AGGREGATE SIZES AND LAND USE TYPES INFLUENCE THE SOIL AGGREGATE STABILITY OF THE HUMID TROPICAL SOIL ENVIRONMENT

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ABSTRACT

The impacts of the land use pattern and its management techniques on the size and stability of soil aggregates are still poorly understood. Thus, this study investigated the best aggregate size class suitable for testing soil aggregate stability under different land use types in a humid southwestern Nigeria. Surface soil samples (0–15 cm) were collected under five land use types: continuous arable maize, pasture, coconut, cacao and cassava plantations. The sizes of the tested aggregates were 2–5, 5–10, 10–13, and 13–15 mm. The soil aggregate size classes from the different land use types were subjected to a 5-min. simulated rainfall of 150 mm h^{-1}. Two sieves with varying aperture sizes (1.0 and 0.5 mm) were used to test these aggregates under the rainfall simulator. The stability of soil aggregates tested on the 0.5 mm sieve did not significantly vary among aggregate size classes, regardless of land use types. However, there were significant variations in the stability of the soil aggregates evaluated on the 1.0 mm sieve between different land use types and aggregate size classes. The order of aggregate stability for soil under pasture (80.4%) > coconut (77.8%) > cocoa (65.9%) > cassava (51.1%) > maize (33.1%). The amount of soil organic carbon in the soils is directly correlated with this trend. The aggregate size classes of 5–10, 10–13 and 13–5 mm did not significantly differ in stability while the 2–5 mm class had significantly lower stability than the other classes. Due to significant high correlations of stability with soil organic carbon, aggregate size classes of 5–10 and 13–15 mm appear to be the best suitable for routine determination of aggregate stability in the study environment.

Keywords: *Macroaggregates; Management practices; Rainfall simulator; Aggregate size class*

INTRODUCTION

Soil aggregate stability is an important indicator that is controlled by the interactions between the soil environment, management approaches, and land use patterns (Zhang *et al*., 2008). The shape, size, and spatial arrangement of the aggregates in combination with pore size distribution are referred to as soil structure (Zhang *et al*., 2021). Since it controls the depth to which plant roots penetrate, the amount of water that can be stored in the soil, and the flow of air, water, and soil fauna, surface soil aggregates, particularly those between 0 and 15 cm depth, can have an impact on crop yield and soil productivity (Hermavan and Cameron, 1993; Langmaack, 1999; Abrishamkesh *et al.*, 2011; Alvarez et al., 2012). Thus, when evaluating the vulnerability of soil to water erosion, the size of the soil aggregates is crucial. According to Bartlová *et al*. (2015), the analysis of aggregate sizes is one of the most widely used techniques for the determination of soil structure. Aggregate stability has been the subject of extensive research since the early 19th century (Yoder, 1936). Thus, the continued interest in aggregate stability studies demonstrates its pivotal role in soil behaviour, as well as the fact that it is poorly understood.

Soil aggregates can be characterized by a variety of methods, and different approaches have been introduced and used to characterize this solid phase of soil structure (Dexter, 1988; Amezketa, 1999; Diaz-Zorita *et al*., 2002; Rohoskova and Valla, 2004). The stability of soil aggregates differs with aggregate size due to the principle of porosity exclusion (Dexter, 1988), and partly because of the different mechanisms responsible for aggregation (Tisdall and Oades, 1982; Truman and Bradford, 1990). Le Bissonnais (1996) reported that the final fragment size distribution of fairly unstable silty soil (ranging from 2 to 20 mm in diameter) was not affected by initial aggregate sizes after immersion in water. Le Bissonnais and Arrouays (1997) also used 5–3 mm aggregates, while Amezketa *et al*. (1996) used 2–1 mm aggregate, with no significant differences among the different classes. Little did they consider the different soil types and land use types.A number of factors influence aggregate stability, which has different implications for soil. While certain practices enhance soil aggregation, others may be detrimental to aggregate formation. Aina (1979) found that continuous tilling of the soil surface on an arable farm altered some soil physical properties, aggregate sizes, and stability. Following changes in land use, the variations in soil aggregate size distribution and stability may lead to substantial alterations in soil structure, which may have an impact on a variety of soil properties, including strength, gas, water, and heat exchange (Ball *et al*., 2005).

