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Effect of land use on potassium form of coastal plain sands of Nigeria

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ABSTRACT
The study evaluated the effects of land use on the forms of potassium in the coastal plain sands (CPS) landscape of southeastern Nigeria. It was observed that both land use and topography did not influence the distribution of different forms of potassium. Mineral constituted approximately 97.4%, whereas non-exchangeable (1.9%) and readily available (0.7%) forms represented 2.6% of total potassium. The relationships established between reserve, exchangeable and soluble indicated the origin of readily available potassium. Mineral form of potassium associated directly with clay, electrical conductivity, organic matter, sodium and acidity, but indirectly with sand, pH and base saturation. Reserve and fixed potassium each associated with organic matter, whereas fixed form additionally associated with sand and clay. Clay increases the tendencies for the release of potassium, whereas sand acts on the contrary including leaching losses. The study confirmed that organic matter, particle size fractions, extent of weathering and soil development influence the dynamics of potassium within the landscape of CPS of southeastern Nigeria.

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Potassium; land use; pedogenesis; remote sensing; acid sands

1. Introduction

The geology of coastal plain sands (CPS) of Benin formation comprised deltaic marine sediments of cretaceous to recent age with dominant facies that originate from acidic plutonic igneous rocks and possesses typical characteristics of quartz arenite.[1] Quartz arenite are characterised by such highly resistant minerals as quartz, K-feldspar and clay and potassium is among the final weathering products of feldspar.[2] The particle size fractions (psf) of the highly weathered CPS are dominated by sand to the detriment of fine sand and silt fractions which are residences of potassium.[3,4] The crop production system within the study area is low input type which does not supply sufficient ameliorative quantity of potassium,[5] suggesting that mineralogical potassium is the dominant source. These are confirmations that the major source of potassium in the CPS of southeastern Nigeria is K-feldspar.

In conditions of very intense or extreme weathering as found in the oxisols or ferralsols in the humid tropical regions, appreciable amount of potassium is liberated from feldspar (i.e. substantial destruction) to the extent that the soils could no longer serve as a source of

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reserve potassium.[2] The CPS of southeastern Nigeria are dominantly ultisols or acrisols, characterised by base saturation (BS) of less than 35%, indicative of severe weathering inferior only to the oxisols and characteristically very low in potassium.[6,7] The potassium content of the ultisols is superior only to that of oxisols among the major soil classes common within the humid tropical regions.[8] These are confirmations that soil formation equally significantly influences the relative abundance of potassium forms within soil profiles. It was reported that parent material,[9] topography,[10] climate and time [11] significantly influence the distribution and variability of potassium forms in soils. Additionally, soil type,[12] land use,[13–16] crop type and extent of use [17,18] and management [19] significantly influence the distribution of potassium forms.

In circumstances of low input production systems, ameliorative application of potassium is never practised to the extent that replenishes plant uptake [9,18,20] and the result is gross deficiency in already very poor potassium status soils as present in CPS of southeastern Nigeria. The present intensive and extensive, low input, low efficiency agricultural production system, population upsurge and soil degradation impinge on the forest.[21–23] The consequence is progressive conversion of forest to arable and fallow land uses. These affect the dynamics of potassium within the landscape of CPS of southeastern Nigeria. Therefore, this research studied the effect of land-use changes on the forms of potassium in the CPS of southeastern Nigeria.

2. Materials and methods

2.1. Description of the study area

The study was carried out in locations underlain by CPS in Akwa Ibom State, southeastern Nigeria (Figure 1). The State is located between approximately latitudes 4°30′ and 5°30′N and longitudes 7°28′and 8°20′E, and covers an area of approximately 7249 km^2, out of which approximately 70% is CPS and 5% is the accompanying alluvium. Akwa Ibom State was carved out of Cross River State in 1987. In 1986 (i.e. prior to the creation Akwa Ibom State in 1987), the population of the settlements within its bounds was 2,100,565 and has grown to 3,902,051 in 2006 and to a projected total of 5,272,029 in 2015 at a growth rate of 3.4%.[24,25]

The climate is characterised by distinct rainy (March/April–October) and dry (November–March) seasons. Rainfall distribution in a year is bimodal (with peaks in July and September) and high intensity with annual range varying between 2000 mm in the northernmost portion and 4000 mm along the coast.[26] Temperature is uniformly high, averaging between 28°C and 30°C, and relative humidity is high (approximately 75%). Previously, the study area belonged to the humid tropical forest zone of southern Nigeria [27] and the vegetation resulted from the interaction of climate, humidity, rainfall and soils.[28] However, prolonged resource exploitation facilitated the conversion to a mixture of derived vegetation type. The area is currently characterised by secondary forest of predominantly wild oil palm trees of various densities and woody shrubs such as *Chromolaena odorata* and various grass undergrowth such as *Imperata cylindrica* which are indicators of land degradation.[29]

The predominant land use is the cropping-bush fallow-cropping closed system operated with the primitive hand tools of hoes and machetes. It has been described as a

