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FACTORS AND PROPERTIES INFLUENCING SOIL AGGREGATE STABILITY IN KATSINA STATE, NORTH-WESTERN NIGERIA

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ABSTRACT

Soil aggregate stability is not only an important indicator for controlling soil losses and improvement of soil quality, but also improving nutrient availability and water use efficiency. Therefore, this study was carried out to assess the factors influencing soil aggregate stability and determine their relationship with some soil properties in Katsina State situated between Sub-Humid and Dry Sub-Humid Agro-ecological zones of Nigeria. Variation in Agro-ecological zones and Geological formations were the factors that significantly influenced soil properties with resultant effect in variation in mean weight diameter and aggregate stability across the State. Clay, divalent calcium and magnesium cations, and cation exchange capacity significantly correlated with mean weight diameter (MWD) under dry (r = 0.449*, 0.552**, 0.530** and 0.617** respectively), and water conditions (r = 0.583**, 0.418**, 0.334* and 0.417** respectively) and water stable aggregates (r = 0.593**, 0.376*, 0.326* and 0.376* respectively). Their significant relationship indicated their key role in influencing nature of soil aggregate stability and conservation for sustainable uses within the Sub-Humid and dry Sub-Humid Agro-ecological zones of Nigeria.

Keywords: Aggregate stability**;** geological formations; agro-ecological zones

INTRODUCTION

Soil aggregate stability is the measure of the resistance of soil structure against mechanical or physico-chemical destructive forces (Singh *et al*., 2019). It is considered a result of complex interactions among biological, chemical and physical components in the soil (Tisdall and Oades, 1982; Laskar, 2011).

Singh et al. (2019) considered aggregate stability as one of the main soil properties controlling soil erodibility (Cerda, 1996; Angers, 1998). Angers (1998) stated that the resistance of soils to degradation is largely controlled by the presence of stable macro-aggregates. It is also referred to as one of the major factors influencing plant growth by its adverse impact on root penetration, soil temperature and gas diffusion, water transport and seedling emergence, as well as physical processes such as infiltration and aeration (Nimmo, 2004; Martínez-Trinidad *et al.* (2012). Increase in aggregate stability reduces the soil loss and increases the quality of macro-aggregates and total and effective porosity. It also helps in reducing the loss of carbon, nitrogen and phosphorous (Kasper *et al.*, 2009). Therefore, it is appropriate to consider it as an important factor not only for increasing soil productivity and soil quality, but also improving nutrient availability and water use efficiency (Byung *et al.,* 2007; Laskar, 2011; Siddique *et al.,* 2017).

Soil aggregate stability has served as an important indicator for controlling soil losses and improvement of soil quality, particularly in an area such as the Loess Plateau of China (Kalhoro *et al.*, 2017). Several researches have suggested that soil organic matter can improve the formation of soil aggregates and increase the mechanical stability of aggregates by binding soil mineral particles, which determines the coherence of inter-particle bonds (Whalen *et al.*, 2003; Laskar, 2011; Siddique et al., 2017).

Soil aggregate stability is commonly documented as a key indicator of soil quality (Martínez-Trinidad *et al.,* 2012; Nciizah and Wakindiki, 2014; Oyetola, 2014; Siddique *et al.,* 2017; Singh *et al.,* 2019). It is a key factor of soil resistivity to mechanical stresses, including the impacts of rainfall and surface runoff, and thus to water erosion. It indicates the ability of soil aggregates to resist disruption when acted upon by outside forces such as rain drops, but it differed from dry aggregate stability which is used for wind erosion prediction. Siddique *et al.* (2017) reported that large aggregates are more sensitive to management effects on organic matter, serving as a better indicator of changes in soil quality. Greater amounts of stable aggregates suggest better soil quality (Arshad *et al.,* 1996; Kemper and Rosenau, 1986). Abrishamkesh *et al.* (2011) further buttress that when the proportion of large to small aggregates increases, soil quality generally increases. Therefore, aggregate stability is crucial for sustainability of soils and crop production.

