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EFFECT OF SLOPE CURVATURE AND GRADIENT ON SOIL PROPERTIES AFFECTING ERODIBILITY OF COASTAL PLAIN SANDS IN AKWA IBOM STATE, NIGERIA

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ABSTRACT
A study was conducted to assess the effect of slope curvature and gradient on soil properties affecting erodibility of coastal plain sands in Akwa Ibom State. Twelve locations comprising six each of concave (CC) and convex (CV) slopes, and three slope gradients, namely, gentle (GS), moderate (MS) and steep slopes (SS) in CC and CV were identified for the study. Bulk and core soil samples were collected from the top 30 cm soil depth at three slope positions of slope curvature and gradient categories for physical and chemical characterization, and derivation of microaggregate stability indices and erodibility factor, K. Results showed that coarse sand (CS), fine sand (FS), bulk density (Bd), total porosity (TP) and saturated hydraulic conductivity (K_{sat}) were significantly ($p \leq 0.05$) higher on CC than CV, and among the slope gradients, GS > MS > SS. The interaction of slope curvature and gradients was significantly higher on CC than CV. A similar pattern of differences was also observed inorganic matter (SOM), calcium (Ca), magnesium (Mg), and other exchangeable cations, but the effect of slope curvature and gradients interaction was not significant. The microaggregate stability indices, water dispersible clay (WDC), water dispersible silt (WDS), dispersion ratio (DR), clay dispersion ratio (CDR), modified clay ratio (MCR), clay flocculation index (CFI), aggregated silt + clay (ASC) and aggregated clay (AC) were significantly higher on CV than CC, and differences among slope gradients and interaction of slope curvature and gradients were not significant. The erodibility factor, K, was significantly higher on CV than CC, while the slope gradients were similar in their effects on K. Linear regression analysis showed that K-factor was highly significantly related to CS, FS, Si, Cl, Bd, TP and K_{sat}, as well as WDC, WDS, CDR, DR, CR, MCR, CFI, ASC and AC. However, CS, Si, K_{sat}, Cl, ASC and WDS which explained > 40% of the variability in K-factor could be relied upon as indices of soil erodibility in the coastal plain sands in Akwa Ibom State.

Key words: erosion prediction, soil structures, soil erosion, shear resistance, soil degradation

INTRODUCTION
Soil erosion is widespread in the humid tropics (Lal, 2001), and is the most common process of soil degradation, the long-term decline in its productivity and capacity to function, because it depletes the soil's productive potential and diminishes the resource base. In Nigeria, the unmitigated menace of accelerated erosion, resulting mainly from the nature of the soils, the vagaries of climate and anthropogenic activities, has caused tremendous damage to the environment through pollution, depletion of the soil organic carbon pool and nutrient reserves and loss of biodiversity, and a threat to sustainable agricultural production and the livelihoods of the majority of the population (Ogban and Ekerette, 2000; Ogban and Edoho, 2011; Obalum *et al.,* 2012; Ogban and Otobong, 2016). Soil erosion thus constitutes a national hazard whose knowledge and management is a prerequisite to agricultural land development.

Soil erosion and degradation are due to energy input factors (climate and topography), protection factors (vegetation, socioeconomics and land management) and resistance factors (soil characteristics and management). Further, soil erosion is a function of two opposing forces, i.e., the driving force of the erosion agents and the resisting force of the soil. While the driving force is due mainly to rainfall characteristics (raindrop impact) and runoff (Blanco and Lal, 2008; Ezeabasili *et al.,* 2014) in relation to topography, vegetation, socio-economics and land management, the resisting force is due to the inherent properties of the soil, both of which vary spatially from one location to another. However, the inherent characteristics and properties of the soil determine the soil erosion process, because the deterioration of the soil physical properties manifests through soil's ability to accept rainwater, permit root growth and resist runoff and accelerated

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erosion (Wischmeier and Mannering, 1969). The inherent susceptibility of soils to erosion by rainfall or by surface flow or both is usually called soil erodibility (Renard *et al.,* 1997). Soil erodibility, is, therefore, the intrinsic factor that determines the ease of soil detachability and transportability (Hillel, 2004), and is the essential parameter in the prediction of soil erosion (Blanco and Lal, 2008; Yang *et al.*, 2018). It is expressed quantitatively as the *K-factor* of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), and strongly requires the understanding of the parameters influencing it (Yang *et al.*, 2005). Soil erodibility can be evaluated by using runoff plots, which can be expensive, time consuming and is not feasible in all places. It can also be estimated using the nomograph developed by Wischmeier *et al.* (1971) but which may not apply to all situations (Rejman *et al.*, 1999). Soil erodibility can as well be estimated using various soil erodibility indices based on soil characteristics (Kumar *et al.*, 1995). Soils differ in their erodibility. Consequently, a soil with relatively low erodibility may show signs of serious erodibility, yet, a soil could be highly erodible and shows little erosion, because of the spatial variability in the active (rain splash and run off energy, terrain and land use), and passive (vegetation and soil) erosion factors (Hillel, 2004; Blanco and Lal, 2008). That is, soils with lowest erodibility should, but do not necessarily have the lowest erosion rates. However, Ezeabasili *et al.* (2014) observed that soils with high erodibility were highly susceptible to erosion.

The *K* index is the integrated response of several direct and indirect measurable soil properties to erosion. Fu *et al.* (1999) related the vulnerability of soils to erosion to land use and soil management, while Igwe *et al.* (1995) reported that the vulnerability of soils to erosion depended, among other factors, on the nature of the soils. The soil properties that influence soils' resistance to erosion are soil texture, soil structure or aggregate stability, shear strength, infiltration capacity, organic matter and chemical contents (Morgan, 2001; USDA, 2013), but soil texture and structure are the principal factors (Ritter, 2012), because they either predispose the soil to erosion or retard it. Hillel (2004) and Yang *et al.* (2018) reported that coarse textured soils, soils with lower silt content, but higher clay and organic matter contents, soil structural stability and high permeability have low erodibility and vice versa. Chude *et al.* (2011) found that low soil nutrient status could render a soil susceptible to erosion, due to poor vegetation density and which could adversely affect soil organic matter and its stabilising effect on soil aggregates (structure) and infiltration capacity and rate of soil erodibility. Similarly, the chemical nature of the soil, such as high concentrations of Ca and sesquioxides have been found to enhance soil aggregation, promote good structure, increase permeability (Hillel, 2004; Lal and Shukla, 2005) and reduced erodibility, while high Na concentrations degrade soil structure and reduce permeability (Hillel, 2004; Davies and Lacey, 2009; Davis *et al.*, 2020), thus increasing erodibility. The study of soil properties could therefore be used to infer a soil's erodibility status.