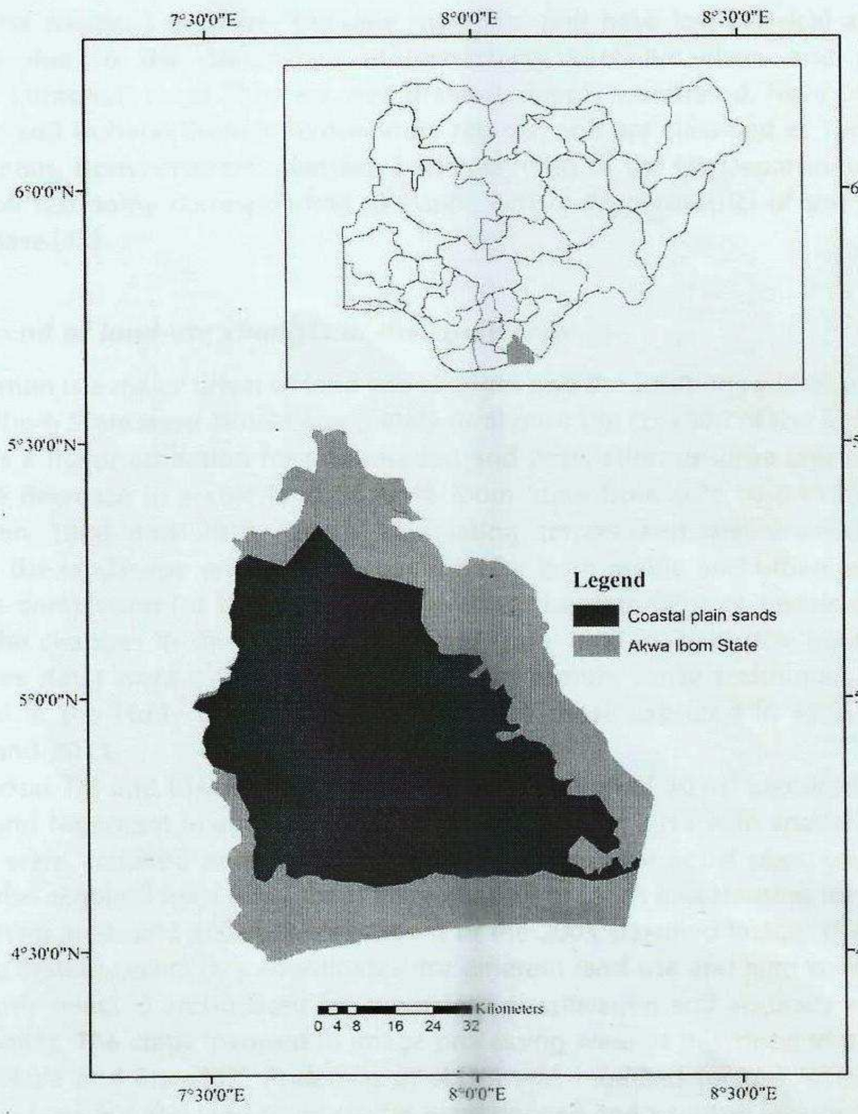

Figure 1. Map of Akwa Ibom State showing area covered by CPS.

sedentary form of shifting cultivation. The farmers are restricted to their own farmland and cannot move about. The average farm size is less than 0.5 ha because the farmer cannot handle a larger area with this method of cultivation. Additionally, fragmentation of land among the community and family members does not give any member more than this size of land in any one place.[23,30] A farmer could have several small parcels of farm scattered over a wide area. The principal food crops grown are yam, cassava, maize and cocoyam and the dominant tree crop is oil palm.

The area under CPS in Akwa Iboms State is characterised by flat terrain and low-lying lands, with height above sea level increasing gradually from approximately 13 m in the coast to a maximum elevation of 130 m towards the northernmost portions. The profiles of CPS vary from sand on the surface to fine loamy in the subsurface. They are characterised by the dominance of sandy textured grains comprising larger quantities of coarse fractions over fine textured materials, and have low physical and chemical fertility due to the dominance of low-activity kaolinitic clays, and low organic matter content.[31–33] They are well drained, deeply weathered, have udic moisture regime and isohyperthermic temperature regime, and are classified as Typic Paleudult in siliceous, isohyperthermic families [34] according to the US Department of Agriculture soil taxonomy corresponding to Haplic Acrisol (Hyperdystric) of the World Reference Base.[35]

2.2. Trend of land-use changes in the study area

Population is a major driver of land-use changes and the locations within the bounds of Akwa Ibom State were almost completely rural prior the creation of the State. State creation is a major attraction for urbanisation and population upsurge and is responsible for the decrease in arable land in Akwa Ibom State from 0.22 to 0.11 ha per person between 1986 and 2013. Gently undulating terrain and well-drained soil found within the landscape on CPS are attractions for both arable and urban land uses and initiate completion for these land uses even at the detriment of sustainability. Therefore, the changes in the different land uses from 1986 to 2013 (the newest available land-use data) were estimated with the aid of remote sense techniques. The images utilised in the study based on availability were those captured in 1986, 2003, 2007, 2008 and 2013.

Landsat TM and ETM+ images with spatial resolution of 30 m^2 captured in 1986 and 2003 and Nigeriasat images captured in 2007, 2008 and 2013 with spatial resolution of 32 m^2 were acquired and used for the study. Large-scale aerial photographs of 2002 were also acquired from Akwa Ibom State Ministry of Lands and Housing for the selection of training areas and accuracy assessment of the 2003 classified image. The global positioning system points (x, y coordinates) for different land-use and land cover types were randomly selected and utilised for supervised classification and accuracy assessment of the images. The steps involved in image processing were as described in Ituen et al.[36] and Tokula and Ejaro.[37] Anderson et al.[38] was modified for use in the study area and five land-use and land cover classes were defined and adopted for use. The modified land-use and cover classes (referred to as land-use subsequently) include water, forest, urban or built-up, farm land and fallow.

Prior to actual enhancement and classification, the images were layer stacked and area of interest tools used to create subset of the study area. Distortions due to weather and season were not expected as the images were captured during the dry seasons (i.e. cloud-free period) of their respective years. The images were subjected to principal component analysis for compression and reduction of redundancy as the resultant non-redundant and uncorrelated principal component bands are easier to interpret compared to raw images. Supervised signature extraction was adopted in conjunction with the maximum likelihood algorithm to derive meaningful classes from the images. Bands 4-3-2 found to be very useful in discriminating the land-use classes were combined for this purpose. The result of accuracy evaluation for the processed images produced KAPPA estimate of strong agreement beyond chance.[39,40] The land use and land cover maps of the study area produced are presented as Figures 2–6 for 1986, 2003, 2007, 2008 and 2013, respectively.

