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Microaggregate Stability of Tropical Soils and its Roles on Soil Erosion Hazard Prediction

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1. Introduction

Soil aggregate stability influences a wide range of physical and biogeochemical processes in the agricultural and natural environments, including soil erosion [3]. The relative preponderance of aggregates of various sizes in the soil and their stability to external forces are, therefore, an issue of major concern to soil scientists. By definition, an aggregate is a composite body or granule of loosely bound mineral particles within a soil, the binding of which is characteristically mediated by a relatively minor amount of organic matter [Encyclopedia of Soil Science, ESS 2008]. The mineral and organic particles involved in such a natural conglomeration, otherwise known as aggregation, cohere to each other more than to the neighbouring particles and/or aggregates [ESS 2008]. Soil aggregates are therefore soil structural units of which classical soil research recognizes two major size-based categories, macroaggregates and microaggregates. Collapse of macroaggregates yields microaggregates. Thus, macroaggregates may be viewed as having microaggregates as their building blocks. Sometimes, external forces acting on a soil can also foster formation of aggregates from dispersed materials. It is the interplay of aggregate formation and breakdown that results in soil structure [54]. Although extremities in either of these structure-promoting processes are undesirable, they are considered an agronomic and environmental problem only in the case of breakdown. This is because it is much easier to break down over-sized aggregates into favourably sized ones than to achieve aggregation in structurally dilapidated soils. Consequently, studies on the responses of soil aggregates to natural and anthropogenic forces appear to tilt more towards stability or otherwise of soil aggregates than to their coalescence by these forces. Soil aggregation includes the processes of formation and stabilization, both of which occur continuously and concurrently [3]. Soil aggregate/structural stability may be defined as a measure of the ability of the soil structural units to resist change or the extent to

which they remain intact when mechanically stressed by environmental factors [ESS 2008]. The environmental factors that become important in this regard generally depend on climate and soil characteristics related to the nature of the parent materials and age of the soil. Another important factor is the intensity of disturbance related to land use and management [1]. To understand the importance of climate, it will be good to first state that water is such an indispensable entity in the discussion of soil aggregate stability that the subject is sometimes referred to as aggregate stability to water. Climate sets the limit of change in the state of water in the soil, whether the soil's response to the major climatic variables (rainfall and temperature) would be limited to mere wetting and drying or would also include freezing and thawing. In the tropical climate, soils are subject to frequent wetting and drying cycles in the short term during the rainy season and in the long term between the distinct rainy and dry seasons. Although freezing and thawing constitutes a greater stressor to soil aggregates, it rarely occurs in the tropics and therefore should be de-emphasized here for the sake of the scope of this chapter. In terms of inherent soil characteristics, tropical soils generally show a higher aggregate stability compared to temperate soils [55], and this is due mainly to mineralogy of the former being characterized by dominance of oxides and kaolin clays [54]. Nevertheless, aggregate stability remains a valid topic in the tropics, especially in the broad area of environmental management, because many soils in the region are regarded as structurally fragile and unstable. This is due to other soil-related and certain climatic peculiarities of the region. The soil-related factors militating against the aggregate stability of the majority of tropical soils include the sandy nature of their parent materials, which often reflects in the texture of the soils. It has been reported that the resistance of soil aggregates to raindrop impact decreases with a decrease in clay content of the soil [40]. Most other soils occurring in areas with heavy rainfall, even when not originally sandy, have been so intensively washed by runoff and leaching that their texture tends toward coarseness [33]. It is perhaps because of the vast area occupied by soils in these categories, commonly referred to as 'tropical sandy soils' in the literature, and the effect of the sandy texture on their aggregate stability that considerable research goes into their management [FAO 2007]. The coarse texture of the soils, coupled with the low concentration and high mineralization rates of organic matter (the typical aggregating agent) in them, implies impaired aggregation. Again, most tropical soils have long weathering history as is often evident in their low silt content [33], and this also contributes to frustrating aggregation processes in the soils. Indiscriminate deforestation, inappropriate land use and non-sustainable soil management options are also a common feature of agriculture in the region. In terms of climate, the aforementioned long-term wetting and drying cycles in most of the tropical region can have important implications for the aggregate stability of the soils. Also, the characteristic rainstorms and the associated heavy raindrops in especially the humid tropics can have considerable splash effect [38] and, therefore, are a force to reckon with in soil aggregate destabilization. It is thus clear that most tropical soils are structurally fragile and susceptible to many forms of erosion including accelerated and catastrophic erosion. [3] noted that good soil structure, known by the presence of well formed and stable aggregates, is the most desirable of all soil attributes for sustaining agricultural productivity and for preserving environmental quality. In the above context, a good understanding of the aggregate stability of tropical soils and its relationship