Soil aggregate size distribution varies from one land use to another. It is essentially affected by soil types, crop production types, climatic factors, tillage practices, and other kinds of management practices put in place. For instance, soil aggregates were found to be more stable under reduced tillage compared with conventional tillage (Pagliai *et al*., 2004). However, the success of reduced tillage, according to Rasmussen (1999), depends on the local soil type and climatic conditions. The effects of land use on soil structure in terms of crop production systems are dependent on diverse rooting habits, types of organic matter, rhizosphere processes, and the number of additions that are providing surface soil protection (Broersma *et al*., 1997). Proper quantification of surface soil aggregates under different land use types is crucial for developing management strategies that reduce the impacts of structural instability. In this study, we set out to determine the optimal size class appropriate for routine aggregate tests, and to offer recommendations on the technique for assessing soil aggregate stability in humid southwestern Nigeria.

MATERIAL AND METHODS

Soil samples were collected from the experimental farmlands of the Institute of Agricultural Research and Training, Ibadan, Nigeria. This area falls within the longitudes 7° 15' N and 7° 30' N and latitudes 3° 45' E and 4° 0' E. Ibadan is characterized by a humid tropical climate with a mean annual rainfall of about 1500 mm. The soils across the area belong to Alfisol (Soil Survey Staff, 2022). Soil samples were collected under five different land use types which were Paddock, Forest (the forested area had been under fallow for more than 35 years before this study), Cocoa Plantation, Cassava Plantation and Arable land under maize cultivation. Surface soil samples were collected at random from each land use type (4 cluster samples from each land use type), air-dried, and allowed to pass through different sieve classes. The sieves were arranged in a nested fashion such that aggregate classes of 2-5 mm, 5-10 mm, 10-13 mm and 13-15 mm were separated under each land use type, making a treatment combination of five land use types and four aggregate sizes.

A laboratory rainfall simulator with hypodermic needle drop-forms was used to test the soil aggregates for their stability to withstand raindrop impact. Some characteristics of the storm produced by the rainfall simulator are presented in Table 1.

Table 1. Characteristics of simulated rainfall used for the study.

Characteristics	Value
Rainfall Intensity	128 mm hr^{-1}
Median drop diameter (D50)	1.45 mm
Drop velocity	5.1 m/s
Kinetic energy per drop	2.07 * 10-5 J
Kinetic energy per square metre	332.63 J m-2
Kinetic energy per square metre per unit of time	27.72 J m-2 min-1
Height of drop	1.75 m
Duration of Storm	12 min

Following the procedure outlined by Almajmaie *et al*. (2017), an equivalent of 15 g (oven-dried base) of soil clods from each aggregate class was put on a 1.0 mm sieve size and placed directly under the rainfall simulator for a period of five minutes. The same procedure was repeated using a 0.5 mm sieve. The amount of soil detached during the rainstorm was collected underneath the 0.5 mm sieve. After the storm, the soil left on the 0.5 mm sieve was washed through the sieve into a moisture can. The coarse fragments greater than 0.5 mm left on the sieve were washed into a separate moisture can. They were then both oven-dried at 105°C to a constant weight.

The aggregate stability index was computed by calculating the percentage of stable soil left on a 0.5 mm sieve after the rainfall simulation test. This percentage was however corrected for coarse materials greater than 0.5 mm. The aggregate stability index is presented in Equation 1.

$$SI = \frac{W_f - s}{W_i - s} \, x \, 100 \quad (1)$$

where, SI is the stability index (%), W_f is the oven-dried weight (g) of soil remaining on top of 0.5 mm sieve, W is the initial weight (g) of soil on the sieve before rainfall simulation (i.e. 15 g), and s is the weight (g) of coarse particles greater than 0.5 mm.

In addition, some basic soil properties that were relevant in explaining observed results were measured under the land use types. They include particle size analyses, organic carbon, exchangeable sodium, calcium and potassium as well as the pH.