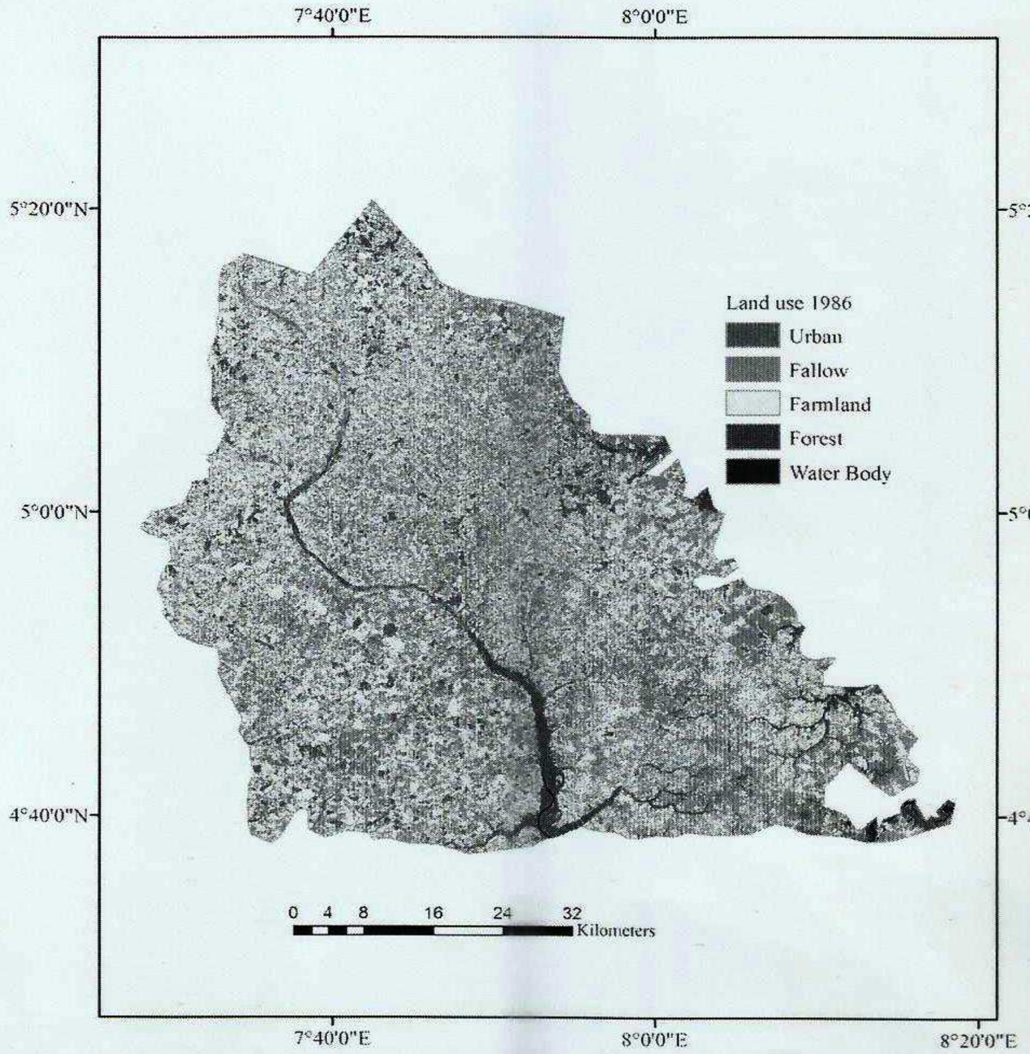

Figure 2. Land uses of area covered by CPS in Akwa Ibom State in 1986.

2.3. Field studies

The fact that extensive farming is not a common feature in the study made it difficult to identify locations that have single land use across a toposequence in a low input, low efficiency agricultural system practised in tenured and fragmented units of farms. The type of extensification practised in the study area is the simultaneous utilisation of many of the fragments of farm land distributed as far away as kinsmen ownership system permits. Three representative and contiguous toposequences per land use were selected in Use Offot (longitude 7°58′396″ and latitude 5°01′849″), Ntak Inyang (longitude 7°55′818″ and latitude 5°04′964″) and Idu (longitude 8°00′212″ and latitude 5°01′895″) for forest, fallow and arable to give a total of nine land uses in the study area. Oil palm plantation that is more than 40 years of age and established immediately after deforestation was used to represent forest. Fallow land use is land formerly used for crop production but abandoned as a result of very poor yield and that has stood for a maximum of four

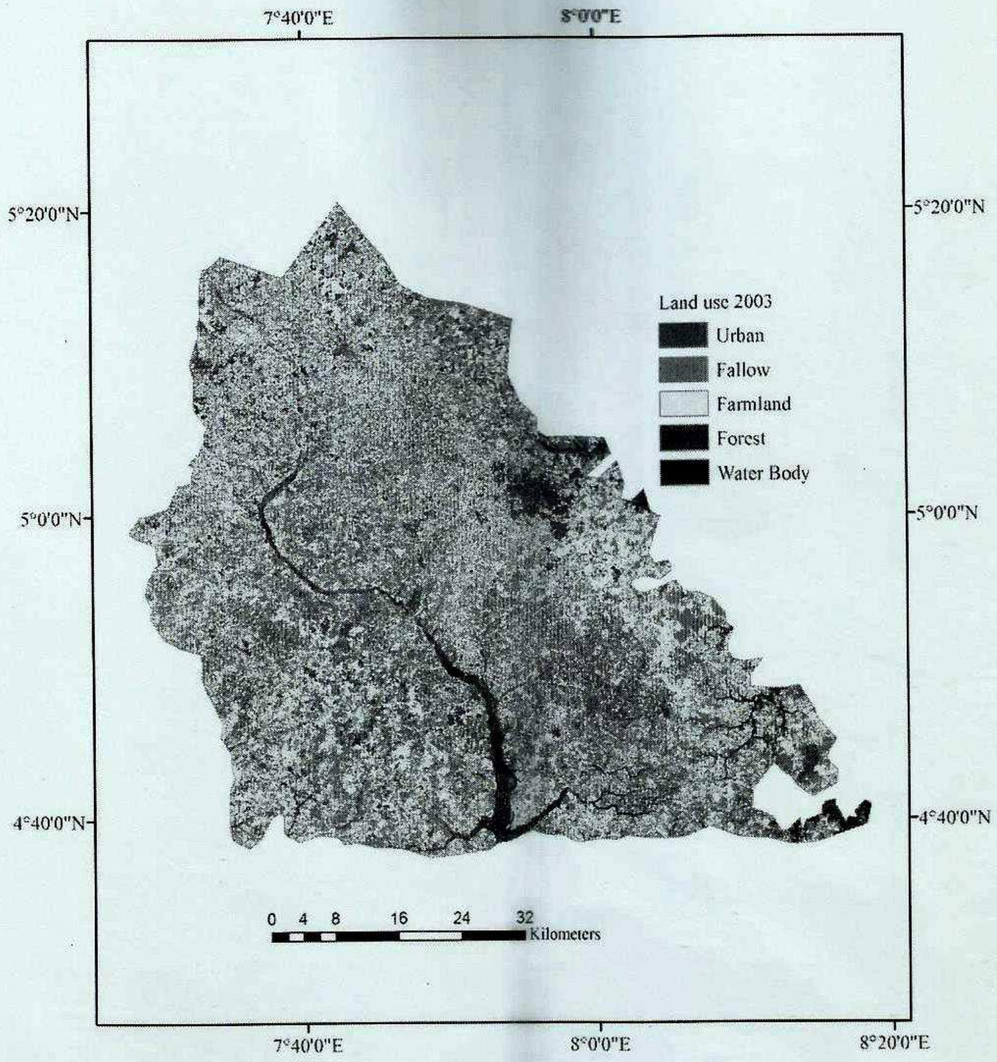

Figure 3. Land uses of area covered by CPS in Akwa Ibom State in 2003.

years. Arable land use is a cassava farm from which maize crop had been harvested. The practice in the study area is continuous cropping interrupted by one year of fallow in overlapping circles of different major annual crops such as cassava, maize, vegetables, yams and cocoyam, which can only be abandoned on the condition that returns (yield) remain very low because of degradation.

Surface (0–15 cm) and subsurface (15–30 cm) soil samples were collected during the rainy season from the upper, middle and lower slope positions of the selected 9 toposequences to give a total of 54 samples. Soil samples were collected and preserved in sampling bags for laboratory analysis.