with their erodibility is needed to guide the management of these soils against erosive and similar degradative forces. In spite of the generally higher aggregate stability of tropical soils compared to temperate soils [55], soil erosion remains a major threat to agricultural productivity in the tropical region. Proper management is necessary to position these soil resources for continued support of agricultural and allied activities while not compromising environmental quality. Soil aggregate stability has been shown to give some guide on the relative stability of Ultisols from sub-tropical China to externally imposed destructive forces and, hence, to be an appropriate indicator of the relative susceptibility of the soils to detachment, runoff and interrill erosion [63, 53]. Our focus here is on microaggregation and the relationship between microaggregate stability and erodibility of tropical soils.

2. Appropriate aggregate stability indices for assessing erosion hazards in tropical soils

The derivation of many aggregate stability indices involves all aggregate-size classes and, as a result, such indices provide information on the overall stability of the soil. A typical example and, perhaps, the mostly widely used of such indices is the mean-weight diameter (MWD) of aggregates. However, the MWD is often regarded as index of macroaggregate stability of soils, probably because of the preponderance of macroaggregate-size classes over microaggregate-size classes in its computation. Where authors of the papers reviewed in this chapter fail to specify which of macro- and microaggregate stability their indices represent, we regard the indices as representing macroaggregate stability rather than microaggregate stability, provided their determination did not involve dispersion. The MWD and indeed all such aggregate stability indices which integrate aggregate-size classes into one number are regarded as macroaggregate stability indices in this chapter. The use of such indices to assess erodibility may prove suitable in temperate soils, but may not in highly weathered tropical soils known for their oxyhydroxidic mineralogy and very stable microgranular structure [17]. The question remains which of macro- and microaggregate stability more closely relates to erodibility of the majority of tropical soils. To answer this question, we need to first understand the mechanisms that are generally responsible for the breakdown of macro- and microaggregates. The main mechanisms of aggregate breakdown for macro- and microaggregates are slaking and dispersion, respectively. Slaking is the initial break-up of macroaggregates into microaggregates when immersed in water, caused by pressure due to entrapped air [38] and/or by differential swelling [ESS 2008]. Unlike slaking, dispersion liberates the soil colloidal particles that are more transportable during erosion. Hence, microaggregate stability is often referred to as colloidal stability. This suggests that microaggregate stability may be a better indicator of potential soil erosion hazards. Some studies have related potential soil loss or, more specifically, the erodibility of tropical soils to their aggregate stability at both the macro and micro levels. These studies tend to support the view that erosion in the soils is related more to microaggregate stability than to macroaggregate stability. For instance, Igwe et al. [19] compared the predictability of soil loss by selected macro- and microaggregate stability indices for some soils from southeastern Niger-