The concept of aggregate stability depends on both the forces that bind particles together and the nature and magnitude of the disruptive stress (Laskar, 2011). Various factors studied and found to affect soil aggregate stability can be grouped into biotic (soil organic matter, activities of plant roots, soil fauna and micro-organisms), abiotic (clay minerals, sesquioxides, exchangeable cations and environmental (soil temperature and moisture) (Chen *et al.,* 1998; Laskar, 2011).

Oyetola (2014) study indicated that land use types had a significant effect on soil aggregate stability, that there are relationships among soil aggregate stability parameters and organic carbon, iron and aluminium content of the soil studied. Different management practices also are found to affect the soils aggregate stability as an index of soil structure status and soil quality (Josa *et al.,* 2010; Abrishamkesh *et al.,*2011). Aggregation is influenced by agricultural practices such as tillage, cropping systems, and the types of fertilizers applied (Whalen *et al.,* 2003). Tillage disrupts aggregates mechanically, changes the soil climate (temperature, moisture, aeration) and accelerates organic matter decomposition, reducing the proportion of stable aggregates - 0.25 mm (Cambardella and Elliott, 1993; Balesdent *et al.,* 2000; Whalen et al., 2003). Soil dry aggregate with clods at cultivated surface is reported to help in controlling wind erosion, while aggregates greater than 0.84 mm were generally considered as non-erodible by wind (Laskar, 2011). Hermawan and Bomke (1997) found significant correlation between soil organic carbon and aggregate stability, and attributed it to binding action by humic substances and other microbial bye-products (Shepherd *et al.,* 2001; Laskar, 2011).Despite the influence of several factors on aggregate stability, Siddique *et al.* (2017) reported that correlation between aggregate stability and other soil properties such as erodibility, compaction, crusting status is not always consistent but at times difficult to establish.

The landscape within Katsina State is situated within climatic zone that experiences wind erosion during dry season, while water erosion occurs during rainfall period. Therefore, understanding soil aggregate stability and the factors influencing it is important for controlling soil losses and improvement in soil quality of the state. However, there still exist scanty information on factors and properties influencing soil aggregate stability in Katsina State. Therefore, this study was carried out to assess the factors influencing soil aggregate stability and determine their relationships with some selected soil properties in Katsina State situated between Sub-Humid and Dry Sub-Humid Agro-ecological zones of North-western Nigeria.

MATERIALS AND METHODS

The Study Areas

The study was conducted across six Local Government Areas (LGAs) namely: Funtua, Jibia, Katsina, Mai Adua, Malumfashi and Zango (Figure 1). The study areas are situated between Sub-humid and Dry Sub-humid Agro-ecological zones, characterized by Northern Guinea and Sudano-Sahelian savanna vegetation. The vegetation has under gone modification by cultivation, grazing and bush burning (Ojanuga, 2006). The study sites are distributed across Katsina State from south to north, and situated between latitude 11°22'12.7" to 13°09' 04.2"N and longitude 007°37'40.3" to 008°43'27.9" E. Katsina State is underlain by Crystalline basement rocks which comprise of three major lithological groups: migmatite-gneiss, schist belts, and the older granites. There are some minor occurrences of Cretaceous sediments represented by the Gundumi formation of the Sokoto Basin in Mai Adua and around Katsina Town and the Chad formation occurring as a westerly extension of the Nigerian sector of the Chad Formation around the north-eastern part of the State (Malomo, 2004).