The accurate prediction of soil erosion and development of conservation measures strongly require knowledge of the structural stability indices and erodibility models of soils (Ogban, 2017). Although no single measurable soil property could represent the soil erodibility (Lal, 1990), soil aggregate stability had been found to be strongly correlated with soil erodibility (Bryan, 1968).This is because the amount of soil erosion depends to a large extent on the resistance of soil aggregates to the disruptive energy of raindrop impact, and, the stability of soil aggregates also affects the ability of surface soil to accept a continuous heavy rainfall; the latter being a critical factor in the prevention of accelerated soil erosion. Usually, soil erosion begins with breakdown of soil aggregates (organo-mineral complexes), and soils with weak aggregate (structural) stability erode faster than those with high aggregate stability (Darboux and Le Bissonnais, 2007). Therefore, many of the indices of aggregate stability also relate to soil erodibility. Macroaggregate and microaggregate stability are indices of erodibility, but the stability of microaggregates is essential for improved macroaggregation, stable soil structure, and reduced erodibility (Hillel, 2004; Igwe and Obalum, 2013; Juriga and Simansky, 2018). Igwe *et al.* (1999a) and Igwe (2005) reported that soil erosion by water is directly linked to microaggregate or colloidal stability.

Soil microaggregate stability is measured indirectly with indices derived from soil properties (Isikwue *et al.,* 2012; Igwe and Obalum, 2013), which can also be used to estimate the K-factor and erosion status of the soil (Igwe and Obalum, 2013). Igwe and Obalum (2013) reported the suitability of the microaggregate indices for assessing soil erodibility and potential soil loss in the tropical region, and that it is microaggregate rather than macroaggregate stability that is closely related to erodibility and a better indicator of potential soil erosion hazards than the latter in tropical soils. The potential of a soil to erode has been estimated using the water-dispersible clay (WDC) and its associated indices (Igwe *et al.*, 1995; Amezketa *et al.*, 1996; Calero *et al.*, 2008). Igwe (2003) together with Ogban and Otobong (2016) found water-dispersible clay (WDC), clay dispersion ratio (CDR), dispersion ratio (DR), clay ratio (CR) and modified clay ratio (MCR) significantly related and could be used to predict erodibility in soils of South-eastern Nigeria. Similarly, Ogban (2017) reported that aggregated clay (AC), aggregated silt plus clay (ASC) and clay flocculation index (CFI) correlated significantly with erodibility in southern Nigeria. Iboto (2017) observed significant relationship between WDC, WDS, ASC, AC and erodibility on the coastal plain sands in Akwa Ibom State.

Historic soil erosion on slopes can affect the susceptibility of soils to subsequent erosion (Ritter, 2012), depending on the nature of the slopes. For instance, soil erodibility increases with increasing slope convexity and gradient (gentle < moderate < steep slopes) because denudational energy increases correspondingly, affecting soil formation as well (Alewell *et al.*, 2008). Consequently, the topsoil becomes thinner, subsurface soil is more erodible than the original topsoil because of poorer structure and lower organic matter content, which accentuate soil erosion (Ritter, 2012). On the other hand, areas where deposition occurs, usually on concave and or gentle to moderate slope, have deeper topsoil depth, increased vegetation and organic matter content, stable soil structure, increased permeability and infiltration capacity and reduced erodibility. Thus, erosion is reduced on concave slope (Stefano *et al.,* 2000) while convex slopes are highly erodible and easily degraded (Schoonover and Crim, 2015).

Accelerated soil erosion is widespread, severe and of concern to researchers, farmers and society in humid tropical south-eastern Nigeria (Ogban and Ekerette, 2000). It has not only created spectacular features on the landscape, yields of crops have declined, threatening livelihoods (Ogban and Edoho, 2011; Ogban and Otobong, 2016). Although studies (Mbagwu, 1986; Obi *et al.*, 1989; Igwe, 2003; Ogban and Edoho, 2011) have attributed soil erosion in the area to soil properties accentuated by climatic factors, terrain and soil characteristics, little is known about the inherent nature of the soils in relation to slope characteristics and their susceptibility to erosion in the study area. Knowledge of the nature of the basic soil properties and characteristics in relation to topographic features is therefore important to predicting their erodibility and developing quality soil management practices for the soils formed on the coastal plain sands. The study was conducted to determine the effect of slope curvature and gradient on inherent properties, micro-aggregate stability and erodibility; to determine the indices that could be used to predict the erodibility factor, *K* or index of erodibility for the coastal plain sands in Akwa Ibom State, Southern Nigeria.

MATERIALS AND METHODS

Study Location

The study was conducted on the coastal plain sands in Akwa Ibom State, Nigeria. Akwa Ibom State is located between latitudes 4°50′ and 5°50′N, longitudes 7°30′ and 8°30′ E, while the area of the coastal plain sands is found between latitudes 4°40′ and 5°15′ N and longitudes 7°30′ and 8°15′ E. The climate of the State is the hot humid tropical, characterized by two seasons; the wet and dry seasons. The wet or rainy season lasts between April and October, while the dry season occurs through November to March. The area is characterised by rainfall varying from 3000 mm along the coast to about 2000 mm on the northern fringes. Temperatures are uniformly high even with climate change, averaging 28°C with relative humidity ranging from 75 to 95%, while evapotranspiration ranges from 4.11 to 4.95 mm (Enwezor *et al.,* 1990; Udosen, 2017).

The coastal plain sands are derived from unconsolidated tertiary sandstones of the Benin formation, with the associated shale and limestone (Petters *et al.*, 1989). The area also consists of hilly topography, owing to geomorphic processes such as cycles of erosion and denudation, with rainfall as the principal agent. The soils are characterized by low organic matter content, poor structural stability and highly susceptible to accelerated erosion. The vegetation of the study area has been almost completely replaced by secondary forest of predominantly wild oil palm trees and woody shrubs with various undergrowths. The landscape comprises cultivated and fallow lands.

Field Methods

A reconnaissance survey was undertaken to identify the locations of study in the area. Twelve locations (slopes), which were interspersed without a definite order and for which local differences in climate cancelled out, were selected for the study. Six of the slopes were replications of concave (CC) while six were for convex (CV) slopes. Also, each slope curvature comprised three steepness categories, namely, gentle slope (GS), moderate slope (MS) and steep slope (SS). The gradients of the slopes were; GS is < 10%, MS is 11-27% and SS is > 27% (van Gool *et al.,* 2005). Therefore, slope curvature and gradient constituted the factors in the study. On each slope, bulk soil samples were collected from the top 30 cm depth at the upper, middle and lower slope positions, to give a total of 36 soil samples (i.e., 2 slope curvatures × 3 slope gradients × 6 replications) for characterization of physical and chemical properties. Also, undisturbed core soil samples were collected from the same depth using metal cylinders measuring 7.2 cm long and 6.8 cm internal diameter for the determination of soil bulk density and saturated hydraulic conductivity (K_{sat}).