Particle size analyses for sand (20-2000 μm), silt (2 -20 μm) and clay (< 2 μm) fractions were by hydrometer method as described by Gee and Or (2002). Organic carbon was determined by loss-on-ignition (LOI) as described by Cambardella *et al.* (2001). The pH of the soil was determined in a 1:2.5 soil-water ratio, using a glass electrode pH meter to read the soil-water suspension. The exchangeable cations (calcium, Ca; magnesium, Mg; potassium, K; and sodium, Na) in the soil were determined by first extracting the soil sample with 1 M NH_4OAc (ammonium acetate) solution as described by Okalebo *et al*. (1993). The amounts of exchangeable Na and K in the extracts were determined using a flame photometer while Ca and Mg (result not reported in this paper) were determined by an atomic absorption spectrometer (AAS).

The experiment was a completely randomised design of 5 (land use types) by 4 (aggregate classes) factorial combinations. The aggregate stability data as well as selected chemical properties were subject to two-way analyses of variance. Mean separation was undertaken using Student-Newman-Keuls (SNK) method after a significant F-ratio had been detected.

RESULTS

Soil aggregates and aggregate stability

From the results of the analysis of variance (ANOVA, Table 2), the effect of land use types on soil aggregate stability was significant at 1% using a 1.0 mm sieve, while the effect of the aggregate class was significant at 5%. The effect of interactions between land use types and the aggregate class was also significant at 1% level. However, using 0.5 mm sieve, the effects did not show any significant differences for land use types, aggregate classes and their interactions (Table 2).

Table 2. Analysis of variance results of the measured soil properties.

	Source	F-Ratio	Level of Significance
1 mm sieve (Aggregate Stability)			
	LUT	61.32	1%
	AGGCLASS	3.77	5%
	AGGCLASS x LUT	3.46	1%
0.5 mm sieve (Aggregate Stability)			
	LUT	2.25	ns
	AGGCLASS	2.03	ns
	AGGCLASS x LUT	0.75	ns
Organic Carbon			
	LUT	145.23	1%
	AGGCLASS	8.13	1%
	AGGCLASS x LUT	5.65	1%
Exc. Calcium			
	LUT	39.42	1%
	AGGCLASS	3.09	5%
	AGGCLASS x LUT	2.58	1%
Exc. Potassium			
	LUT	161.95	1%
	AGGCLASS	10.70	1%
	AGGCLASS x LUT	8.80	1%
Exc. Sodium			
	LUT	8.53	1%
	AGGCLASS	2.07	ns
	AGGCLASS x LUT	0.94	ns

LUT: Land use types; AGGCLASS: Aggregate size class; ns: not significant.

In terms of management practices, the soil aggregate stability across different land use types indicate that the land use for pasture had higher aggregate stability than other land use types, although not significantly higher than coconut plantation (Table 3). The arable land with maize that has been subjected to continuous cultivation year after year has the least soil aggregate stability, and significantly lower than other land use types. Considering the different aggregate sizes (Fig. 1), aggregate classes 5–10, 10–13 and 13–15 mm did not significantly differ in soil aggregate stability. However, aggregate class 2-5 mm was significantly lower than 10–13 and 13–15 mm, but not significantly different from aggregate class 5–10 mm. Thus, the aggregate sizes can be grouped into two classes based on their response to the aggregate stability test: i) sizes 10–13 and 13–15 mm, ii) sizes 2–5 and 5–10 mm. It is very important to know if the clod size ranges being tested behave homogenously or not.

Organic carbon distributions among land use types and their interactions with aggregate stability

The distribution of organic carbon among the land use types is presented in Table 3. Similar to soil aggregate stability, the soil organic carbon concentration was significantly higher ($p < 1\%$) in the pasture than other treatments while the soil under cassava plantation had the least organic carbon concentration (Table 3).

Table 3. Different properties measured among the land use types using 1.0 mm sieve

Land use type	Pasture	Coconut Plantation	Cocoa Plantation	Cassava Plantation	Maize Land
Aggregate Stability (%)	80.4a	77.8a	65.9b	51.1c	33.1d
Organic Carbon	2.38a	2.23a	1.75b	0.97c	1.06c
Exch. Magnesium	1.10c	1.73a	1.10c	1.48b	0.45d
Exch. Potassium	0.17e	0.53a	0.28c	0.22d	0.34b
Exch. Sodium	0.87a	0.15d	0.64ab	0.21cd	0.50bc

Exch.: Exchangeable; a, b, c, d, e – Mean within rows followed by the same letter are not significantly different ($p<0.05$).