ia. They found that all microaggregate stability indices predicted soil loss better than their macroaggregate stability counterparts. Some other researchers reported weak correlations between soil erodibility and macroaggregate stability indices for some Nigerian soils [30, 31]. The soils in question are by virtue of their parent materials dominated by quartz and, as is the case with many tropical soils, are at an advanced stage of weathering. Hence, such other minerals as Fe-oxyhydroxides and kaolinite abound in them, and these are the minerals that are known to cause highly stable aggregation [54]. Since these predominant minerals do not expand rapidly when immersed in water, slaking proceeds rather slowly in the soils. The implication is that the soils show fairly high macroaggregate stability which is a misrepresentation of their high erodibility and erosion status [33]. Considering the widely accepted role of soil organic matter in aggregate formation and stabilization/destabilization, the choice of microaggregate stability for the prediction of potential erosion hazards in tropical soils would also be explained by the relative influence of organic matter on macro- and microaggregate stability. Macroaggregates are generally considered more sensitive to soil organic matter concentrations—and hence are less stable—than microaggregates [58]. Whereas the theory of macroaggregates being less stable than microaggregates may hold true for tropical soils, that of macroaggregates being more sensitive to soil organic matter concentrations than microaggregates remains a controversial topic. It has been shown that the relationships between aggregate stability indices and organic matter concentrations in tropical soils are generally characterized by weak correlations [55], and these are thought to be due mainly to the relatively lower organic matter status of the soils. However, inconsistencies characterize the response of macro- and microaggregation to organic matter concentrations in tropical soils. The relationship between macroaggregate stability and soil organic matter concentration has been reported to be non-significant [17, 31, 64] or positively significant [7, 18, 26] or negatively significant [23]. There are indications that these relationships may depend on method of assessment of macroaggregate stability as well as on location. Soil clay content is another factor that may dictate the nature of organic matter effect on macroaggregate stability of tropical soils [61]. Similarly, the relationship between microaggregate stability and organic matter concentration in tropical soils has been reported to be non-significant [23] or positively significant [12, 42, 64, 51] or negatively significant [30, 33, 34]. There are indications that these relationships may depend on microaggregate stability index adopted by the authors as well as on the contents of organic matter in the soil relative to other microaggregating agents.

3. Soil microaggregation and microaggregate stability

There are a lot of inconsistencies in the literature regarding the appropriate size boundary between macro- and microaggregates. The placement of size boundary for the classification of aggregates into macro- and microaggregates and the delineation of their upper and lower limits, respectively appear to depend on the researcher's orientation and location. We adopt here the categorization scheme proposed by Oades and Waters [46], which specifies the boundary between macro- and microaggregates as 0.25 mm, and this is consistent with the

use of 0.25 mm as the boundary between water-stable and water-unstable aggregates in aggregate stability studies. In the hierarchy of aggregate size order, the lower boundary of microaggregates is taken to be 0.02 mm [46]. However, these upper and lower boundaries may be exceeded in highly weathered tropical soils where the association between microaggregates and clay-sized granules often form a kind of continuum of very stable aggregates [59, 49]. The stable microgranular structure is often manifested in form of pseudo-sands composed of clay particles that are strongly cemented together by Fe oxides [31].

Microaggregates are formed in a number of ways, each influenced by a number of factors. The process of microaggregation combines break-up of aggregates due to slaking and aggregates due to subsequent attrition [14]. Factors that influence microaggregation may differ between the temperate and tropical regions. Some researchers working in a German temperate soil reported that microaggregation depended strongly on the size distribution of primary particles rather on land use [39]. Conversely, an assessment of microaggregate stability under different land use types in a Nigerian tropical soil revealed a strong dependence of the soil microaggregation on land use [51]. This implies that the agents of stabilization of microaggregates in tropical soils are sensitive to land use.

The high aggregate stability for which tropical soils are reputed is not limited to macroaggregates. As already noted, microaggregates formed in tropical soils at advanced stages of weathering are also of very high stability [59, 46, 28]. In spite of this, microaggregate stability may still be a good indicator of the erodibility of tropical soils because of its direct link with silt and clay dispersion. Mineralogy appears to have a great influence on microaggregate stability of soils [45]. In this regard, the major microaggregating agents in tropical soils are Fe and Al oxides [17, 64, 31, 2, 28, 57]. However, in hardsetting lowland soils with low organic matter concentration and which are prone to seasonal flooding, microaggregation may be achieved through practices that enhance the organic matter concentration in them, since the roles of Fe and Al oxides in such soils may be dispersive rather than microaggregating [27]. Also, the microaggregating effect of Fe_2O_3 has been reported to be masked in some soils with relatively high concentrations of organic matter (1.39-6.79%) while that of exchangeable Ca and Mg became evident due to the tie-up of these elements with organic matter and hence their minimal leaching [Opara 2009]. Closely related to the effect of Fe and Al oxyhydroxides on the microaggregate stability of tropical soils is that of the non-expanding clay types, which dominate the clay mineralogy of the soils [30, 2006, 61, 57].