Laboratory Methods

The bulk samples were air-dried and sieved through a 2 mm mesh for particle-size analysis using the Bouyoucos hydrometer method with sodium hexametaphosphate solution as the dispersant to obtain total clay (TCl) and total silt (TSi), and deionised water to obtain water dispersible clay (WDC) and silt (WDS) (Mbagwu and Auerswald, 1999; Igwe, 2005; Igwe and Nkemakosi, 2007). Soil bulk density was determined by oven-drying the core samples to constant weight at 105°C, and values of bulk density computed as described in

Grossman and Reinsch (2002). Total porosity was calculated from soil bulk density, ℓ_b. The K_{sat} was determined using the constant head permeameter method (Reynolds and Elrick, 2002). Soil microaggregate indices were calculated as follows:

$$Dispersion\ Ratio\ (DR) = \frac{\%\,WDS + \%\,WDC}{\%\,TS + \%\,TC} \quad (1);$$
(Singh and Khera, 2008)

$$Clay\ Dispersion\ Ratio\ (CDR) = \frac{\%\,WDC}{\%\,TC} \quad (2);$$
(Igwe and Nkemakosi, 2007; Opara, 2009)

$$Clay\ Ratio\ (CR) = \frac{(\%\,silt + \%\,sand)}{\%\,clay} \quad (3);$$
(Singh and Khera, 2008)

$$Modified\ Clay\ Ratio\ (MCR) = \frac{(\%\,silt + \%\,sand)}{(\%\,clay + \%\,organic\ carbon)} \quad (4);$$
(Singh and Khera, 2008)

$$Silt\ Clay\ Ratio\ (SCR) = \frac{(\%\,silt)}{(\%\,clay\,)} \quad (5);$$

$$Clay\ Flocculation\ Index\ (CFI) = \frac{\%\,TC - \%WDC}{\%\,WDC} \quad (6);$$
(Igwe and Nkemakosi, 2007)

$$Aggregated\ Silt + Clay\ (ASC) = \%\,TC + TS - \%\,(WDC + WDS) \quad (7);$$
(Igwe *et al.*, 1999b)

$$Clay\ Aggregation\ (CA) = \%\,TC - \%\,WDC \quad (8)$$
(Igwe *et al.,* 1999b)

The concept of the *smaller the value, the more stable* the microaggregates (are for) was applied to Equations (1) to (7), and *the bigger the value, the more stable* the microaggregates (are for) to Equations (8) to (10) (Igwe and Obalum, 2013). The erodibility factor, *K*, was calculated with the revised modified *K* equation of Auerswald *et al.* (2016). Auerswald *et al.* (2014) reported that the equation produces *K* values that were similar to those of the nomograph developed by Wischmeier *et al.* (1971). The modified equation is as follows:

$$K = K_1 \times K_2 + 0.043 \times (A - 2) + 0.033 \times (P - 3) \quad (9);$$

where K_1 is $2.77 \times 10^{-5} \times (f_{si+vfs} \times (100 - f_{Cl})^{1.14}$ and $K_2 = (12 - f_{OM})/10$, K is the soil erodibility factor, f_{Si+vfs} is mass fraction (%) of silt plus very fine sand in the fine earth fraction, f_{Cl} is mass fraction (%) of clay in the fine earth fraction, f_{OM} is mass fraction (%) of organic matter in the fine earth fraction, *A* is soil structure index (1 to 4) increasing from very fine granular to blocky, platy or massive (Wischmeier *et al.,* 1971); *P* is permeability index (1 to 6) increasing from rapid to very slow in a way that 1 is > 15 cm h^{-1}, 2 is 5-15 cm h^{-1}, 3 is 1.5-5.0 cm h^{-1}, 4 is 0.5-1.5 cm h^{-1}, 5 is 0.1-0.5 cm h^{-1}, and 6 is < 0.1 cm h^{-1} (Wischmeier *et al.,* 1971).

Organic carbon was determined by the wet oxidation method (Nelson and Sommers, 1996) and organic matter was obtained by multiplying the values of organic carbon by a factor of 1.72. Exchangeable bases (Ca, Mg, K and Na) were determined by the methods described by Sparks (1996) and exchangeable acidity by the KCl procedure. Effective cation exchange capacity (ECEC) was obtained by summation of exchangeable bases. Sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) were calculated as follows:

$$SAR = Exchangeable\ (Na) / (Ca + Mg)^{-0.5} \quad (10);$$

$$ESP = Exch.\ (Na) / (Ca + Mg + K + Na) \times 100 \quad (11).$$

Statistical Analysis

Data were fitted into and subjected to a 2 × 3 factorial arrangement and assessed using the analysis of variance in six replications. Significant means were separated using the Duncan's new multiple range test at 5% level of probability. Correlation analysis was used to study the association between soil erodibility and soil physical and chemical properties, while the relationships between them were studied using regression analysis.

RESULTS AND DISCUSSION

Effect of Slope Curvature and Gradient on Soil Physical Properties

The data of the effect of slope curvature and gradient on soil physical properties are presented in Table 1 and discussed subsequently.

Particle size distribution

The data of particle-size fractions (psf) averaged over the slope gradients showed that the sand separates were similar between the conclave (CC) and convex (CV) slopes, but coarse sand (CS) was higher on CC than CV (Table 1). Coarse sand (CS) fraction was much higher than fine sand (FS) on both slope curvatures. The silt fraction was significantly (p < 0.05) higher on CV, while clay was significantly (p < 0.05) higher on CC, translating to 42.9% lower in the convex slope than concave slope. The sand fractions were also similar among the slope gradients but higher on the steep slope (SS) than the moderate (MS) and gentle (GS) slopes. The silt and clay fractions were similar but while silt was in the order MS > GS > SS, clay decreased from GS through MS to SS. The higher clay content on CC and the slope gradients could be due to the fact that concave slopes are convergent or receptacles for the inflow soil materials, and together with low gradient slopes generally encourage deposition of eroded soil particles (Stefano *et al.,* 2000; Alewell *et al.,* 2008; Griffiths, 2018) compared to CV and steep slopes (Wubie and Assen, 2020). The curvature × gradient interaction effect was generally similar among the psf in all locations of the study, but Cl was higher in CC × GS and CC × MS than in other interactions.

Table 1: Effect of slope curvature and gradient on soil physical properties

	CS	FS	TS	Si	Clay	Bd	TP	K_{sat}
	g kg^{-1}					Mg m^{-3}	m^3 m^{-3}	cm h^{-1}
Curvature								
CC	760.00^a	100.00^a	860.00^a	40.00^b	100.00^a	1.45^b	0.45^a	29.48^a
CV	730.00^a	110.00^a	840.00^a	90.00^a	70.00^b	1.53^a	0.42^b	16.26^b
Gradient								
GS	740.00^a	90.00^a	830.00^a	70.00^a	100.00^a	1.42^c	0.46^a	32.19^a
MS	730.00^a	100.00^a	830.00^a	80.00^a	90.00^a	1.49^b	0.44^b	21.51^b
SS	760.00^a	110.00^a	870.00^a	50.00^a	80.00^a	1.57^a	0.41^c	14.91^b
Interaction (curvature × gradient)								
CC × GS	760.00^a	80.00^b	840.00^a	50.00^a	110.00^a	1.39^a	0.47^a	47.28^a
CC × MS	720.00^a	110.00^a	830.00^a	50.00^a	120.00^a	1.47^a	0.45^a	27.36^a
CC × SS	790.00^a	100.00^a	890.00^a	30.00^a	80.00^a	1.49^a	0.44^a	13.80^b
CV × GS	730.00^a	110.00^a	840.00^a	90.00^a	70.00^a	1.44^a	0.46^a	17.10^b
CV × MS	730.00^a	100.00^a	830.00^a	100.00^a	70.00^a	1.51^a	0.43^a	15.66^b
CV × SS	730.00^a	110.00^a	840.00^a	90.00^a	70.00^a	1.66^a	0.38^a	16.02^b