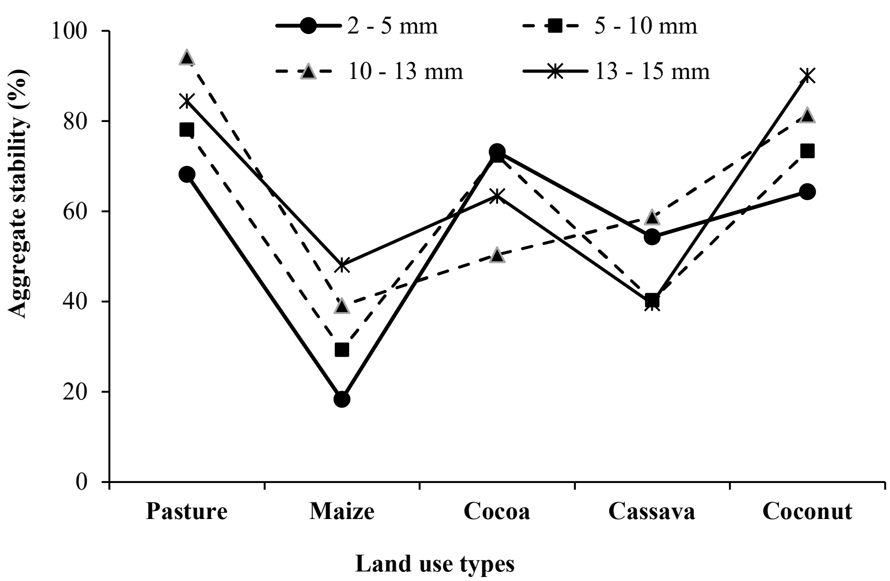

Fig. 1: Soil aggregate stability within aggregate classes and across different land use types

In relation to soil aggregate classes, the soil organic carbon within the aggregates did not show a definite pattern among the land use types (Fig. 2). While soil organic carbon concentrations in pasture and coconut plantations were dominated with those in 10–13 and 13–15 mm, the organic carbon in maize and cassava plantations were dominated by those in 2–5 and 5–10 mm classes. However, the organic carbon concentration in cocoa plantation was dominated by those in aggregates that fall into 2–5 and 10–13 mm classes.

In terms of the correlation between soil organic carbon and aggregate stability, aggregate stability determined with a 1.0 mm sieve had a significant relationship ($R^2 = 0.56$) with soil organic carbon, nevertheless no significant relationship observed when 0.5 mm sieve was employed (Fig. 3). In spite of significant correlation between soil organic carbon and aggregate stability when 1.0 mm sieve was used, the correlation coefficients (R^2) were, however, different within the aggregate classes (Fig. 4). The correlation coefficients were in the order of 13–15 mm ($R^2 = 0.85$) > 5–10 mm ($R^2 = 0.83$) > 2–5 mm ($R^2 = 0.68$) > 10–13 mm ($R^2 = 0.49$).

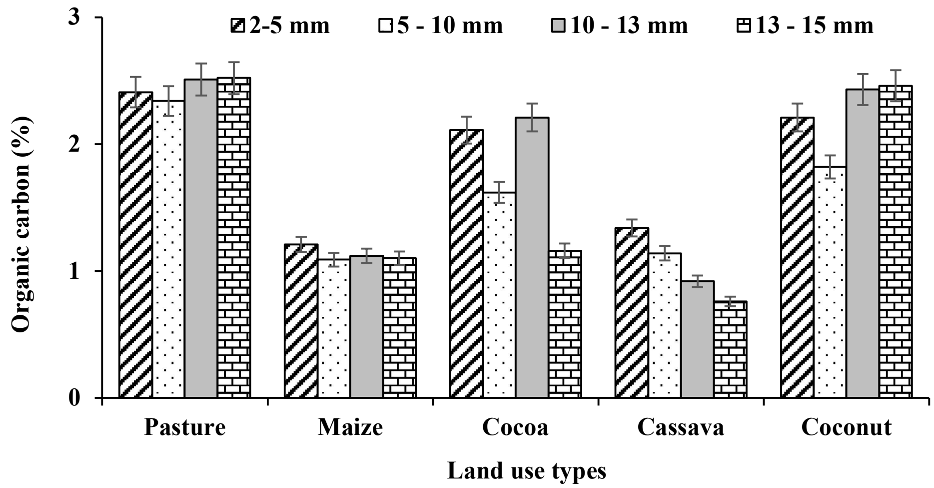

Fig. 2: Level of organic carbon within aggregate classes among different land use types