2.4. Laboratory analysis

The soil samples were processed and used for laboratory analysis described below. Particle size analysis was carried out using the method of Dane and Topp.[41] Soil organic carbon

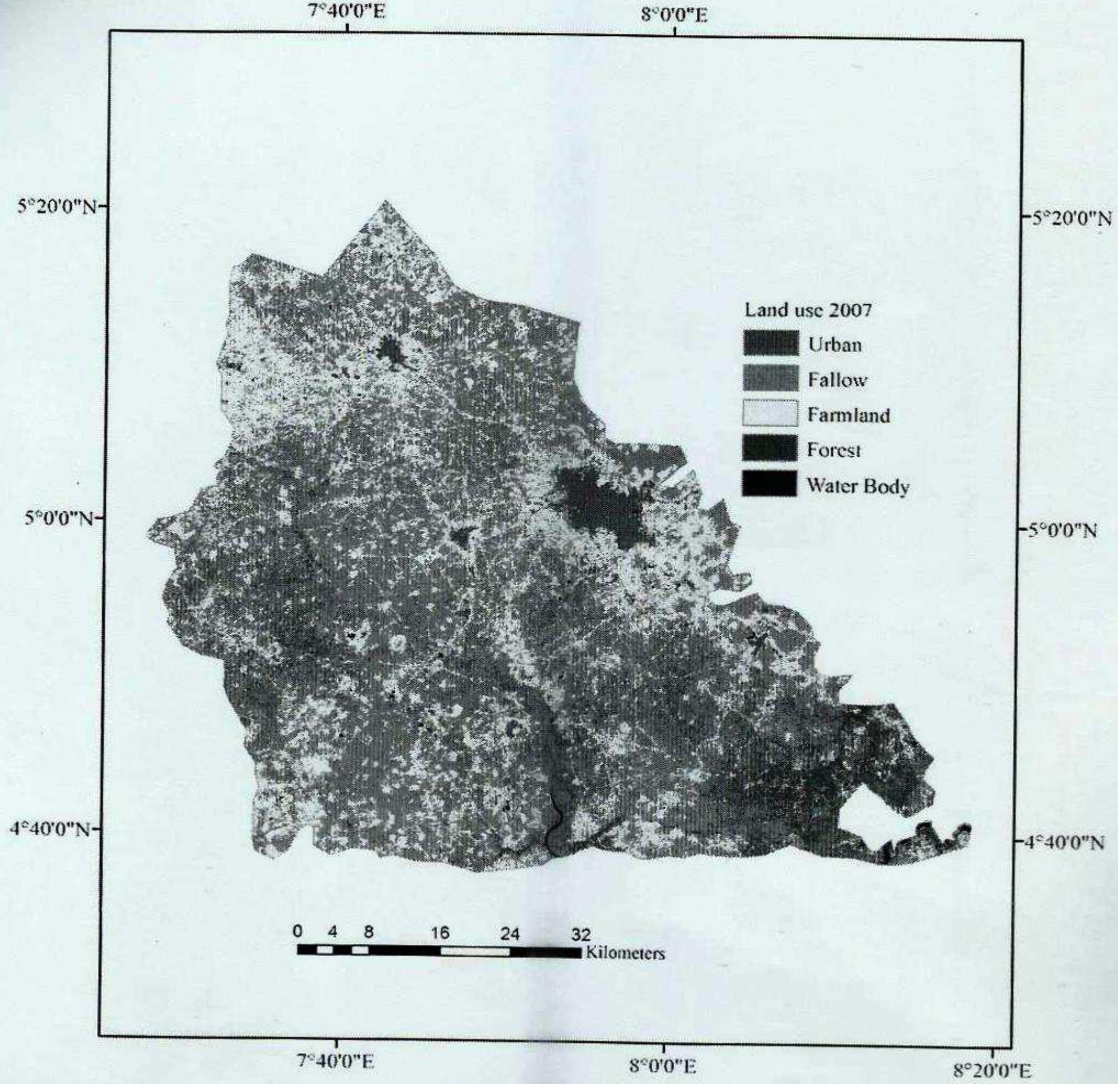

Figure 4. Land uses of area covered by CPS in Akwa Ibom State in 2007.

content was determined as described in Sparks.[42] Soil pH was determined in 1:2.5 (soil: water) solution using a pH meter.[43] Exchangeable bases were extracted with Mehlich No. 3 extraction.[44] Potassium (K) and sodium (Na) contents were determined with a flame emission spectrophotometer, and calcium (Ca) and magnesium (Mg) with an atomic absorption spectrophotometer. Available phosphorus was determined colorimetrically according to the Bray and Kurtz [45] method. Exchangeable acidity (EA) was extracted with unbuffered potassium chloride solution and titrated with 0.01 M solution of sodium hydroxide to the first permanent pink endpoint as described by Anderson and Ingram,[46] while effective cation exchange capacity (ECEC) and BS were determined through summation.[47]

Soil samples ground to pass through 0.17 mm sieve were digested in $HF–HClO_4–HNO_3$ acid mixture for the estimation of total potassium.[48] Reserve potassium (K) was estimated in the soil samples boiled in HNO_3,[49] whereas fixed K was determined as described by Jackson.[50] Exchangeable K was extracted from the soil samples with