CC - concave slope, CV - convex slope, GS - gentle slope, MS - moderate slope, SS - steep slope, CS - coarse sand, FS - fine sand, TS - total sand, Si - silt, Bd - bulk density, TP - total porosity, K_{sat} - saturated hydraulic conductivity

The high concentration of CS and reduced amounts of FS, Si and Cl on each slope curvature, gradient and curvature and gradient interactions indicated that the finer psf were detached and transported from the slopes in runoff and or infiltrating water (Stefano *et al.*, 2000), similar to reports by Obi and Asiegbu (1982), Blanco and Lal (2008) and Igwe (2011) that finer soil separates are easily transportable relative to the coarse fragments. Soils whose matrix is dominated by skeletal, non-reactive psf have high detachability potential because the potential for aggregate formation is low. Hillel (2004) and Yang *et al.* (2018) observed that coarse textured soils, with low silt, but high clay and organic matter contents, soil structural stability and high permeability would have low erodibility and vice versa. Similarly, Carbery *et al.* (2005) reported that soils with a high percentage of FS tended to be erodible due to the weak bonds between particles, ease of slaking and detachment by raindrop impact and scouring by flowing water. Yang *et al.* (2018) also found that the detached fine particles have the tendency to clog drainage pores, thereby reducing water infiltration, increasing overland flow and aggravating the menace of soil erosion.

Bulk density and total porosity

Whereas bulk density was significantly ($p \leq 0.05$) higher on CV than CC slope, it however varied significantly ($p \leq 0.05$) in the order of SS > MS > GS (Table 1). The interaction effect of curvature × gradient was not significant in all locations (Table 1). Wubie and Assen (2020) also observed similarity in the effect of curvature and gradient. The pattern of differences in Bd was attributed to particle-size distribution; Bd was generally higher where TS was correspondingly high. Obalum *et al.* (2011) made similar observation among landforms and slope positions in an inland-valley soil. The present observation is evident in the negative but significant ($p \leq 0.01$) correlation between Bd and TS (Table 4). Total porosity (TP) was significantly ($p \leq 0.05$) higher on CC than CV and also different ($p \leq 0.05$) among GS, MS and SS (Table 1). The interaction effect of curvature and gradient on total pore space was similar but in the order of GS > MS > SS on CC and CV. The trend in TP was similar to clay on CC and CV, and GS, MS and SS, and to the reverse pattern in bulk density. However, because of the low content of colloidal clay, its effect on TP may be negligible. Therefore, the differences in the volume fraction of pores were attributed to Bd. Generally, both Bd and TP are functions of soil texture and organic matter content (Hillel, 2004; Twum and Nii-Annang, 2015; Athira *et al.*, 2019). The observed values of Bd and TP may however not inhibit root penetration and infiltration into the soils (Koorevaar *et al.*, 1983).

Saturated hydraulic conductivity

Saturated hydraulic conductivity (K_{sat}) was significantly affected ($p \leq 0.05$) by the main effects of slope curvature and gradient, being 81.5% higher on CC than CV, and higher ($p \leq 0.05$) on GS than MS and SS by approximately 50 and 116% respectively (Table 1). Similarly, the interaction effect of slope curvature and gradient was significantly ($p \leq 0.05$) higher on CC × GS (243%) and CC × MS (98%) than CC × SS, and not significant among CV × GS, CV × MS and CV × SS; the effect of interaction being generally significantly higher on CC than CV (Table 1). The lower K_{sat} on CV compared to CC, and on SS than MS and GS, indicated increased overland flow because of low resident time water infiltration in soils on CV and steep slopes. In addition, the coarse texture and often dry state of the soils enhance water repellency and increase the potential for erosion (Ritsema and Dekker, 1994). The trend in K_{sat} was reverse to Bd and similar to TP; changes in Bd and TP for macroporosity or effective porosity of the soil have orders of magnitude change in K_{sat} (Ahuja *et al.*, 1984). The K_{sat} affects the two-dimensional infiltration, ponding, deep percolation and soil erodibility; highly erodible soils usually have low K_{sat} and infiltrability, although the rainfall characteristics can alter the infiltration rate (Hillel, 2004). Data in Tables 1 and 2 show that K_{sat} was high where TP, Cl, and SOM were correspondingly high, and where Bd was low. The K_{sat} being generally > 1.00 cm h^{-1}, the lower class limit for rapid conductivity (Mbagwu, 1995) in this study, portended also low plant available water capacity because coarse-textured soils lose water readily at the low suction range and thus the need for soil management practices that would increase the resident time for water, infiltrability and soil water retention capacity. Moreover, the more water infiltrates, the less it causes soil erosion.

Effect of Slope Curvature and Gradient on Soil Chemical Properties

The data for the effect of slope curvature and gradient on soil chemical properties are shown in Table 2.

Organic matter

Soil organic matter content (SOM) was significantly ($p \leq 0.05$) higher by 28.3% on CC than CV, similar among GS, MS and SS, and unaffected by the curvature and gradient interaction (Table 2). However, though not different, SOM was in the order: GS > MS > SS on CC and CV. The SOM content was within the range of 2.0-3.0% and rated as medium for the soils (Enwezor *et al.*, 1981, 1990). Organic matter and soil nutrients are essential for promoting favourable soil aggregation and good structure, and its loss adversely affects soil erodibility (Giovannini *et al.*, 1988). Therefore, the higher organic matter content on CC compared to CV soils in this study was a good indicator of higher stability of microaggregates and resistance of the soils to raindrop impact and runoff energies. This is because organic matter produces compounds that bond soil particles, thereby increasing soil aggregation and infiltration and reducing runoff and erosion (Yang *et al.,* 2018).

Exchangeable Ca, Mg, K and effective cation exchange capacity (ECEC)

The exchangeable cations and ECEC were generally significantly ($p \leq 0.05$) higher on CC than CV, and differed among slope gradients thus GS > MS > SS; the interaction effect of slope curvature and gradient was generally similar (Table 2). The results showed that the exchangeable cations were consistently conserved on CC than CV, and on low than high slope gradients, reflecting the fact that deposition occurs on landforms where the flow of water and its erosion potential is low (Berhe *et al.,* 2014). The distribution of the exchangeable cations appeared related to SOM, and could be the source of the cations, especially given the low content of clay in the soils. The ECEC was dominated by Ca followed by Mg, indicating a disposition for flocculation and stability of aggregates on CC compared to CV and where the gradient was low than steep. Flocculation in the soils could occur through the electrostatic interaction of negatively charged clay with positively charged divalent cations Ca^{2+} and Mg^{2+} (Hillel, 2004; Lal and Shukla, 2004; Davies and Lacey, 2009), the preliminary process in microaggregation. ECEC was significantly higher ($p \leq 0.05$) on CC than CV and GS and MS than SS; the effect of curvature and gradient interaction was not significant. The pattern of differences appeared to reflect losses of nutrient chemical species due to erosion on CV but conserved on CC (Lal and Shukla, 2005; Schoonover and Crim, 2015).