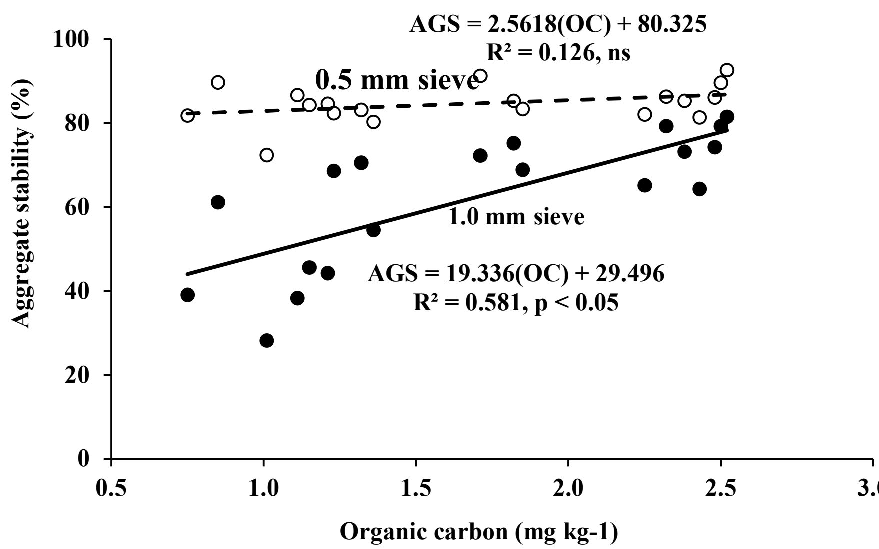

Fig. 3: Interactions between aggregate stability and soil organic carbon using 0.5 and 1.0 mm sieves. AGS = Aggregate stability; OC = Organic carbon.

Exchangeable bases distribution among land use types

Table 3 shows the distributions of soil exchangeable bases (Ca, K, and Na) across different land use types. There was no discernible pattern in the distribution of these elements across land use types. For example, while coconut plantation had the highest soil exchangeable calcium and potassium, pasture management had the highest exchangeable sodium. The ANOVA table in Table 2 displays the level of significant differences in these elements and their interactions with aggregate classes.

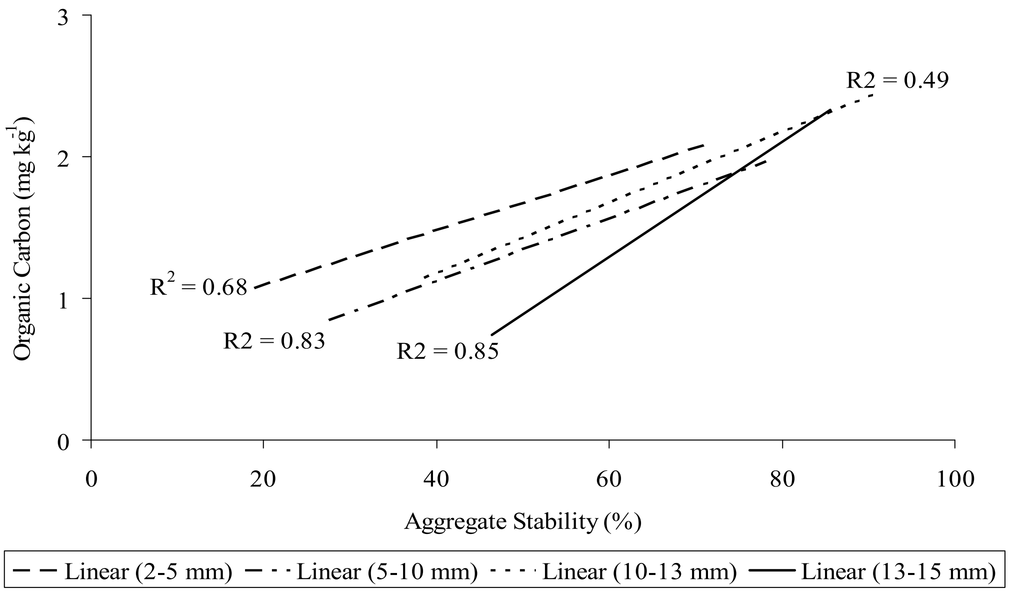

Fig. 4: Correlation coefficients between aggregate stability and soil organic carbon within aggregate classes using 1.0 mm sieve