In tropical soils, soil organic matter may act as a dispersing/deflocculating agent [31], as a microaggregating agent [26, 51] or as a facilitator to the microaggregating effect of Fe-Al oxides [28], depending on its relative abundance in the soils. By contrast, the effect of soil organic matter concentration on microaggregate stability of temperate soils appears not to be pronounced [39]. Apart from protecting the surface against raindrop impact, organic matter may impart hydrophobic characteristics to the soil, thereby reducing the slaking that usually precedes dispersion [38]. In some Fe-Al oxidic tropical soils from Malaysia, it was polysaccharide constituent of soil organic matter rather than total organic matter that influenced microaggregate stability [57]. Notably, the soil content of Fe and Al oxyhydroxides is not easy to manipulate by regular soil management practices [5]. The inference that can be

drawn here is that the view that organic matter is not the main aggregating agent in tropical soils rich in Fe-Al oxyhydroxides [5] may not always apply to microaggregation, but the exact role of organic matter may depend on its concentration in the soil and on its chemical composition as may be determined by the prevailing land use and soil management.

4. Aggregate breakdown mechanisms and erosion processes

Some tropical soils occurring in high-intensity rainfall zones have the tendency to slake and form seals, thereby resulting in considerable runoff and soil erosion [50, 13]. Although rainfall impact and slaking cause much greater breakdown of macroaggregates than microaggregates, these two factors can also be important for microaggregate stability and soil erodibility in at least two ways. First, slaking precedes dispersion. And this is the reason why, even though slakability is different from dispersibility, soils with high slaking potential are at high risk of interrill erosion [41]. Second, sealing and crusting often accompany slaking. Seal is defined as the orientation and packing, at the very surface of the soil, particles dispersed from soil aggregates due to the impact of rain drops, thereby rendering the soil relatively impermeable to water [44]. This is the first stage of seal formation. As the ponded water infiltrates or evaporates, the soil particles suspended in it get deposited on the soil surface, thereby increasing the thickness of the seal. This is the second stage of seal formation. The entire seal eventually dries out to become crust, a thin but much more compact and hard layer than the material directly beneath [44, 60]. Both seals and crusts are therefore formed in the same way and occur commonly in the semi-arid regions [44, 60]. Crusts formed due to the first and second stages of seal formation are called structural crusts and depositional or sedimentary crusts, respectively [44, 38].

Most tropical soils are highly weathered and lacking in expanding clay types. Where they occur, the associated shrink-swell hazard is mostly concentrated in the subsoil where there is increased content of clay particles due to translocation and illuviation or residual accumulation of clay [33]. Because of this, slaking is due more to compression of air entrapped inside aggregates during wetting than to swelling. In the absence of swelling, the intense rainstorms experienced in the tropical region may result in sedimentary sealing and crusting especially in soils with reasonably high clay content but with disproportionately low concentration of organic matter [62]. Surface sealing and crust formation are an important factor in erosion processes, for they influence detachability of soil particles from aggregates, as well as infiltration rate and surface roughness which determine runoff volume and speed, respectively [38].

For soil erosion in interrill areas, three generally recognized sub-processes completely define soil erosion; and they include detachment, transport and sedimentation [38]. Some researchers working with sandy-loam soils in the semi-arid tropics have obtained results which suggest that the erodibility of a soil depends on the relative proportion of aggregates in the soil, being higher when the aggregate size distribution shows a greater proportion of large-sized aggregates [35]. Others working with low-activity-clay tropical soils reported that the satu-

rated hydraulic conductivity increased with an increase in structural stability of the soils [61, 48]. Increased saturated hydraulic conductivity implies reduced weakening and dispersion of the soil aggregates following rainfall and/or irrigation and, hence, less susceptibility to erosion. It appears therefore that, with respect to erosion, the predominance of large-sized aggregates in soils is not always an indicator of good soil structure, but the stability of the soil pore system is.

It has been shown that, in tropical soils, disruption of macroaggregates leaves them as microaggregates rather than as primary particles [17]. Disintegration of soil macroaggregates into microaggregates following rainfall, slaking, dispersion and sealing can decrease infiltration and saturated hydraulic conductivity of the soil [36, 37]. These effects which ultimately increase soil loss can be more severe in soils of low organic matter concentration [37], as those occurring in the tropical region. The main mechanism of microaggregate breakdown is dispersion into primary particles, and this is influenced by the electrolyte concentration of the soil solution and the applied water, exchangeable sodium percentage and mechanical disturbance [38]. Electrolyte concentration and the dispersion it induces can lead to a situation whereby re-deposition of the dispersed particles cause clogging of water-conducting pores in the soil, in which case the hydraulic conductivity becomes drastically reduced [10]. The roles of exchangeable sodium percentage and electrolyte concentration in microaggregate stability are also evident in tropical soils [31, 32], probably due to the effect of ions on the amount of aggregates cemented by Fe-Al oxyhydroxides.