Exchangeable sodium (Na), sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP)

There were significant differences ($p \leq 0.05$) in the main effects of CC and CV on all parameters except Mg, Na and SAR (Table 2). SOM, Ca, K, EA, ECEC, Am-Fe and Am-Al were significantly higher on CC than CV, while ESP, Cr-Fe and Cr-Al were significantly higher on CV than CC. This indicates that soil constituents important in aggregation and aggregate stability were conserved on CC than CV. Similarly, slope gradient had significant ($p \leq 0.05$) effect on Mg, K, Na, EA, ECEC, SAR and ESP but there was no consistent pattern of differences among GS, MS and SS. The main effects of slope gradient did not significantly affect SOM, Ca, Cr-Fe, Cr-Al and Am-Al, indicating that it may not be critical to the conservation of these parameters in the soil.

Table 2: Effect of slope curvature and gradient on soil chemical properties

	SOM	Ca	Mg	K	Na	EA	ECEC	SAR	ESP	Cr-Fe	Cr-Al	Am-Fe	Am-Al
	(g kg^{-1})	(cmol kg^{-1})							%	(mg kg^{-1})			
	Curvature												
CC	26.50^{a}	5.30^{a}	1.66^{a}	0.13^{a}	0.05^{a}	2.50^{a}	9.64^{a}	0.14^{a}	0.76^{b}	508.62^{b}	352.66^{b}	388.82^{a}	229.89^{a}
CV	21.40^{b}	4.48^{b}	1.58^{a}	0.11^{b}	0.05^{a}	2.07^{b}	8.30^{b}	0.13^{a}	0.89^{a}	582.15^{a}	426.13^{a}	356.19^{b}	197.18^{b}
	Gradient												
GS	25.30^{a}	4.84^{a}	1.80^{a}	0.13^{a}	0.05^{b}	2.65^{a}	9.45^{a}	0.12^{b}	0.70^{b}	588.89^{a}	415.61^{a}	399.78^{a}	220.57^{a}
MS	24.60^{a}	5.22^{a}	1.59^{b}	0.12^{b}	0.06^{a}	2.28^{b}	9.27^{a}	0.15^{a}	0.85^{a}	525.35^{a}	396.61^{a}	374.26^{a}	208.38^{a}
SS	21.90^{a}	4.62^{a}	1.48^{b}	0.12^{b}	0.06^{a}	1.93^{c}	8.19^{b}	0.14^{a}	0.93^{a}	521.91^{a}	355.97^{a}	343.49^{b}	211.66^{a}
	Interaction (curvature × gradient)												
CC × GS	29.40^{a}	5.10^{a}	1.78^{a}	0.13^{a}	0.05^{a}	2.92^{a}	9.98^{a}	0.13^{a}	0.69^{b}	533.30^{a}	398.90^{a}	390.81^{a}	225.48^{a}
CC × MS	25.90^{a}	5.44^{a}	1.50^{a}	0.12^{a}	0.06^{a}	2.63^{a}	9.76^{a}	0.15^{a}	0.83^{a}	497.30^{a}	342.83^{a}	403.18^{a}	218.51^{a}
CC × SS	24.20^{a}	5.36^{a}	1.70^{a}	0.13^{a}	0.05^{a}	1.94^{a}	9.19^{a}	0.14^{a}	0.76^{b}	495.25^{a}	316.24^{a}	372.48^{a}	245.69^{a}
CV × GS	21.20^{a}	4.57^{a}	1.81^{a}	0.13^{a}	0.05^{a}	2.37^{a}	8.93^{a}	0.12^{a}	0.71^{b}	644.49^{a}	432.32^{a}	408.75^{a}	215.66^{a}
CV × MS	23.40^{a}	5.00^{a}	1.68^{a}	0.12^{a}	0.06^{a}	1.93^{a}	8.79^{a}	0.15^{a}	0.86^{a}	553.40^{a}	450.38^{a}	345.33^{a}	198.25^{a}
CV × SS	19.70^{a}	3.87^{a}	1.25^{b}	0.10^{b}	0.06^{a}	1.91^{a}	7.20^{a}	0.13^{a}	1.09^{a}	548.57^{a}	395.70^{a}	314.49^{a}	177.63^{a}

CC - concave, CV - convex, GS - gentle slope, MS - moderate slope, SS - steep slope, SOM - soil organic matter, EA - exchangeable acidity, ECEC - effective cation exch. capacity, SAR - sodium adsorption ratio, ESP – exch. sodium percentage,
Cr-Fe - crystalline-iron; Cr-Al - crystalline-aluminium; Am-Fe - amorphous-iron; Am-Al - amorphous-aluminium

The interaction effect of curvature and gradient significantly ($p \leq 0.05$) affected Mg, K and ESP. However, while the interaction effect on Mg and K was lower in CV × SS than other curvature and gradient interactions, the effect on ESP was variable being significantly higher in CV × SS, CV × MS and CC × MS than CC × SS, CV × SS and CC × GS. The results showed that interaction between curvature and gradient was not important to the conservation of the parameters in the soil. Both ESP and SAR were respectively less than 1% and significantly less than the 13 and 15% threshold values expected in dispersive soils (Davis *et al.,* 2020). Clay dispersion is therefore not a potential problem in the low activity clay (LAC) soils which predominate in the study area (Levy *et al.,* 1993).

Crystalline and amorphous oxides of Fe and Al

The results of crystalline Fe and Al oxides showed significantly ($p \leq 0.05$) higher values in CV than CC, while the more reactive amorphous Fe and Al was significantly ($p \leq 0.05$) higher (Am-Fe, 9.2%; Am-Al, 16.6%) in CC than CV soils (Table 2). The main effects of the slope gradients on the concentrations of the crystalline and amorphous oxides were not significant. Differences among the slope gradients and curvature and gradient interactions were generally similar. Moreover, the crystalline oxides were more abundant than the amorphous oxides in all slope forms which is characteristic of soils in environments at an advanced stage of weathering (Olatunji *et al.*, 2015). The dynamics of SOM, Ca, K, EA, ECEC, Am-Fe and Am-Al showed higher concentrations on CC and low slope gradients where soil resistance against erosion may be greater than the shear stress of rain drop and run off. Compared to CC, run off especially could have contributed to the translocation of soil materials and consequently the lower concentrations of the parameters in CV. This could explain the concentration of the more active and mobile Am-Fe and Am-Al in CC soil and the accumulation of the less mobile Cr-Fe and Cr-Al in CV soil. These results are in consonance with reports by Olatunji *et al.* (2015) and Jaworska *et al.* (2015). However, the abundance of these oxides is important in the formation and stability of micro-aggregates in tropical soils reputed to be poor in organic matter (Pronk *et al.*, 2011; Igwe and Obalum, 2013). Six *et al.* (2004) and Peng *et al.* (2015) attributed the formation of stable microaggregates on gentle sloping lands to the hydroxides of Fe and Al. Ahn (1979) showed that the microaggregation found in tropical soils with very low organic matter represented a more intrinsic quality of the mineral soil.