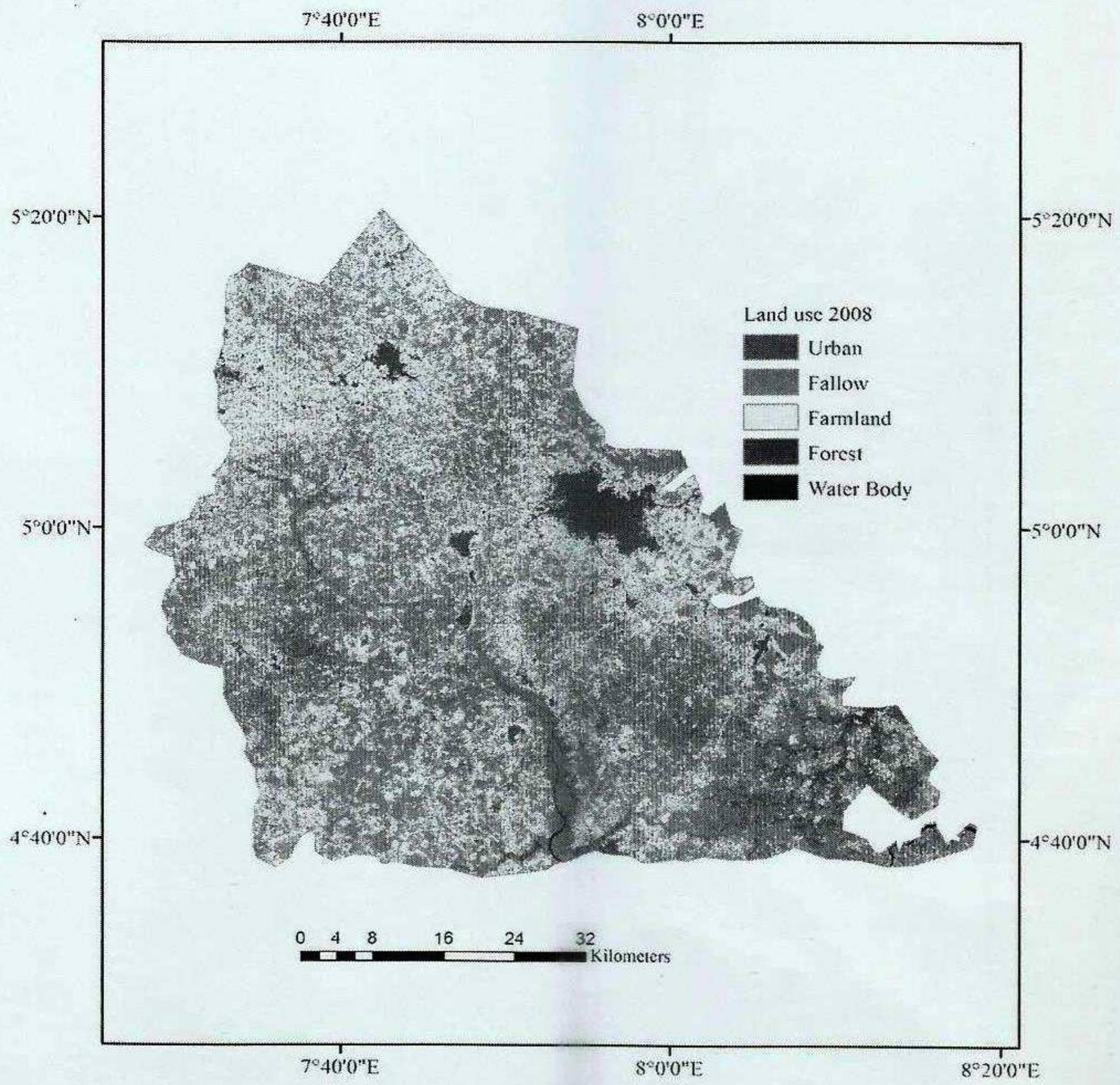

Figure 5. Land uses of area covered by CPS in Akwa Ibom State in 2008.

neutral normal ammonium acetate, while solution K was extracted using distilled water and the summation of solution and exchangeable was the readily available K. Potassium content of the extracts was determined using a flame photometer. Non-exchangeable or slowly available potassium was determined as the difference between reserve and readily available potassium. Mineral or structure K was obtained as a difference between total K and reserve.[12,51]

2.5. Statistical analysis

Soil samples were collected in a 3 × 3 factorial experiment in randomised complete block design with three replications. The two factors were land use (forest, fallow and arable) and slope position (upper, middle and lower). Data collected in the study were analysed using analysis of covariance (ANCOVA) with subsurface and surface soil as the dependent and independent variables, respectively. The subsurface

3. Results

3.1. Changes in land use within CPS geomorphic unit

The land-use maps of CPS geomorphic unit in Akwa Ibom State are shown in Figures 2–6 representing 1986, 2003, 2007, 2008 and 2013, respectively. The distribution of urban land use indicated a drift towards few central locations such as the State capital that manifested very high concentration of urban land use in comparison to other locations. Farmlands are equally found to concentrate within the fringes of urban land use, while fallow and forest followed in that order. This corresponded with the fact that no major farming activity goes on within the study area; rather, there were indiscriminate establishments of small farms by a large number of individuals within the fringes of urban land use.

There was progressive and gradual increase in the coverage of agricultural (farmland and fallow) land use within the study area. Among the three land uses considered, fallow had the largest spatial coverage, while forest had the least (Table 1). Cumulatively, agricultural land use occupied between 76.7% and 85.7% of the study area, implying that this amount of land is constantly going through the circle of cropping and fallowing with accompanying influence on nutrient recycling and pedogenesis.

Point-to-point change detection revealed that there were continual interchange between fallow and farmland and losses in forest to the benefits of agricultural land use. The fact that cumulatively less than 7% of the study area was under urban and water land use indicated that up to 93% was either under agricultural or to a less extent forest land use. Inclusive in the forest land use were plantations which are major sources of income and in such situations, there is progressive deforestation for the establishment of oil palm and to less extent rubber and cacao plantations. These interchanges between different land uses are significant in nutrient management and recycling, and variations in the forms of potassium in the soil.

3.2. Effect of land use and slope positions on soil properties

The psf of the CPS were dominated by sand fractions and the results shown in Tables 2 and 3 indicated that land use and topography did not significantly affect the distribution

Table 1. Distribution of land uses within the study area between 1986 and 2013.

		Farmland	Fallow	Forest	Urban	Water body	Total
1986	Area (ha)	182,360.3	234,410.9	58,043.2	67,144.9	1715.7	543,675
	(%)	33.5	43.1	10.7	12.4	0.3	100
	Cumulative (%)	33.5	76.7	87.3	99.7	100	
2003	Area (ha)	203,807.6	262,332.3	69,874.5	5516.6	2144.0	543,675
	(%)	37.5	48.3	12.9	1.0	0.4	100
	Cumulative (%)	37.5	85.7	98.6	99.6	100	
2007	Area (ha)	178,846.3	245,042.1	98,903.1	18,632.2	2251.2	543,675
	(%)	32.9	45.1	18.2	3.4	0.4	100
	Cumulative (%)	32.9	78.0	96.2	99.6	100	
2008	Area (ha)	233,009.2	223,468.4	52,764.8	32,267.7	2164.8	543,675
	(%)	42.9	41.1	9.7	5.9	0.4	100
	Cumulative (%)	42.9	84.0	93.7	99.6	100	
2013	Area (ha)	214,905.0	246,690.7	56,835.6	23,174.1	2069.6	543,675
	(%)	39.5	45.4	10.5	4.3	0.4	100
	Cumulative (%)	39.5	84.9	95.4	99.6	100	

Table 2. Effect of land use and slope position on the soil properties in the study area.

Soil properties		Land use			Slope position		
		Arable	Fallow	Forest	Upper	Middle	Lower
Sand	(g kg^{-1})	825.22	829.78	834.22	827.56	843.11	818.67
Silt		56.22a	47.56a	25.11b	47.33ab	27.33b	56.22a
Clay		118.44	120.67	138.44	125.11	127.33	125.11
Organic matter		4.01	3.84	4.36	3.97	4.00	4.25
pH		5.72a	5.54b	5.57ab	5.68	5.63	5.52
Calcium	(cmol kg^{-1})	3.91a	3.44ab	3.29b	4.18a	2.93b	3.53b
Magnesium		1.29	1.33	1.07	1.37	0.98	1.33
Potassium		0.09ab	0.10a	0.08b	0.09	0.09	0.08
Sodium		0.06	0.06	0.06	0.06	0.06	0.06
Acidity		1.92	2.36	2.52	2.29	2.10	2.29
ECEC		7.27	7.30	7.02	8.00a	6.16b	7.44a
Base saturation	(%)	72.91a	68.34ab	63.78b	70.43	67.97	66.63

Note: ECEC = Effective cation exchange capacity; Row values with similar alphabets are not significantly ($p < .05$) different.

of sand and clay, but silt content of the soils. The silt content of the forest was lower than that of fallow and arable, and this could be attributed to the similarities among the two land uses. These two land uses (agricultural) are continually interchanged in the process of crop production as they are almost continually manipulated in a circle of at least once in four years, which was the maximum fallow period as practised in the study area. The effect of topography on the particle size distribution of the soils revealed that the silt content of the upper slope position was not significantly different from that of the middle, but from that of the lower, while that of the middle slope was also not significantly different from that of the lower. This indicated the overlapping effect of slope (gravity) and erosion on the distribution of psf. Particle size distribution is a compositional soil variable and the accumulation of sand fractions at the lower slope position will invariably lead to reduction in either silt or clay content and in this case silt. It was further confirmed that the locations that manifested significant differences in the silt content were the lower slope position of the forest and fallow land uses which were significantly different from each other (Table 3). This is a further confirmation of the similarity in the particle size distribution of the agricultural land use and therefore their difference from forest land use.