The exchangeable calcium significantly varied among land use types at the 1% level, but not at the 5% level for aggregate classes. The interaction between land use types and aggregate classes, on the other hand, was significant at the 1% level. Meanwhile, the exchangeable potassium for land use types, aggregate classes, and their interactions differed significantly at the 1% level (Table 2). In contrast, the significant differences among the land use types in relation to the soil exchangeable sodium was observed at 1% level, but not with aggregate classes or their interactions with land use types.

Another important observation was the significant interaction of aggregate stability between the land use types and aggregate classes. This implies that aggregate sizes behaved differently under the land use types (Fig. 3). From Fig. 3, the land use types showed strong variations in aggregate stability across different aggregate size classes.

DISCUSSION

The significant differences among the land use types and aggregate classes for the aggregates placed on a 1.0 mm sieve in contrast to the non-significant difference found when the 0.5 mm sieve is a very important observation especially when considering the methodology used in quantifying aggregate stability. The question is which of these two observations should be accepted as a valid test of aggregate stability? Research has documented several methods for the determination of soil aggregate stability (Yoder, 1936; Le Bissonnais, 1996; Nimmo and Perkins, 2002; Jimba and Lowery, 2010). Many of these methods vary in their precision in quantifying soil aggregate stability. In general, any good aggregate stability measure must be sensitive and be able to distinguish between soils of varying stability. From this study, a significant difference in aggregate stability was expected especially among the land use types. From field observations, the mechanically tilled continuous arable land had higher rates of soil erosion taking place as evidenced by frequent rills, and was expected to have lower stability compared with land under permanent cultivation. Thus, the results of measurements using a 1.0 mm sieve seem to have captured these differences in the stability of soil aggregates. For instance, the values of organic carbon content plotted against the respective soil aggregate stability for both 1.0- and 0.5-mm sieves (Fig. 3) show that a 1.0 mm had a higher significant correlation than the 0.5 mm sieve. Soil organic carbon content has been shown by several authors to make the most important contribution to soil aggregate stability in tropical Alfisol, especially in humid tropics (Idowu, 2003; Are *et al*., 2018). Therefore, the stability results obtained under a 1.0 mm sieve seem to be more valid measurements than that of the 0.5 mm sieve. The presence of a high coarse sand fraction in the soil could explain why there was no discernible difference in the measurements using a 0.5 mm sieve. The coarse sand fraction in the soils varied between 40 and 60% (results not presented in this paper). The large-sized coarse sand particles caused a blockage of the mesh of the sieve. Thus, they prevent the broken-down soil from being washed away from the sieve. This inflated the amount of soil remaining on top of the 0.5 mm sieve after the rainfall simulation test. Thus, for further interpretation of results in this study, the stability values obtained under the 1.0 mm sieve gave a better differentiation of aggregate stability measured under the different land use types.

The significant difference in aggregate stability among the land use types was expected since the land use types had experienced different cultivation histories. The land use types under the permanent crop production had aggregates with significantly higher stability than the continuous arable lands of maize and cassava. This might have been due to the following:

i. significantly higher levels of organic matter in the surface soil of permanent crop cultivations when compared with arable lands.
ii. higher earthworm activities were observed under the permanent crops compared to the arable land use. Significant quantities of earthworm casts were found on the soils of land with permanent cultivation while these casts were virtually absent under the continuously cultivated land. Previous authors have shown a positive correlation between earthworm population density and aggregate stability (Sojka and Upchurch, 1999; Are *et al*., 2009; Józefowska *et al*., 2021)

It is worth noting that there were further significant differences in aggregate stability even among the permanent crops (Table 3). The aggregate stability was of the order of coconut > cocoa. The variation might likely be due to the quantity and quality of the organic material produced under these land use types. While the cocoa plantation had a lot of leaves acting as surface residue, the coconut plantation had a combination of both the leaf residue and bush re-growth under its canopy. These different sources of organic matter might have contributed to different levels of aggregate stability. This however needs further investigation.