Effect of Slope Curvature and Gradient on Microaggregate Stability and Erodibility

Microaggregate stability

The clay dispersion or microaggregate stability indices WDC, WDS, DR, CDR, CR, MCR and SCR were generally significantly ($p \leq 0.05$) higher on CV, while CFI, ASC and AC were significantly ($p \leq 0.05$) higher on CC, and all indices, except for MCR, were not affected by slope steepness (Table 3). Also, the interaction of slope curvature and gradient had similar effect on microaggregate stability. In microaggregate stability, the principle of *the smaller the value, the better*, applies to WDC, WDS, DR, CDR, CR, MCR and SCR, while the principle of *the bigger the value, the better* applies to CFI, ASC and AC. In other words, the smaller the value of the indices, the less dispersive or erodible the micro-aggregates in the first category and vice versa for the second category in soils in which microaggregates predominate. The implication is that more clay dispersion or erosion had occurred in the first category in CV soil, which is corroborated by the lower values of the indices in the second category on the same slope curvature, compared to CC.

The pattern in slope gradient and slope curvature and gradient interaction was not consistent. It is observed in Tables 2 and 3 that CFI, ASC and AC like the more reactive amorphous oxides are higher and that the latter may be associated with the stability of the microaggregates in CC than CV. Thus, the results showed that soil on CV was potentially more susceptibility to intrinsic erosion or loss of microaggregate stability than on CC. Sabzevari *et al.* (2010) obtained similar results although with a wider range of factors that affect soil erosion.

Table 3: Effect of slope curvature and gradient on microaggregate stability indices

	WDC	WDS	DR	CDR	CR	MCR	SCR	CFI	ASC	AC
	g kg^{-1}								%	
					Curvature					
CC	30.00^b	20.00^b	0.37^b	0.33^b	13.54^a	8.41^b	0.46^b	0.67^a	9.69^a	7.73^a
CV	40.00^a	40.00^a	0.52^a	0.64^a	15.04^a	11.06^a	1.29^a	0.36^b	8.59^a	2.65^b
					Gradient					
GS	40.00^a	30.00^a	0.43^a	0.43^a	10.45^a	8.10^a	0.78^a	0.57^a	9.43^a	6.02^a
MS	40.00^a	30.00^a	0.47^a	0.52^a	13.59^a	9.66^a	0.99^a	0.48^a	10.31^a	5.34^a
SS	30.00^a	20.00^a	0.44^a	0.50^a	18.83^a	11.45^b	0.86^a	0.50^a	7.69^a	4.23^a
					Interaction (curvature × gradient)					
CC × GS	30.00^a	20.00^a	0.35^a	0.28^a	7.97^a	6.23^a	0.40^a	0.72^a	11.01^a	8.91^a
CC × MS	30.00^a	20.00^a	0.39^a	0.35^a	10.17^a	7.55^a	0.48^a	0.65^a	11.12^a	8.51^a
CC × SS	20.00^a	10.00^a	0.38^a	0.37^a	22.48^a	11.44^a	0.49^a	0.63^a	6.95^a	5.78^a
CV × GS	40.00^a	40.00^a	0.52^a	0.59^a	12.94^a	9.97^a	1.15^a	0.41^a	7.84^a	3.12^a
CV × MS	50.00^a	30.00^a	0.54^a	0.69^a	17.01^a	11.76^a	1.50^a	0.31^a	9.49^a	2.16^a
CV × SS	40.00^a	30.00^a	0.50^a	0.63^a	15.18^a	11.46^a	1.23^a	0.37^a	8.43^a	2.68^a

CC - concave slope, CV - convex slope, GS - gentle slope, MS - moderate slope, SS - steep slope, WDC - water dispersible clay, WDS - water dispersible silt, DR - dispersion ratio, CDR - clay dispersion ratio, CR - clay ratio, MCR - modified clay ratio, SCR - silt + clay ratio, CFI - clay flocculation index, ASC - aggregated silt + clay, AC - aggregated clay

Soil erodibility factor, K

Soil erodibility factor, *K*, was significantly ($p \leq 0.05$) higher by about 20% on CV than CC, but similar on GS, MS and SS (Figure 1). The lower erodibility in CC than CV soils followed the pattern of differences in the soil properties in Tables 1-3, for instance, Cl, Bd, TP, K_{sat}, SOM, Am-Fe and Am-Al, CFI and AC which were less favourable to erodibility on CC than CV. The observed K was therefore attributed to the factors identified in this study, that is, the soil properties mediated by slope characteristics that depict increasing or declining erodibility.

Similarly, the interactive effect of slope curvature and gradient on K-factor (Figure 2) was significant ($p \leq 0.05$) on GS but similar on MS and SS, and indicated that soils on GS were highly susceptible to erosion (*K*) on CV than on CC, while soils on MS and SS of both curvatures were less prone to erosion. It could be inferred from Figure 2 that soils of gradients on CV slope had higher susceptibility to erosion (*K*) than on CC slope, indicating greater resistance to erosion on CC soils compared to CV soils. The implication is that soils on CV slopes need suitable soil surface management practices to enhance soil infiltrability and conservation against erosion forces.

Correlation matrix of soil erodibility and soil properties

The association of soil erodibility factor, *K*, and soil properties showed that there were positive significant (**) relationships between K and FS, Si, Cl, Bd, WDS, CFI and ASC, and WDC (*), and negative significant (**) relationships with CS, TP, K_{sat}, DR, CDR, MCR, and CR (Table 4). The positive relationship of *K* with FS and Si skeletal fractions indicated the vulnerability of these psf to dislodgement and translocation; these soil particles being in the range of 0.05-0.25 mm are the most vulnerable to detachment. It is also for this reason that there is a negative correlation between these psf and structure stability. This explains the vulnerability of soils in the area to accelerated erosion and there are spectacular erosion features too. That is, the more FS and Si content of the soil the much more readily susceptible it is to slaking, dislodgement and soil loss. The positive relationship with Cl and Bd was probably in connection with the soil's predisposition to the build-up of runoff. This is associated with the fact that clay particles are highly cohesive and sticky and less easily eroded due to the influence of electrostatic forces, and the higher the bulk density the more closely packed the soil particles and decrease in total pore space, and consequently, the lower the soil infiltrability and water transmission and the higher the tendency for overland flow and erosion through scouring. Thus, while the shear resistance of the soil may be high, due to Cl and Bd, the soil may eventually yield to the shear stress of running water.