Other soil properties such as organic matter, exchangeable magnesium, sodium and acidity were neither significantly influenced by land use nor topography. Yet, land use influenced the variability of pH, calcium, potassium content and BS, whereas topography influenced calcium content and ECEC. In as much as the pH of the soils was found to be significantly different from each other, it was neither as a result of topographic nor interaction effect but land use. The pH of the soils was found to fall within a narrow range of between 5.7 and 5.6 and classified as moderately acid, which is one of the characteristics of CPS. The effect of land use resulted in a similar trend in the variability of calcium, potassium content and BS (Table 3). Topographic factors are responsible for the variation in the calcium content and ECEC of the soils studied. The calcium content and ECEC of the upper and middle slope positions were significantly different from each other. The combined effect of land use and topography manifested such gradation that upper slope positions possess the highest amount of calcium content of the soils in all land uses which decreased downwards in a similar trend (Table 3).

Table 3. Interaction of land use and slope position on the variation of soil properties in the study area.

			Arable			Fallow			Forest		
Soil properties			Lower	Middle	Upper	Lower	Middle	Upper	Lower	Middle	Upper
Sand		(g kg^{-1})	838.01	867.57	838.01	807.37	826.16	832.76	846.09	791.48	820.77
Silt			53.75ab	31.80ab	45.62ab	71.80a	37.50ab	46.37ab	24.16b	37.01ab	44.65ab
Clay			105.03	103.39	119.24	123.39	132.45	120.00	131.69	164.15	133.33
Organic matter			4.34	4.21	3.82	4.13	3.66	3.83	4.15	4.45	4.03
pH			5.52	5.78	5.52	5.56	5.56	5.76	5.58	5.62	5.59
Exchangeable	Calcium	(cmol kg^{-1})	3.79b	2.79bc	4.88a	3.24b	3.33bc	3.80ab	3.65bc	2.64c	3.82ab
	Magnesium		1.21	0.91	1.72	1.72	1.09	1.20	1.07	0.94	1.22
	Potassium		0.08b	0.08b	0.09ab	0.11a	0.09ab	0.10ab	0.07b	0.08b	0.09ab
	Sodium		0.06	0.07	0.06	0.07	0.06	0.05	0.06	0.06	0.06
	Acidity		2.04	1.92	2.32	2.58	2.56	2.05	2.73	1.96	2.27
ECEC			7.06	5.68	8.96	7.83	6.78	7.34	7.48	6.01	7.64
Base saturation		(%)	71.87	68.00	73.10	67.33	66.52	70.38	63.53	64.40	70.00

Note: ECEC = Effective cation exchange capacity; Row values with similar alphabets are not significantly ($p < .05$) different.

3.3. Distribution of different forms of potassium

The effect of land use and slope positions on the distribution and variability of the different forms of potassium within the CPS landscape is as shown in Tables 4 and 5. It was observed that both the land uses studied and slope positions did not significantly influence the distribution and variability of the different forms of potassium within the CPS landscape. The dominant form of potassium is the structure or mineral which constitutes approximately 97.4%, indicating that less than 3% represented the non-exchangeable and readily available forms. The proportions of the remaining forms of potassium within the soil were 1.9% and 0.7% for the non-exchangeable and readily available forms, respectively. The total potassium content of the CPS ranged between 12.4 and 22.99 cmol kg^{-1} (Tables 4 and 5), out of which between 12.02 and 22.56 cmol kg^{-1} are mineral forms. These forms exist in the mineral structures of feldspar and mica and are difficult to extract because they reside mainly in resistant fine sand and silt fractions. The dominance of sand fractions within the particle size distribution to the detriment of clay and silt may have been responsible for the homogeneity of the distribution of the mineral fraction of potassium within the CPS landscape. Additionally, the mineral or structure form of potassium may not significantly vary as it is geogenic in origin and manifests the characteristics of CPS parent material (quartz arenite). The homogeneity of the structure form of potassium which dominated the total form may have been responsible for non-significance in the distribution of total potassium, which comprised other forms of potassium apart from itself. The soils are at an advanced stage of development and would have literally lost most of its potential potassium through intense weathering that the leftovers reside in the recalcitrant sand and silt fractions (mineralogical fractions), and hence the effects of topography did not manifest in the distribution and variability of the forms of potassium.

Non-exchangeable (reserve and fixed) and readily available (water-soluble and exchangeable) forms were found to be characteristically very low. Reserve and fixed ranged between 0.10 and 0.13 cmol kg^{-1}, respectively, water soluble ranged between 0.02 and 0.04 cmol kg^{-1}, whereas exchangeable ranged between 0.08 and 0.09 cmol kg^{-1}. The water-soluble and exchangeable forms of potassium are readily available for plant uptake and continually and insufficiently participated in the circles of crop production without commensurate ameliorative supply. These combined with the low capacity of the geological components of the CPS are responsible for the very low amount of readily available forms of potassium, and such quantities in soils will not support sustained high crop yield. The study indicated that neither land use nor topography significantly influenced the distribution and variability of the various forms of

Table 4. Effect of land use and slope position on the forms of potassium.

		Total	Structure	Non-exchangeable		Readily available	
				Reserve	Fixed	Water soluble	Exchangeable
	(cmol kg^{-1})						
Land use	Arable	15.43	14.99	0.12	0.20	0.04	0.09
	Fallow	14.65	14.20	0.11	0.24	0.02	0.09
	Forest	19.73	19.35	0.10	0.17	0.02	0.08
Slope position	Upper	18.30	17.82	0.13	0.22	0.04	0.09
	Middle	14.84	14.42	0.11	0.21	0.02	0.09
	Lower	16.67	16.30	0.10	0.17	0.02	0.08

Table 5. Interactive effect of land use and slope position on the forms of potassium.

		Arable			Fallow			Forest		
		Lower	Middle	Upper	Lower	middle	Upper	Lower	middle	Upper
Total	(cmol kg^{-1})	12.53	19.12	22.99	16.98	12.40	13.28	19.79	15.02	17.32
Structure		12.02	18.56	22.56	16.47	11.97	12.78	19.61	14.87	16.78
Reserve		0.10	0.10	0.16	0.11	0.12	0.09	0.09	0.10	0.11
Fixed		0.25	0.20	0.13	0.17	0.31	0.26	0.12	0.09	0.29
Soluble		0.02	0.02	0.07	0.02	0.02	0.01	0.02	0.02	0.03
Exchangeable		0.09	0.08	0.09	0.10	0.10	0.08	0.07	0.08	0.09

Note: ECEC = Effective cation exchange capacity.

potassium within the CPS. The insignificant quantity of the readily available form (water soluble and exchangeable) that scarcely satisfies the requirement for plant growth and its continual depletion as a result of inadequacy in replenishment is responsible for uniformity in their quantities and by extension the non-exchangeable (reserve and fixed) forms. The total form of potassium manifests the combination of entire sources within the soil, and as long as the prevalent processes did not cause variability in the distribution of their various forms, significant variability will not be observed within the soils of the study area.