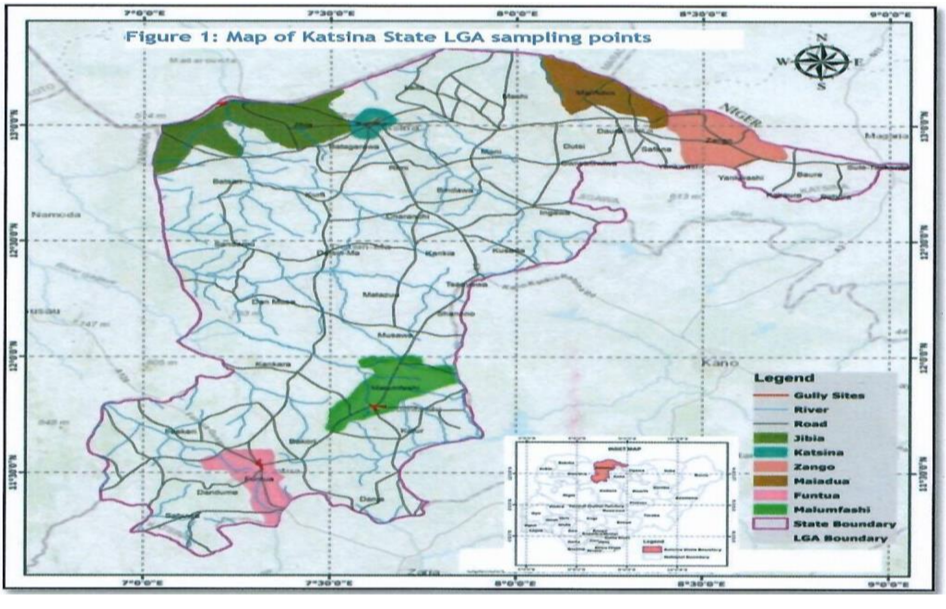

Figure 1: Map of Katsina State showing Local Government Areas studied

The areas are characterised by a tropical climate with marked rainy and dry season, harmattan dust and cold condition in the dry season. The rainy season commences in April/May through to October and the dry harmattan season is from November to April. The study areas are characterized by mean annual rainfall of 772 to 1,051 mm/ annum. The mean monthly minimum temperature ranged between 12.9 and 21.0^{0}C, whereas maximum temperature varied between 29.2 and 39.0^{0}C (NBS, 2006; Akintola, 1986; Kowal and Knabe, 1972). The mean monthly maximum temperature was highest in April before the commencement of rains and decreases to the lowest values at the peak of rainfall in August.

Land use system across the Local Government Areas (LGA) is that of mixed farming. The crops that are grown in these areas are millet, sorghum, maize, cowpea, sesame and groundnuts. Animals kept include cattle, goats, sheep, local chickens and guinea fowls.

Field Studies

Twelve soil profile pits were dug across the study areas, with two profile pits in each LGA. Soil samples were collected and described from the identified pedogenic horizons according to Soil Science Division Staff (2017) for laboratory analyses. Thirty-eight (38) soil samples were collected across the study areas.

Laboratory Analysis

Soil samples of less than 2 mm size were used for laboratory analysis. Particle size distribution was determined by hydrometer method (Gee and Bauder, 1986), while bulk density determination was by the method described by Blake and Hartge (1986). Stable aggregate and the Mean Weight Diameter (MWD) in both dry and water (wet) forms were determined using method described by Kemper and Rosenau (1986). Four sieves (4.5 mm, 2.5 mm, 0.25 mm and 0.053 mm wire meshes) were used under dry and water sieving conditions to obtain aggregate fractions of >2.5 mm (large macroaggregates) 0.25 – 2.5 mm (small macroaggregates) and 0.053-0.25mm (microaggregates).

The distributed soil aggregates were collected separately in each sieve and weighed on an electrical balance to calculate the distribution of the various soil aggregates. The remaining soil sample in each sieve was recorded to calculate the water stable aggregate (WSA), dry stable aggregate (DSA), mean weight diameter (MWD) by using the following formulae.

$$\text{WSA or (DSA)} = \left[\frac{\text{mass of dry aggregate} - \text{ sand}}{\text{mass of dry soil sample} - \text{ sand}}\right] \times 100$$

where the mass of dry aggregate means the remaining mass of soil (before wetting) after each sieve and mass of dry soil sample means the total mass of soil sample, whereas for WSA, the mass of dry aggregate means the remaining mass on dry soil (after wetting) after each sieve.

$$\text{MWD} = \sum_{i=1}^{n} XiWi$$

where, MWD represents mean weight diameter. Sum of products of i, the mean diameter Xi, of each size fraction and Wi is the proportional of the total sample mass,

occurring in the corresponding size fraction, and the summation was carried out over all n size fractions, including the one that passes through the finest sieve.
Saturated hydraulic conductivity was estimated using the core soil sampled with the aid of constant head permeameter as describe by Young (1976). The hydraulic conductivity was then calculated using the formula:

$$K_s = \frac{V \times L}{A \times T(H_{in} - H_{out})}$$

Where: K_s= Hydraulic conductivity; V= Volume of water collected over time; L= Length of core sampler; A= Area of core sampler; T= Time taken to collect the volume of water V; H_{in} = Head of water in core sampler; H_{out} = Head of water outside the core sampler.