Generally, polyvalent cations cause flocculation whereas the monovalent cations cause dispersion [38]. It appears, however, that in hardsetting tropical soils with low organic matter concentration and that are prone to seasonal flooding, the flocculating role of polyvalent cations and the dispersive role of monovalent cations are usually not evident [27]. On the other hand, polyvalent cations (Ca^{2+} and Mg^{2+}) are good microaggregating agents under upland soil conditions, provided there is sufficient organic matter in the soil to retain these cations against leaching [51]. For a range of tropical soils all from Nigeria, factors that have been identified to influence soil dispersion include presence and concentration of monovalent cations (mostly K^+) in prospective irrigation water [27], soil reaction (pH), sodium adsorption ratio, and soil properties related to cation exchange [32, 23, 26]. In the same region, elemental contents in silt fraction were reported to influence microaggregate stability [24].

5. Assessment of soil microaggregate stability

Microaggregate stability is normally assessed by the extent of dispersion of microaggregates into granules and/or primary particles. This is difficult to do under field conditions where the dynamic nature of this soil property may not permit attainment of reliable data. Consequently, most methods of assessment of microaggregate stability are based either on conceptual model of microaggregation involving the finer and colloidal particles or on the response of isolated microaggregates to simulated dispersive force in the laboratory. Although the disintegration forces applied in the laboratory may attempt to simulate those found in the

field, they do not fully duplicate field conditions [3]. Forces applied to achieve dispersion during microaggregate stability tests may even be bigger and too sudden compared to the ones that cause dispersion under field conditions. Results of such tests are, however, still useful for they allow for a discrimination between soils in accordance with field observations [3], thereby providing information that can guide management decisions. Some of the methods that have been applied to tropical soils are summarized (Table 1). The information presented in this table shows that all the indices have to do with clay and/or silt dispersion in water. Although either of the water-dispersible clay (WDC) and water-dispersible silt (WDS) can be used to do the assessment of microaggregate stability, most researchers prefer using indices that include both.

One observation that is noteworthy is the seemingly lack of agreement among the soil microaggregate stability indices included in this review. This lack of agreement is evident in the inconsistent pattern in which these indices relate to other soil properties, including soil contents of oxides and organic matter, both of which have been shown to be very important in microaggregation. For instance, WDC and clay dispersion ratio (CDR), both of which are indices of colloidal stability, have been reported to correlate with soil organic matter concentration in a contrasting manner [30]. It appears thus that, under certain conditions, some colloidal stability indices serve better, but under some other conditions, the same colloidal stability indices may not be suitable.

6. Soil erosion hazards in tropical soils and the need for prediction

The more widespread forms of erosion are rill and interrill erosion. Soil erosion can have both on-site and off-site effects which are the lowering of soil productivity and deposition of sediments, respectively. Crop yields are usually used as a proxy measure of soil productivity loss to erosion. Deposition of sediments, mostly colloidal particles detached from the soil by agents of erosion, occurs after they are transported by surface runoffs generated during rainfall (in the case of water erosion) and turbulent winds (in the case of wind erosion). Water erosion also results in the transport of runoff-laden solutes and dissolved contaminants and is thus a major source of land and water pollution. The problem is experienced more in the humid and sub-humid tropics where the rains often come as rainstorms. Here, soil loss to water erosion can be over 50 tons $\text{ha}^{-1}\text{yr}^{-1}$ [50, 15]. In contrast, the impact of wind erosion is felt more in the semi-arid and arid tropical climates, with soil loss rate that often surpasses that due to water erosion. In the West African Sahel, for instance, soil loss to wind erosion can be in the range of 58-80 tons $\text{ha}^{-1}\text{yr}^{-1}$ [34].