3.4. Effect of CPS on the forms of potassium

Mineralogy and weathering play a significant role in the dynamics of potassium in soils. The total potassium was found to be very similar to structure form and hence was excluded in the study of the relationships between potassium forms and other soil properties shown in Table 6. The contribution of structure in the characteristics of other forms of potassium indicated that there was a highly significant ($p \geq .01$) relationship between the mineral and fixed ($r = -0.36$), mineral and water-soluble ($r = 0.42$) forms. These were indications that those released from the mineral forms as a result of weathering made potassium available in the water-soluble forms, out of which some portions were rendered

Table 6. Relationship between the forms of potassium and other soil properties in the study area.

		Forms of potassium				
		Structure	Reserve	Fixed	Soluble	Exchangeable
Forms of potassium	Reserve	0.23				
	Fixed	−0.36**	0.12			
	soluble	0.42**	0.81**	−0.02		
	Exchangeable	−0.19	0.60**	0.23	0.70**	
Sand		−0.49**	0.11	0.42**	−0.10	0.36**
Silt		0.05	−0.03	−0.18	−0.03	−0.02
Clay		0.53**	−0.11	−0.37**	0.14	−0.39**
pH		−0.39**	0.16	0.208	0.05	0.22
Electrical conductivity		0.36**	−0.17	−0.04	−0.10	−0.17
Organic matter		0.53**	−0.37**	−0.47**	−0.21	−0.35**
Exchangeable	Calcium	−0.20	0.16	0.08	0.16	0.06
	Magnesium	−0.26	0.10	0.03	0.12	0.06
	Sodium	0.48**	−0.20	−0.06	−0.28*	−0.37**
	Acidity	0.38**	−0.02	0.17	−0.28*	−0.06
ECEC		−0.06	0.14	0.03	0.15	0.03
Base saturation		−0.40**	0.15	0.15	−0.06	0.36**

Note: ECEC = Effective cation exchange capacity.

unavailable for use by the plants in the fixed form. The reserve form equally highly significantly ($p \geq .01$) correlated with both soluble ($r = 0.81$) and exchangeable ($r = 0.60$), indicating that they were released from the reserve form of potassium. These suggest that water-soluble forms of potassium in CPS originate from the structure and reserve forms with majority from the reserve form, whereas available originates only from the reserve forms. Inasmuch as the soils depended largely on the reserve forms for the release of readily available potassium, the very little capacity to release makes it difficult for the soil to ever have good supply. Also water-soluble form, which is another source of readily available potassium, could originate from mineralogical component of the soil, but the disadvantage is that a large proportion of releases from the mineralogical weathering is fixed (i.e. $r = 0.36$ out of $r = 0.42$). This is assuming that the potassium released from mineralogical weathering is partly readily available in the water-soluble form and partly fixed, leading to the tendencies that minimal quantities remain in solution. This is consistent with the characteristics of CPS.

In the relationships between the potassium forms and other soil properties, it was observed that highly significant ($p \geq .01$) correlation existed between the mineral or structure form and sand ($r = -0.49$), clay ($r = 0.53$), pH ($r = -0.39$), electrical conductivity ($r =$ 0.36), organic matter ($r = 0.53$), sodium ($r = 0.48$), acidity ($r = 0.38$) and BS ($r = -0.40$). The clay component of the psf increases the tendencies for the release of potassium, whereas the sand acts in the contrary. This is because the psf are dominated by sand fractions, out of which fine sand which is the major source of potassium is minimal. Soil pH and organic matter content significantly influence the release of potassium from quartz arenite in a process referred to as acidolysis and chelation, respectively. But in this instance, it was observed that the contribution of chelation is more than acidolysis.

The non-exchangeable forms of potassium including reserve ($r = 0.37$) and fixed (0.47) each highly significantly ($p \geq .01$) correlated with organic matter, whereas fixed form additionally significantly ($p \geq .01$) correlated with sand ($r = 0.42$) and clay ($r = 0.37$). The water-soluble form of the readily available potassium significantly ($p \geq .05$) correlated with exchangeable sodium ($r = -0.28$) and EA ($r = -0.28$), while exchangeable potassium significantly ($p \geq .01$) correlated with sand, clay, organic matter, sodium and BS ($r = 0.36$, 0.39, −.035, −0.37 and 0.36, respectively). These are confirmations of the influence of organic matter, psf, extent of weathering and soil development on the dynamics of potassium within the landscape of CPS of southeastern Nigeria. The significance of organic matter is an indication that land use and changes could play important roles in the dynamics of potassium in the CPS.

4. Discussions

4.1. Land-use changes and dynamics of potassium

The dominance of quartz arenite within the humid tropical ecology of CPS landscape of southeastern Nigeria significantly influences the processes of soil genesis and nutrient dynamics. These soils are highly weathered and classified as ultisols or acrisols and the extent of development left the soils with very minimal amount of readily available potassium to the detriment of plant growth and development. The land use and management systems of the study area never make provision for appropriate ameliorative application of potassium as the major source of potassium is geological K-feldspar known to be low in the different forms of potassium. Then evidently the potassium content of the CPS is intrinsically and characteristically low in the different forms of potassium.

The soil organic matter content of the study area was found to have been significantly influenced by the different land uses. It had already been reported that acid sands of southeastern Nigeria are inherently low in organic matter due to the effect of environment and land-use practice.[33] Inasmuch as the different land uses did not manifest a significant effect in the dynamics of potassium, but for the peculiarities of the environmental characteristics of southeasterrn Nigeria, forest, fallow and farm land uses play an important role in the accumulation of organic matter, moderation of pH and soil temperature and these are the major determinants of the extent of weathering and release of nutrients within the mineral lattices. But the effect of very high temperatures, long period of torrential rainfall and infiltration characteristics subjects the study area to high rate of weathering, mineralisation and intensive leaching. These result in almost complete breakdown and loss of entire potassium within the mineral lattices, poor capacity of the literally unavailable organic matter to retain nutrients or participate in chelation of potassium due to high mineralisation rates and very high rate of loss of materials in solution due to leaching.[55]

Under the forest land use, accumulation of organic matter and reduced leaching moderate soil temperature and pH to the extent that could decrease the loss of total potassium content in the soils, and the contrast is true for fallow and farmland.[13,14,16,18] Therefore, the prevailing condition in the study area is the decreasing trend in the total potassium content from forest to agricultural (fallow to arable) land use. This implies that approximately 85.7% of the study area occupied by agricultural land use is continually and cyclically exposed to the processes of potassium mining. This was further indirectly confirmed with point-by-point change detection that revealed the evidence of continual interchange between fallow and farmland uses in a four-year circle.