Soil pH was determined potentiometrically in water at 1:2.5 soil solution ratio. Exchangeable bases (Ca, Mg, K and Na) were determined using ammonium acetate (NH_4OAc) extraction method and their values summed to obtain the total exchangeable bases (TEB) as described by Thomas (1982). Cation exchange capacity (CEC) was determined by neutral (pH 7.0) NH_4OAc saturation method (Rhoades, 1982). Organic carbon (OC) was determined by Walkley-Black dichromate wet oxidation method (Nelson and Sommers, 1982).

Statistical Analysis

Conventional descriptive statistical analyses were performed to evaluate the soil physical and chemical properties and aggregate stability. Effect of factors of LGAs, Agro-ecological zones (Sub-humid and Dry Sub-humid), Geology (Crystalline basement complexes and Cretaceous Sediment) and Land-use (Urban area and Forrest area) on mean differences in the physico-chemical properties and aggregate stability were analysed using General Linear Model analysis of variance and t – test (IBM SPSS,2015). Mean variation between LGAs were ranked using Duncan multiple range test (DMRT). The relationship between the soil properties and aggregate stability of the soil were determined using correlation analysis (IBM SPSS, 2015 and StatPoint, 2005).

RESULTS AND DISCUSSION

Soil Physical and Chemical Properties

Summary and ranking of results of the physical, chemical and aggregate stability properties of the soils for the LGAs are presented in Table 1. Field study showed that soil depth varied from shallow to very deep (28 – 230 cm). Petro plinthite restricted soils depth at Mai Adua, while Katsina and Zango were generally very deep as were developed on sediment formations. The study areas across the State were dominated by sand particle (40 to 920 g kg^{-1}) compared to silt (20 to 460 g kg^{-1}) and clay (40 to 280 g kg^{-1}). Silt and sand were significantly different across the LGAs and were attributed to their geological formations. Silt was significantly highest in Funtua followed by Malumfashi where loessial material overlay Crystalline basement complexes (Maniyunda *et al.*, 2016; Maniyunda, 2018), with least mean value in soils of Katsina, Mai Adua and Zango associated with Cretaceous sediments. Mean sand value was significantly highest in Zango followed by

Katsina, Jibia and Mai Adua which were at par (Table 1). This is further buttressed by the significant variation in both mean values of sand and silt as influenced by the geological formations of the parent materials (Table 2). The trend influence variation in soil texture with sandy loam and loam dominating Crystalline basement complexes, while sand and loamy sand dominated the Cretaceous sediments. Bulk density range between 1.09 and 1.63 Mg m^{-3} and rated as low to medium, while saturated hydraulic conductivity of the soils was between 0.62 and 2.85 cm/hr and rated as moderately low to moderately high (Soil Science Division Staff, 2017).