Table 4: Correlation coefficients between soil erodibility indices and physical properties

	CS	FS	TS	Si	Cl	Bd	TP	K_{sat}	OM	Ca	Mg	WDC	WDS	DR	CDR	MCR	SCR	CFI	ASC	CR
CS	1.000																			
FS	-0.458**	1.000																		
TS	0.736**	-0.145	1.000																	
Si	-0.888**	0.138	-0.739**	1.000																
Cl	-0.896**	0.043	-0.741**	0.869**	1.000															
Bd	-0.318*	-0.012	-0.286*	0.263*	0.395**	1.000														
TP	0.299*	0.019	0.270*	-0.251	-0.374**	-0.986**	1.000													
K_{sat}	0.470**	-0.331**	0.365**	-0.336**	-0.387**	-0.531**	0.519**	1.000												
OM	0.051	-0.065	0.168	0.029	-0.044	-0.156	0.200	0.279*	1.000											
Ca	0.142	-0.159	0.134	-0.162	-0.049	-0.115	0.151	0.207	0.303*	1.000										
Mg	0.066	-0.089	0.006	-0.041	-0.028	-0.060	0.076	0.056	0.103	0.249	1.000									
WDC	-0.512**	-0.053	-0.427**	0.515**	0.612**	0.180	-0.173	-0.197	-0.082	-0.077	-0.095	1.000								
WDS	-0.748**	0.024	-0.697**	0.877**	0.775**	0.284*	-0.273*	-0.242	0.127	-0.046	-0.118	0.302*	1.000							
DR	0.522**	-0.238	0.359**	-0.410**	-0.483**	-0.136	0.121	0.247	0.096	0.092	-0.080	0.059	-0.217	1.000						
CDR	0.622**	-0.232	0.479**	-0.520**	-0.592**	-0.176	0.159	0.208	0.030	0.016	-0.013	0.066	-0.524**	0.851**	1.000					
MCR	0.766**	-0.064	0.679**	-0.757**	-0.828**	-0.218	0.209	0.264*	0.050	0.113	0.034	-0.672**	-0.679**	0.257*	0.463**	1.000				
SCR	0.343**	-0.174	0.202	-0.060	-0.391**	-0.103	0.092	0.099	0.177	-0.119	0.021	-0.340**	-0.050	0.295*	0.429**	0.454**	1.000			
CFR	-0.622**	0.232	-0.479**	0.520**	0.592**	0.176	-0.159	-0.208	-0.030	-0.016	0.013	-0.066	0.524**	-0.851**	-1.000**	-0.463**	-0.429**	1.000		
ASC	-0.913**	0.115	-0.734**	0.901**	0.968**	0.370**	-0.349**	-0.403**	-0.042	-0.086	0.017	0.444**	0.781**	-0.616**	-0.686**	-0.758**	0-.292*	0.686**	1.000	
CR	0.770**	-0.092	0.664**	-0.789**	-0.801**	-0.161	0.158	0.244	0.082	0.138	0.052	-0.658**	-0.691**	0.294*	0.499**	0.966**	0.422**	-0.499**	-0.747**	1.000
K	-0.806**	0.494**	-0.693**	0.713**	0.649**	0.461**	-0.448**	-0.674**	-0.149	-0.155	-0.117	0.270*	0.656**	-0.359**	-0.445**	-0.501**	-0.121	0.445**	0.691**	-0.508**

* - significant at 5% probability level, ** - significant at 1% probability level; Abbreviations as explained in previous tables

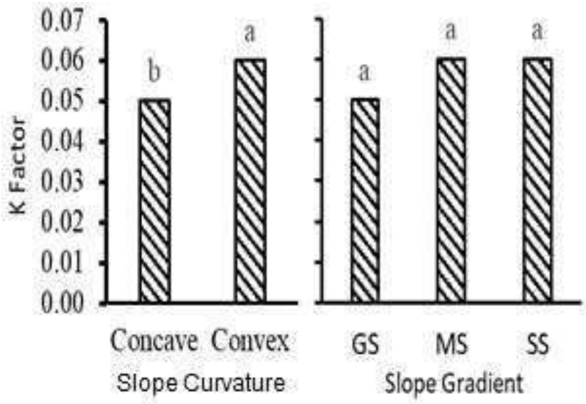

Figure 1: Effect of slope curvature and gradient on erodibility factor, K

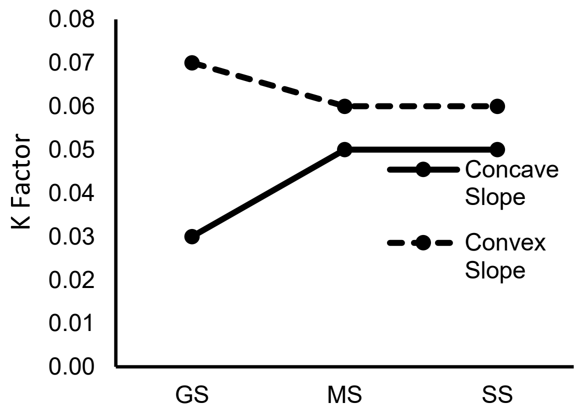

Figure 2: Interaction effect of slope curvature and gradient on erodibility factor, K

The positive relationships of *K* with WDS, CFI, ASC, and WDC contradicted the concept of *the bigger the value the more stable the soil*, because the latter expresses shear resistance and the higher the value of these indices the higher the erosive force required to breakdown aggregates, and ultimately the lower would be the erosion in this tropical soil. Igwe *et al.* (2009) reported a good positive correlation ($r = 0.53$) between K-factor and CFI and recommended its use in predicting soil erosion hazard in South-eastern Nigeria. Generally, the positive relationship of *K* with FS, Si, Cl and Bd alluded to the reduction in the number of drainage pores and water transmission through the soil, and consequently the more runoff water on the soil surface which could lead to exacerbated accelerated erosion (Hillel, 2004). This is because the more clay and silt that infiltrating or runoff water could detach from the soil mass the more the erosion that would occur because these finer particles would seal the pores between the microaggregates resulting in low infiltration rate and reduction in soil hydraulic conductivity. Keli *et al.* (2002) found low Si and high Cl contents, low Bd and high TP, K_{sat} and organic matter in soils with low susceptibility to erosion, because these properties represent suitable particle size distribution and good structural condition for water infiltration and transmission and reduced soil erosion.

The negative relationship of K-factor with CS, TP, K_{sat}, DR, CDR, MCR, and CR alludes to the low transportability of the coarse fragments (CS), impact of pore space on water infiltration and over-land flow (TP and K_{sat}) and the proportion of clay fraction in runoff water (DR, CDR, MCR and CR) as an indication of the detachability and dispersion of the colloidal materials in the soil. Thus, *K* would decline as CS proportion increases and rainwater readily infiltrates and transmitted below the soil surface. Obi and Asiegbu (1982) found coarser psf less readily transportable. Equally, as DR, CDR, MCR and CR decrease in the soil, the more stable the soil or its ability to retain its structure against the action of water. The negative relationships however contradict the concept of *the more the value, the less stable the soil* is; soil erosion increases with dispersibility of the clay fraction. The results of this study were thus dissimilar to Igwe (2003) that any of DR, CDR and WDC could predict erodibility in southeastern Nigeria because of their positive relationships with K-factor. It is thus shown that several factors or covariates affect *K* and must be taken into account when evaluating *K* in the study area. This assertion is in consonance with Lal (1990) that *K* is a function of several interrelated factors.