In those areas where water erosion is the bigger problem, taxonomically different soils can respond differently to erosion under similar conditions. For instance, Inceptisols and Entisols have been reported to be more erodible than Ultisols, due to higher Fe and Al contents of the latter [23]. With respect to crop yields, the productivity of adversely eroded soils can be restored through careful selection of appropriate soil management practices. However, except in a few cases where materials deposited by runoff are properly harnessed, the off-

site effect of soil erosion always constitutes environmental problems. In contemporary agriculture where the emphasis is on not just achieving high yields but also on making agricultural enterprise environment-friendly, such environmental problems arising from soil erosion should be viewed as undermining agricultural productivity.

The problem of soil erosion and the associated negative impacts on agriculture and the environment is particularly severe in tropical sub-Saharan Africa, where it is a major cause of declining and stagnating soil productivity [48]. When considering appropriate soil conservation as an option, the first step is to try to understand the roles of microaggregate stability in checkmating soil erosion and in predicting soil erosion hazards. Prediction of soil erosion hazards involves a quantitative assessment of potential soil erosion in a land resource of an area. Such quantitative information is used in soil erosion hazard mapping for both short-term and long-term planning against erosion and associated deleterious effects, and this can have many agricultural and environmental benefits. Many atimes, erosion hazard maps are viewed as a tool for detailed farm planning and management [30]. Information on potential erosion hazards can also be used to embark on precautionary soil and water conservation measures. For instance, conservation specialists can use such information to select appropriate engineering designs and structures aimed at forestalling the occurrence of erosion in the first place, or controlling erosion in already eroded areas. Once started, rill and interill erosion need to be timely arrested, otherwise they may escalate into gully erosion, which is the more spectacular form of erosion that often threatens the integrity of the environment.

7. Microaggregate stability and erosion hazard prediction for tropical soils

Virtually all known methods of assessing microaggregate stability, discussed earlier, employ the extent of dispersion into primary particles. The relevance of microaggregate stability for assessing potential erosion hazards lies, therefore, on the effects of dispersion on soil hydrophysical processes. Dispersion generally induces processes that are related to soil erodibility such as very fast crusting, slow infiltrability, and great mobility of particles in water [38]. Soil erodibility may be defined as the degree or intensity of a soil's state or condition of being susceptible to erosion [56]. It is just one of the main parameters needed for erosion hazard prediction. The most commonly used index of erodibility is the erodibility factor (K-factor) of the revised universal soil loss equation (RUSLE). Although fragments/sediments detached by raindrops can be finer than the original soil, the detachment is often accompanied by mere displacement (splash effect); the actual transport and sedimentation involve silt- and clay-sized particles [38]. Therefore, microaggregates dispersion is a precondition for soil erosion to be complete. There is evidence from the United States that WDC and CDR can be good estimators of erodibility of some soils in Ohio [4].

Microaggregate stability, when used as a tool for predicting soil erosion hazards, takes into account only the aspect of such hazards that are due to the soil inherent erodibility. One would therefore expect researchers to relate microaggregate stability to only soil erodibility

when assessing potential erosion hazards. However, because soil erodibility is a dynamic soil property, its accurate determination can sometimes be difficult. Acquisition of data for soil erodibility is particularly difficult in the case of the K-factor of the RUSLE, as this requires some basic land-use information as well as pre-measurement soil management specifications, actual practice of which is often tedious and time-consuming. Consequently, not all researchers relate microaggregate stability to soil erodibility; some often relate it directly to soil loss to natural or simulated erosion, while keeping constant such other factors that affect erosion as rainfall, topography, vegetation, and soil management and conservation practices. We reason that, unless the relationship between microaggregate stability indices and erodibility/soil loss are not established by statistical correlations, the effects of such methodological differences may be negligible.

Index	Derivation	Interpretation	References
Clay ratio, CR	$\frac{\% \text{ sand}}{\% \text{ silt} + \% \text{ clay}}$	A	Mbagwu (1986)
Degree of aggregation, DOA†	$\frac{w_a - w_b}{w_a}$	B	Zhang and Horn (2001)
Water dispersible clay, WDC	Clay after particle-size analysis with deionized water only	A	Mbagwu and Auerswald (1999); Igwe (2005)
Water dispersible silt, WDS	Silt after particle-size analysis with deionized water only	A	Igwe and Nkemakosi (2007)
Aggregated clay, AC or Clay aggregation, CA	Total clay – WDC	B	Mbagwu and Auerswald (1999); Igwe (2003)
Aggregated silt + clay, ASC	Total silt and clay – WDS and WDC	B	Igwe et al. (1999a)
Clay dispersion ratio, CDR or Clay dispersion index, CDI	$\frac{\% \text{ WDC}}{\% \text{ total clay}}$	A	Igwe and Nkemakosi (2007); Opara (2009)
Clay flocculation index, CFI	Total clay – WDC/total clay	B	Igwe and Nkemakosi (2007)
Dispersion ratio, DR or Water dispersible clay and silt, WDSCS	$\frac{\% \text{ WDS} + \% \text{ WDC}}{\% \text{ total silt and clay}}$	A	Mbagwu (1986); Igwe (2005); Igwe and Nkemakosi (2007); Sung (2012)