Table 1: Ranking of means of soil properties of the study Local Government Areas

Parameter	Unit	Funtua	Jibiya	Katsina	Mai Adua	Malumfashi	Zango	SE ±	LOS
Clay	g kg^{-1}	126.7	148.6	135	168.0	133.3	96.7	23.3	NS
Silt	g kg^{-1}	400.0a	85.1c	77.5cd	60.0cd	263.3b	33.3d	23.5	**
Sand	g kg^{-1}	473.3d	765.7b	787.5b	772.0b	603.3c	870.0a	38.3	**
Bulk Density	Mg m^{-3}	1.38	1.31	1.28	1.44	1.33	1.32	0.53	NS
Hydraulic Conductivity	cm hr^{-1}	1.86	2.14	1.56	1.85	1.67	2.32	0.29	NS
pH (H_2O)	-	6.76de	7.69b	8.37a	6.43e	7.15c	7.06cd	0.174	**
pH ($CaCl_2$)	-	5.39c	7.13a	7.28a	4.72d	6.36b	5.84c	0.225	**
OC	g kg^{-1}	9.07a	4.17bc	5.63b	2.14c	3.02bc	1.73c	1.40	**
Ca	cmol (+) kg^{-1}	4.38a	3.22b	3.18b	1.54c	3.02b	1.31c	0.44	**
Mg	cmol (+) kg^{-1}	1.97a	1.27b	1.28b	0.70bc	1.23b	0.52c	0.26	**
K	cmol (+) kg^{-1}	1.15	0.55	0.32	0.31	0.78	0.23	0.19	NS
Na	cmol (+) kg^{-1}	0.63	0.22	0.23	0.28	0.41	0.26	0.10	NS
TEB	cmol (+) kg^{-1}	8.13a	5.13b	5.00b	2.82c	5.44b	2.32c	0.74	**
CEC	cmol (+) kg^{-1}	11.32a	6.93b	7.11b	3.66c	7.26b	2.75c	1.25	**
MWD (dry)	mm	3.21a	2.19bc	1.61cd	2.35b	2.70ab	1.39d	0.30	*
MWD (water)	mm	1.10a	0.86a	0.92a	1.11a	0.81a	0.30b	0.18	**
Aggregate Stability (dry)	%	33.62	37.55	32.41	41.57	36.00	37.20	4.21	NS
Aggregate Stability (water)	%	13.34	15.24	10.54	16.77	5.09	0.31	7.39	NS

MWD: Mean Weight Diameter LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01

Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

LOS- Level of Significance

Table 2: Ranking of means of soil properties of the geological formations

Parameter	Unit	Crystalline Basement Complexes	Cretaceous Sediments	SE ±	LOS
Clay	g kg^{-1}	136.8	131.6	10.52	NS
Silt	g kg^{-1}	241.1a	59.0b	23.7	**
Sand	g kg^{-1}	622.1b	809.5a	26.3	**
Bulk Density	Mg m^{-3}	1.34	1.33	0.024	NS
Hydraulic Conductivity	cm hr^{-1}	1.90	1.88	0.13	NS
pH (H_2O)	-	7.23	7.45	0.17	NS
pH ($CaCl_2$)	-	6.46	6.15	0.22	NS
OC	g kg^{-1}	5.35	3.48	0.76	NS
Ca	cmol (+) kg^{-1}	3.52a	2.16b	0.25	**
Mg	cmol (+) kg^{-1}	1.48a	0.89b	0.13	**
K	cmol (+) kg^{-1}	0.81a	0.29b	0.084	**
Na	cmol (+) kg^{-1}	0.41a	0.25b	0.049	*
TEB		6.18a	3.58b	0.42	**
CEC	cmol (+) kg^{-1}	8.48a	4.82b	0.66	**
MWD (dry)	mm	2.67a	1.73b	0.15	**
MWD (water)	mm	0.92	0.78	0.093	NS
Aggregate Stability (dry)	%	35.82	36.33	1.82	NS
Aggregate Stability (water)	%	11.43	8.90	3.15	NS

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01

Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

Soil pH varied between 6.14 and 9.25 and rated slightly acid to very strongly alkaline (Soil Survey Division Staff, 1993) with significant variation between the mean values across the LGAs (Table 1), and were attributed to influence of variation in agro-ecological zones (Table 3) and land-uses (Table 4). The variation in distribution trends of organic carbon, exchangeable bases (Ca, Mg, K and Na), total exchangeable bases (TEB) and CEC were generally similar with mean values of OC, Ca, Mg, TEB and CEC significantly highest at Funtua and lowest at Zango (Table 1). The trend was more influenced by the geological formations (Table 2) and agro-ecological zones (Table 3), while land-uses did not significantly influence variation in their mean values (Table 4). Incorporation of organic matter (Maniyunda *et al.,* 2016; Odunze, 2017) especially in the soils of the Dry Sub-Humid savanna and Cretaceous sediments are expected to improve the soil CEC for more retention of exchangeable bases as the soils are loose associated with high sand fractions.