The crop production system practised in the CPS indicated that potassium mining will continue to increase as the cycles of fallow farmland do not replenish potassium enough to encourage build-up. Very low potassium content of CPS had been severally reported which portend requirement for high fertiliser application for optimum crop yield. The minimal and inadequate application of fertiliser in the crop production [5] system results in suboptimal output.[56] A combination of low yield and population surge created the need for production of more food and the only available alternative to increase food production is intensification and extensification with resultant increase in the nutrient mining and consistent decrease in yield.[21–23] These are indications that the future is bleak with regard to food sufficiency in the areas found on CPS geomorphic unit that characterise approximately 70% of Akwa Ibom State of southeastern Nigeria.

4.2. Effect of CPS on the forms and distribution of potassium

A very broad categorisation of the forms of potassium based on increasing plant's capacity to utilise include mineral (structural), slowly available (reserve and fixed) and readily available (water soluble and exchangeable). The bulk of the total soil potassium is in the mineral form,[57] which is a crystalline, insoluble and relatively unavailable pool that weathers very slowly to release more readily available forms (water soluble and exchangeable) which could be taken up by plants, leached or fixed. There are equilibrium and kinetic reactions between the slowly and readily available forms of potassium that affect the quantity of water-soluble potassium at any particular time and thus the mount of readily available potassium for plants.[57,58] These could explain the strength of the relationship which existed between mineral, fixed and water-soluble potassium. Inasmuch as plants depend entirely on the readily available pool, the mineral potassium constitutes a very large reserve that can be solubilised to a variable extent depending on the prevailing environmental condition, plant type and cropping system.[18] These readily available forms (water soluble and exchangeable) could be immobilised (in the form of fixed or reserve) soon after their release from the mineral forms.

Water-soluble potassium is the form that is directly taken up by plants and microbes and also is the form most subject to leaching and immobilisation in soils. The quantities of soluble K are generally low unless recent amendments have been made to the soil. Sufficiency in ameliorative supply of plant nutrients is not a common practice in low input agricultural production system.[20–22] The resultant minimal quantity of water-soluble K within the soil is influenced by the equilibrium and kinetic reactions that occur between the different forms of potassium, the soil moisture content and the concentration of bivalent cations in solution and on the exchange phase.[57] These led to the strong relationship between mineral and solution potassium in the CPS. The acid sands of coastal plain landscape are dominantly ultisol that have undergone a very high degree of weathering inferior only to oxisols and have lost potassium to a very large extent that will require more extreme environmental conditions for further releases. Releases of readily available from the reserve form of potassium depend more on the quantity of potassium within the solution phase and the exchange sites as influenced by plant uptake and leaching. This is a more dynamic and active process and could explain the stronger association that exist between water soluble and reserved in comparison to the mineral form of potassium. Exchangeable is also a readily available portion of soil potassium that is electrostatically bound as an outer-sphere complex to the surface of clay minerals and humic substances. It is readily exchanged with other cations and is also readily available to plants. The very strong association between the exchangeable and water soluble and with reserve is an indication of the contribution of the three forms in the release and availability of potassium for plant utilisation.

Non-exchangeable or fixed differs from mineral potassium in that it is not bounded within the crystal structures of soil mineral particles. It is held between adjacent tetrahedral layers of octahedral and trioctahedral micas, vermiculites and intergrade clay minerals such as chloritised vermiculites. Potassium becomes fixed because the binding forces between potassium and clay surfaces are greater than the hydration forces between individual K^+ ions. This results in partial collapse of the crystal structures and the K^+ ions are physically trapped to varying degrees, making potassium release a slow and diffusion controlled process.[58] The inverse association between the mineral and fixed form of potassium confirms that the increase in degree or extent of weathering results in a higher degree of fixation of potassium as manifest in ultisols and thus could equally serve as a measure of extent of soil development.[8] This was confirmed by Pedro [2] that appreciable amounts of potassium are liberated from feldspar when weathering is very intensive as in the humid tropics. Under such conditions, the feldspars are also substantially destroyed as found in oxisols or latosols to the extent that they are not able to serve as a source of reserve potassium.

Parent materials of mineral soils are geogenic in origin and significantly influence particle size distribution of soils.[59] The geogenic origin of soil potassium manifests itself in the relationship established between different forms of potassium and the psf of CPS. The mineral or structural potassium found within the sand particles are very tightly held in the quartz mineral fraction and could be very sparingly released under normal environmental condition and the contrast is true for clay. The relationships observed between the mineral form and the psf equally manifest itself in fixed and exchangeable but in the inverse association, implying predisposition to leaching and fixation process as a result of the preponderance of sand fraction, whereas clay content discourages such process and yet does not support the release of the exchangeable form as was equally found with organic matter. Leaching is a consequence of the dominance of coarse sand fractions to the detriment of clay that possesses the capacity to hold nutrients including potassium in the exchange sites. The clay and organic matter contents are known to be the repositories of exchange sites in the tropical soils, but the complexity of the dynamics of potassium within the CPS that are known for very low content of readily available potassium has not displayed such characteristics probably due to the dominance of sandstone and siltstone lithofacies that impose characteristics of quartz arenite. Quartz arenite is characteristically very low in clay and K-feldspar and these are major geogenic sources of potassium. Additionally, organic matter particles hold most positively charged nutrients tightly with the exception of potassium. This is simply because the attraction between potassium ion and organic matter particles is relatively weak, and consequently some potassium leaches from the organic matter particles. The circumstance of very low organic matter which exists with the tropical humid environment of CPS of southeastern Nigeria does not encourage the accumulation of readily available (exchangeable) potassium. The inability of organic matter particles to form a strong bond with potassium may have been responsible for the inverse relationships between organic matter content and both slowly available and readily available forms of potassium. The pedogenic implication of the relationship between mineral or geogenic potassium manifests in the inverse relationship between BS of CPS. BS is an indication of the extent of weathering, pedogenesis or soil development and it was reported that the more highly weathered or developed a soil is, the higher is the quantity of mineral form of potassium that may have been lost [58] as found in the K-feldspar of the quartz arenite in the humid tropical environment of southeastern Nigeria.

5. Conclusions

The distribution of the different forms of potassium within the CPS landscape was dependent on neither land use nor landscape positions, but on other soil properties. The potassium content of the soil was at the lowest threshold that is incapable to sustain optimal crop production. Therefore, the quantities that could be extracted by plant uptake as a consequence of land use are too minimal to manifest differences that could be attributed to land use. The dominant form of potassium is the structure or mineral which constitute approximately 97.4%, indicating that less than 3% represented the non-exchangeable (i.e. slowly available) and readily available in the CPS. The proportions of the remaining forms of potassium within the soil were 1.9% and 0.7% for the non-exchangeable and readily available forms, respectively, which is very low for agricultural production. It was established that weathering releases potassium from the mineral to water-soluble form out of which some portions were fixed. The reserve form equally releases both soluble and exchangeable potassium. The water-soluble form could originate from the mineralogical component of the soil, but the disadvantage is that large proportion of the releases from the mineralogical weathering is fixed, leading to the tendency that minimal quantity remains in solution. The clay component of the psf increases the tendencies for the release of potassium, whereas sand acts in the contrary including increased chances of leaching. The study confirmed that organic matter, psf, extent of weathering and soil development influence the dynamics of potassium within the landscape of CPS of southeastern Nigeria.

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