Regression of Soil Erodibility on Soil Properties

Soil textural fractions, bulk density and porosity

The scatter plots of the relationships between *K* and the correlated parameters showed that CS explained 60.0% ($r^2 = 0.66$**) of the total variation or reduction in *K* (Figure 3), this was followed in a decreasing order by Si ($r^2 = 0.51$**), K_{sat} ($r^2 = 0.45$**), Cl ($r^2 = 42.00$**), Bd ($r^2 = 0.21$**) and TP ($r^2 = 20.00$**). The scatter plots also reflected the correlations between these parameters and *K* (Table 4). However, CS which explained > 60%, and Si, K_{sat} and Cl which explained > 40% of the total variability in K-factor could be used to predict erodibility in these tropical soils.

Microaggregate stability

Similarly, among the clay dispersion indices, ASC ($r^2 = 0.48$**) and WDS ($r^2 = 0.43$**) explained > 40% variability in K-factor. Others, progressively, are CR ($r^2 = 0.26$**), MCR ($r^2 = 0.25$**), CDR ($r^2 = 0.20$**), CFI ($r^2 = 0.20$), DR ($r^2 = 0.13$**) and WDC ($r^2 = 0.07$*). Also, the scatter plots (Figure 4) reflected the correlations between the indices and erodibility in Table 4. For instance, WDC and WDS increased as K increased, indicating that these psf were not resistant to erosion; they could be detached and subsequently lost to the soil. However, among the microaggregate stability indices, ASC and WDS which explained > 40% variability in *K* are the most important for monitoring and predicting erodibility in the area because their coefficients are about twofold larger than coefficients for CR, MCR, CDR and CFI, threefold larger than DR and six fold larger than WDC. Therefore, CS, Si, K_{sat}, Cl and ASC and WDS could be used as predictors of soil erodibility in the coastal plain sands in Akwa Ibom State.

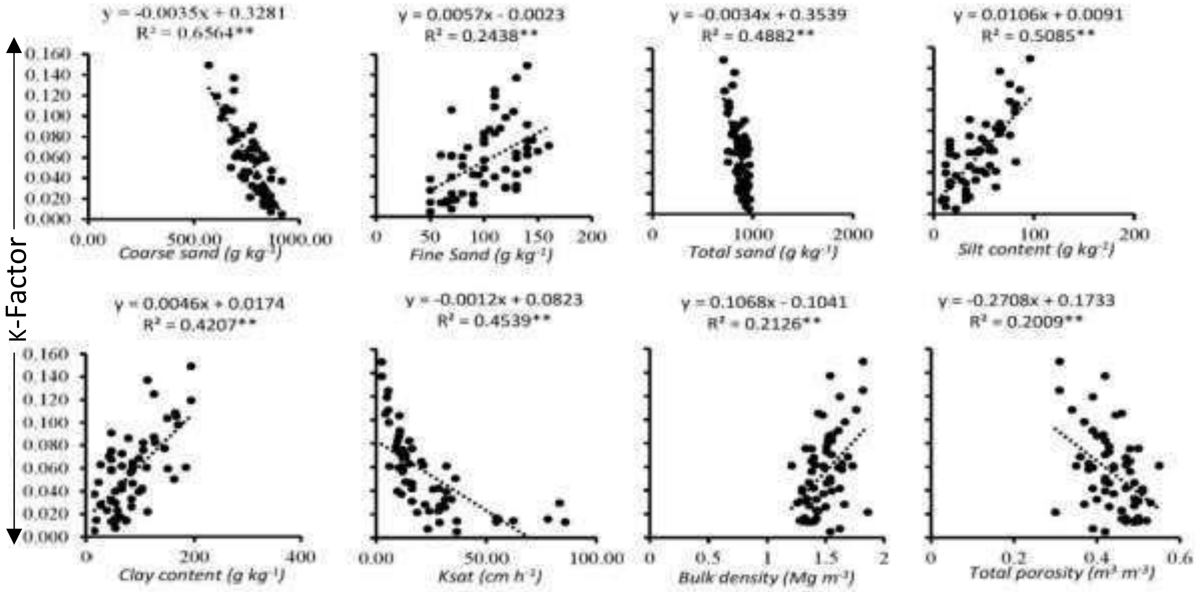

Figure 3: Linear regression of erodibility factor, *K*, on soil physical properties

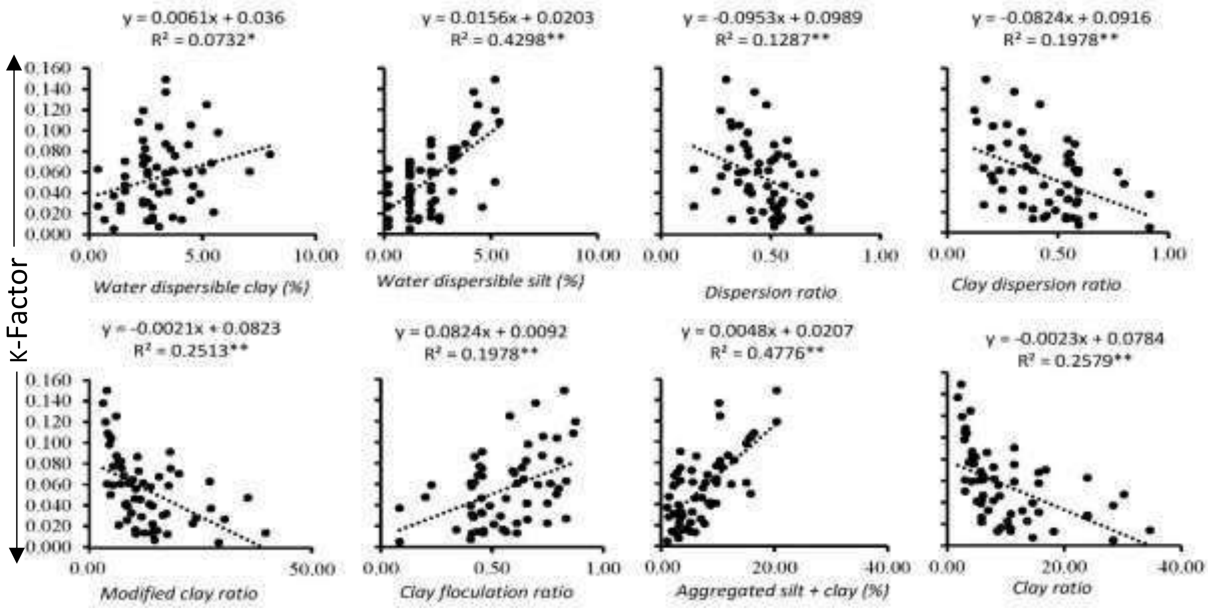

Figure 4: Linear regression of erodibility factor, *K*, on indices of microaggregate stability

CONCLUSION

This study was conducted to evaluate the effect of slope curvature and gradient on soil properties and microaggregate stability indices and predictability of soil erodibility factor *K* on coastal plain sands in Akwa Ibom State. Results of the basic soil properties and microaggregate stability indices showed that the soil was less susceptible to erosion on CC than CV, irrespective of the gradient of slope, because the K-factor was consistently higher on CV than CC. However, the most important soil attributes for monitoring and predicting erodibility in the area are CS, Si, K_{sat}, Cl and ASC and WDS. These could therefore be targeted in soil management to stabilize soil aggregates, maintain soil structural stability and minimize erosion on all sloping lands in the area of the coastal plain sands in Akwa Ibom State.

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