Table 3: Ranking of means of soil properties of the agro-ecological zones

Parameter	Unit	Sub-humid	Dry Sub-humid	SE ±	LOS
Clay	g kg^{-1}	136.2	130.0	16.0	NS
Silt	g kg^{-1}	66.2b	331.7a	20.1	**
Sand	g kg^{-1}	797.7a	538.3b	29.3	**
Bulk Density	Mg m^{-3}	1.33	1.35	0.024	NS
Hydraulic Conductivity	cm hr^{-1}	1.95	1.77	0.200	NS
pH (H_2O)	-	7.51a	6.96b	0.239	*
pH ($CaCl_2$)	-	6.42	6.07	0.329	NS
OC	g kg^{-1}	3.67b	6.04a	1.133	*
Ca	cmol (+) kg^{-1}	2.44b	3.70a	0.394	**
Mg	cmol (+) kg^{-1}	0.99b	1.60a	0.200	**
K	cmol (+) kg^{-1}	0.36b	0.97a	0.121	**
Na	cmol (+) kg^{-1}	0.25b	0.52a	0.065	**
TEB	cmol (+) kg^{-1}	4.00b	6.79a	0.637	**
CEC	cmol (+) kg^{-1}	5.39b	9.39a	1.002	**
MWD (dry)	mm	1.86b	2.95a	0.223	**
MWD (water)	mm	0.80	0.96	0.141	NS
Aggregate Stability (dry)	%	36.66	34.81	2.751	NS
Aggregate Stability (water)	%	10.60	9.22	4.802	NS

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01

Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

Aggregate Stability

The summary and mean values of the results of dry and water stable aggregates (> 2.5 mm) and mean weight diameter for both dry and water forms are presented in Table 1. Stable aggregate after dry sieving ranges from 23.54 to 54.46 % and were considered severe to slight in their limitation to soil loss as an index of wind erosion (Lal, 1994) and the mean values were not significantly different and falls within moderate class. However, increasing aggregate stability will reduce soil loss, hence reduce loss of carbon, nitrogen and phosphorus (Kasper et al., 2009). Incorporation of organic matter is expected to increase stable aggregate (Akinnifesi *et al.,* 2010; Maniyunda *et al.,* 2016; Odunze, 2017) The values of stable aggregate varied between 0.15 and 37.58 % for water sieving and rated as extremely severe to moderate which is an indication of limitation to soil loss through water erosion. There was no significant variation between the locations, geological formations, agro-ecological zones and land-uses for both dry and water stable aggregates. However, the ratings indicated that the soils are more fragile to erosion under rainfall and there is need for some appropriate management practices to conserve the soils against agents of erosion. Soil organic matter is reported by many researchers to improve the formation of soil aggregates and increase the mechanical stability of aggregates (Whalen et al., 2003; Laskar, 2011; Siddique *et al.,* 2017).

Table 4: Ranking of means of soil properties based on land-use

Parameter	Unit	Urban Area	Forrest Area	SE ±	LOS
Clay	g kg^{-1}	139.1	128.2	4.87	NS
Silt	g kg^{-1}	133.3	170.6	45.01	NS
Sand	g kg^{-1}	727.6	701.2	48.63	NS
Bulk Density	Mg m^{-3}	1.30^{b}	1.37^{a}	0.033	*
Hydraulic Conductivity	cm hr^{-1}	1.79	2.02	0.185	NS
pH (H_2O)	-	7.80^{a}	6.77^{b}	0.167	**
pH ($CaCl_2$)	-	6.97^{a}	5.49^{b}	0.192	**
OC	g kg^{-1}	4.40	4.44	1.122	NS
Ca	cmol (+) kg^{-1}	3.15	2.46	0.401	NS
Mg	cmol (+) kg^{-1}	1.26	1.08	0.207	NS
K	cmol (+) kg^{-1}	0.53	0.58	0.148	NS
Na	cmol (+) kg^{-1}	0.28	0.40	0.072	NS
TEB	cmol (+) kg^{-1}	5.17	4.52	0.729	NS
CEC	cmol (+) kg^{-1}	7.09	6.11	1.113	NS
MWD (dry)	mm	2.11	2.31	0.267	NS
MWD (water)	mm	0.87	0.82	0.134	NS
Aggregate Stability (dry)	%	35.15	37.22	2.565	NS
Aggregate Stability (water)	%	10.55	9.69	4.492	NS

