sys *et al*. 1993

Table 5: Summary of Land Characteristics of the land units

Land characteristics	Pedon 1	Pedon 2	Pedon 3	Pedon 4
Annual rainfall (mm)	1502.23	1502.23	1502.23	1502.23
Mean annual temperature (°C)	29.42	29.42	29.42	29.42
Length of dry season (months)	4	4	4	4
Relative humidity (%)	79.56	79.56	79.56	79.56
Slope	0.04	0.25	0.45	0.47
Flooding	No	No	No	No
Drainage	well drained	well drained	well drained	well drained
Texture	SCL	SL	SL	SL
Coarse fragments	<15	<15	<15	<15
Soil depth (cm)	148	200	186	127
Apparent CEC (cmol+/kg soil)	4.45	3.88	3.41	3.31
Base saturation (%)	97.80	43.50	58.85	96.30
Soil pH	5.4	4.9	5.2	4.4
Organic matter (% C, 0-15 cm)	1.48	1.01	0.66	1.64

SCL = Sandy clay loam, SL = Sandy loam, LS = Loamy sand

Table 6: Land suitability ratings of the study area for cacao production

Land qualities	P1		P2		P3		P4	
	A	B	A	B	A	B	A	B
Climate								
Annual rainfall (mm)	85	85	85	85	85	85	85	85
Mean annual temperatures (°C)	85	85	85	85	85	85	85	85
Topography (T)								
Slope (%)	100	100	100	100	100	100	100	100
Wetness (W								
Soil drainage	100	100	100	100	100	100	100	100
Flooding	100	100	100	100	100	100	100	100
Soil Physical Properties (S)								
Texture	85	85	100	100	100	100	100	100
Soil depth (cm)	85	85	100	100	100	100	85	85
Coarse fragment (%)	100	100	100	100	100	100	100	100
Fertility Characteristics (F)								
Soil pH	40	100	40	100	40	100	40	100
Soil organic carbon	60	100	60	100	40	100	85	100
Base saturation	100	100	85	100	85	100	100	100
CEC	40	100	40	100	40	100	40	100
Aggregate suitability	34	78	37	85	37	85	37	85
Suitability symbol	S3	S1	S3	S1	S3	S1	S3	S1

P1 = Pedon 1, P2 = Pedon 2, P3 = Pedon 3, P4 = Pedon 4.
A = actual/current suitability class, B = potential suitability class (after soil fertility improvement)
Aggregate suitability scores: S1(75-100); S2(50-74); S3(25-49); N1(12-24); N2(0-12).

Conclusion

The soils on a toposequence developed in coarse-grained granite and gneiss in the humid rainforest area of southwestern Nigeria were assessed with a view to assessing their suitability for cacao production using the parametric approach. The soils were well drained, dark brown to reddish yellow in colour, varying from sandy-clay-loam to sandy-loam in texture and classified as Typic Isohyperthermic Kandiustalf. The soils were presently marginally suitable (S3) but potentially highly suitable (S1) for cacao production. Their major limitation to cacao production was low fertility. The limiting soil nutrients should be improved upon through the application of appropriate fertilisers. Efficient soil management and nutrient enrichment to improve sustainable cacao production is therefore recommended.

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