A high level of aggregate stability under the long-term pasture was expected. This must have resulted from the influence of organic matter build-up under the grasses and perhaps from animal droppings. Similar observations were made by Aina (1979) working in a tropical environment. On the other hand, the continuous arable maize land gave declining aggregate stability with decreasing aggregate sizes (Fig. 1). In fact, the aggregates ranging from 13–15 mm were about 2.5 times more stable than those of 2-5 mm under the continuous arable land. This same trend of reduction in aggregate stability with decreasing aggregate sizes was also observed for the paddock and the coconut plantation (Fig. 1). While the trend in the soil aggregate stability under the cassava plantation was not very definite, the cacao plantation gave a slight decrease in aggregate stability with increasing aggregate sizes (Fig. 1). This observation may be linked to the quality and quantity of organic matter present in the different aggregate fractions of the soil.

From this study, organic carbon had a very high significant relationship with aggregate stability (Figs. 3 and 4). Thus, soil organic matter content (SOM) is an important determinant in the observed behaviour of the aggregate sizes under the land use types. Since SOM has no definite chemical composition, the soil organic carbon, which is dominant elemental constituent of SOM, is more commonly measured in scientific research (Weil *et al*., 2003). Previous works have shown varied results on the association between soil aggregate stability and SOM cycling. For instance, Puget *et al*. (1999) showed that organic carbon and plant derived carbohydrate increased with aggregate sizes in soils from Paris basin. Similarly, Zhou *et al*. (2020) reported a direct and positive relationship between the soil organic carbon concentration in each aggregate size and bulk soils. However, Lu (2001), in a study of aggregates under mulberry plantation, indicated that the organic matter content increased with decreasing aggregate sizes. Are *et al*. (2011) showed that the soil organic carbon concentrations were generally higher in larger aggregates than the smaller ones. From the above-cited literatures, it is evident that the type of land use may influence the organic matter content in different aggregate sizes. However, further investigation is needed to confirm this.

Although exchangeable calcium, potassium and sodium were significantly different among the different land uses, only exchangeable calcium gave a significant correlation with soil aggregate stability (Table 2). The effect of exchangeable calcium on aggregate stability may be related to its being a divalent cation. Study has shown that calcium has a very significant positive impact soil on soil aggregate stability (Wuddivira and Camps-Roach, 2007). From the results of this work, both organic matter and exchangeable bases were shown to have a significant influence on soil aggregate stability. However, the values of these variables (organic matter and exchangeable calcium) significantly differed for the aggregate classes sampled.

CONCLUSIONS

The study highlights the influence of aggregate size classes on the stability of soil aggregates under different land use types (pasture, coconut, cacao, cassava and continuous arable maize lands) in a humid tropical environment. The soil aggregate size classes from the different land use types were subjected to a simulated rainfall with 1.0 and 0.5 mm sieves to determine the optimal size class appropriate for routine aggregate tests. The soil aggregate stability was of the order of pasture > coconut > cocoa > cassava > maize lands. There were indications that the land cultivation histories, and the quantity and quality of the organic material produced under the land use types played important roles in the significant variations in soil aggregate stability. Furthermore, aggregate stability data obtained using a 1.0 mm sieve provided more valid measurements than the 0.5 mm sieve, with variations across land use types and aggregate classes. From the results of soil aggregate classes, aggregates ranging from 2 to 10 mm can be used for the determination of aggregate stability tests within the studied environment without introducing a strong variability in the results due to varying aggregate sizes. However, aggregates between 10 and 15 mm could be considered homogenous. This finding is very useful since a lot of studies use sieved soil clods to test soil aggregate stability. As a result, while conducting stability tests with soil aggregates, considerable attention to detail is required. The properties of the aggregates used, rather than the bulk soil itself, will provide a more accurate picture of soil stability in the humid tropical soil environment.

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