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01
Note: Means followed by the same letters in the rows are not significantly different at 5% LOS

Mean weight diameter for dry condition (MWDd) after dry sieving range between 0.87 and 3.64 mm and rated as severe to none in their limitation to soil loss (Lal, 1994). Mean values of MWD of soils at Funtua and Malumfashi were statistically similar but those of Funtua were significantly higher than other LGAs. Soils at Malumfashi, Mai Adua and Jibia were statistically at par, while Jibia was also similar to Katsina LGA but significantly higher than Zango which was statistically similar to Katsina LGA (Table 1). The mean values of MWDd at Funtua and Malumfashi indicated that the soils are non-limiting (> 2.5 mm) as stated by Lal (1994) and Angers (1998) also stated that the presence of stable macro-aggregate largely controls soils degradation. Geological formation tends to influence variation in MWDd with soils on Crystalline basement complexes significantly higher than cretaceous sediments. This may be attributed to the less proportion of sand in Basement complex rocks compared to Cretaceous sediments (Maniyunda *et al.*, 2016). Soils in the Dry Sub-humid savanna was significantly higher in MWDd compared to Sub-humid savanna zone. The values of mean weight diameter under water sieving (MWDw) ranged from 0.13 to 1.44 mm and considered as extremely severe to moderate limitation to soil loss. Mean value of MWDw at Zango LGA was significantly lower than all the other LGAs which were observed to be at par statistically. This may be attributed to the low binding force of sand particles to aggregate as the area was characterised by loamy sand over sand textured soils.

Therefore, soils at Zango LGA are considered the weakest in fragility to erosion under rainfall and separate management practices are required to conserve the soils compared to other LGAs. Zango LGA will require soil conservation in form of forest plantation to serve as mulch reducing direct impact of rain splash and run-off, as well as avoid bush burning that may reduce organic matter from leaf litter expected to bind soil particles (Brady and Weil, 2005; Akinnifesi *et al.*, 2010 and Odunze, 2017).

Relationship between Soil Properties and Aggregate Stability Indicators

Results of the correlation matrix of aggregate stability indicators and soil properties studied are presented in Tables 5. Relationship between mean weight diameter (MWD) under dry condition and particle size distribution showed that silt and clay significantly correlated with r values of 0.689** and 0.499**, while sand significantly correlated negatively (r = -0.794). This implied that increase in clay and silt content will increase soil aggregate sizes thereby reducing soil loss via wind erosion. Similarly, Chen *et al*. (1998), Laskar (2011) and Siddique *et al.* (2017) have established that clay minerals have contributed to binding other particles. However, the negative correlation with sand implies that increase in sand content will reduce aggregation of particles, thus increasing soil loss by wind.

Table 5: Correlation matrix between soil properties and aggregate stability of the study areas

Parameters	Mean Weight Diameter (dry)	Mean Weight Diameter (wet)	Aggregate Stability (dry)	Aggregate Stability (wet)
Clay	0.499**	0.583**	0.315	0.593**
Silt	0.689**	0.324*	-0.094	0.099
Sand	-0.794**	-0.481**	-0.009	-0.274
Bulk Density	0.180	-0.022	0.133	0.083
Hydraulic Conductivity	-0.115	-0.171	0.176	-0.243
pH (H_2O)	-0.425**	-0.127	-0.225	0.016
pH ($CaCl_2$)	-0.215	-0.080	-0.199	0.069
Organic Carbon	0.390*	0.263	-0.032	0.144
Calcium	0.552**	0.418**	-0.075	0.376*
Magnesium	0.530**	0.334*	-0.123	0.326*
Potassium	0.646**	0.217	0.009	0.142
Sodium	0.458**	0.221	-0.029	0.067
Total Exchangeable Bases	0.638**	0.387*	-0.077	0.305
Cation Exchangeable Capacity	0.617**	0.417**	-0.078	0.376*
Mean Weight Diameter (dry)		0.531**	0.214	0.434**
Mean Weight Diameter (water)			0.005	0.660**
Aggregate Stability (dry)				0.050

Level of Significance (P): * ≤ 0.05, ** ≤ 0.01.

Significant but negative correlation was observed between pH (H_2O) and MWDd (r = -0.425**) and may be attributed to weak covalent bond developed with hydroxyl ions under higher pH, hence soil structures are easily destroyed and resulted in MWDd falling into micro aggregate class (< 0.25 mm). Increase in OC, Ca, Mg, K, Na, TEB and CEC all significantly increased MWDd, as all significantly and positively correlated with MWDd (Table 5). Chen *et al*. (1998) and Laskar (2011) have also observed that increase in soil organic matter, exchangeable bases and CEC have increased soil aggregate stability. Therefore, incorporation of organic matter in these soils will increase CEC and retain more exchangeable bases thereby increasing sizes of aggregate against harmattan wind erosion across the Sudano-Sahelian region in Katsina State for sustainable soil management via organic matter enrichment. The planting of herbaceous plant known as "Kashe Kwari" is a common and appropriate practice along drains to control erosion in Katsina State, therefore, it is highly recommended along with fertilizer trees such as *Faidherbia albida* which has been found to improve soil quality, nutrients and crop yields in many parts of Africa (Akinnifesi *et al.,* 2010). Aggregate stability under dry condition did not significantly correlate with the soil physico-chemical properties studied in Katsina State.

Under wet sieving, particle size fractions of sand silt and clay significantly correlated with mean weight diameter (water) (Table 5). This implies that increase in finer particles (clay and silt) with more surface area and charges with reduction in sand proportion in soils will bind particles to form macro aggregate of higher MWD that may not be easily eroded by rain water. This was earlier buttressed by the significant difference shown between Funtua and Malumfashi compared to Zango in relation to silt, sand and MWD for both dry and water sieving (Table 1). Significant correlation was observed between MWDw with divalent cation Ca and Mg as well as CEC, hence increasing CEC and these cations will strengthen the bonding of particle with stronger force against water as an agent of soil erosion. Clay significantly correlated with water stable aggregate, and was attributed to the larger surface area contributed by clay to bind soil particles in forming stable aggregate for improving soil quality. Similarly, divalent cation Ca and Mg significantly correlated with aggregate stability (water) (Table 5), thus affirming that strong force due to electrovalent bonding occur between clay negative surface charge and cation that are not easily destroyed. Water stable aggregate also correlated significant with CEC ($r = 0.376^*$), hence increasing CEC will also contribute to improvement of soil quality for their sustainability as cations will strengthen the bonding of particle for strong force against water as an agent of soil erosion.

Highly significant correlation observed between MWDd and MWDw ($r = 0.531^{**}$) may be used to establish linear model equations showing their relationships and may serve as pedo-transfer function. It is also similar for MWDw with water stable aggregate ($r = 0.660^{**}$) as were significantly and highly correlated.

CONCLUSION

The variation of stable aggregate indicators across Katsina State as influenced by several factors and soil physico-chemical properties were studied. Agro-ecological zones influenced by climate and vegetation, and the differences in geological formations significantly influenced soil properties with resultant effect in variation in mean weight diameter and aggregate stability across the State.

Clay, divalent calcium and magnesium cations, and cation exchange capacity significantly correlated consistently with mean weight diameter (dry and water) and water stable aggregate. The relationship between them therefore shows their significant role in influencing the nature of aggregate stability of the soils across Katsina State. Therefore, these soil properties will be playing key role in conservation and management planning of the soils within the Sub-Humid and dry Sub-Humid agro-ecological zones in Katsina State for their sustainable uses.

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