† w_a and w_b stand for the proportion of particles between 0.25 and 0.05 mm obtained by microaggregate size analysis and by particle size analysis, respectively.
A – The smaller the value, the more stable the microaggregates are.
B – The bigger the value, the more stable the microaggregates are.

Table 1. Indices of microaggregate stability commonly applied to tropical soils

Although a good number of studies have been conducted on aggregate stability of tropical soils, our survey of the literature reveals that not many of these studies related the erodibili-

ty of the soils or potential soil loss to aggregate stability. Soil aggregate stability or instability is such a critical factor in erosion processes that erosion is often the first thing that comes to the mind when pondering over usefulness of information on aggregate stability. It is thus surprising that the majority of studies on aggregate stability of tropical soils failed to describe its relationship with soil erosion. Again, among the few studies that did otherwise, only a small proportion used microaggregate aggregate stability indices in spite of the fact that, as we have been able to show earlier in this review, microaggregate stability more than macroaggregate stability corresponds to the dispersion and erodibility of tropical soils. We review in the preceding paragraph only those studies that related soil erodibility or potential soil loss to microaggregate stability in the tropical region.

In southeastern Nigeria, clay ratio (CR) and dispersion ratio (DR) were reported as being close substitutes to the K-factor in the prediction of soil loss [40]. Also in this region, Igwe et al. [29] related the K-factor to selected indices of microaggregate stability for soils from diverse geological formations. Their results showed a good correlation ($r = 0.53$) between K-factor and clay flocculation index (CFI), and they recommended that the CFI alone could be used to predict soil erosion hazard in the area. The stability and soil-loss response of a stony Nigerian tropical soil undergoing intensive cultivation to simulated tillage and stone removal was investigated [30]. This laboratory study revealed that tillage and stone removal led to increases in WDC, DR and CDR; and that this failure in microaggregate stability of the soil increased erosion of the soil. Still working with soils from southeastern Nigeria, Igwe [31] reported that any of DR, CDR and WDC could be used in predicting erodibility of some the soils. The CDR and DR were also found, in a separate study, to have significantly ($r = 0.44$ and 0.39 , respectively) correlated with K-factor of the RUSLE and were therefore deemed good indices for predicting erodibility of soils of eastern Nigeria [32]. All these studies demonstrate the suitability of some microaggregate stability indices for assessing soil erodibility and potential soil loss in the tropical region.

8. Areas of further research

All the indices of microaggregate stability included in this review were developed based on silt and/or clay dispersion which occurs only in wet or submerged soils, and this limits their applicability to erodibility assessment to the case of water erosion [9]. In the semi-arid and arid tropics, wind erosion is a major source of soil and nutrient loss in agricultural soils. An index of microaggregate stability is therefore needed for such soils to also enable the assessment of potential erosion hazards in them. Similarly, there are indications that removal of gravels and stones from tropical soils characterized by high gravel content can confer higher erodibility to such soils [43, 25]. This implies that, for this category of soils, the use microaggregate stability indices determined from routine laboratory measurements as indicators of soil erodibility may be misleading. It may therefore be necessary to correct microaggregate stability results for gravel content, especially when they are intended for use in the assessment of soil erodibility. Research is needed on the best method of doing such a correction as may be confirmed by a good agreement between the ensuing results and field-measured

erodibility of the soil. Also, some researchers have reported good correlations between their microaggregate stability indices and soil contents of silt [57] or clay [26, 51], just as others have reported that elemental contents in silt fraction affected microaggregation [24]. Silt is known to be the soil particle that is most susceptible to loss during erosion [52], and the data presented by Igwe and Ejiofor [2005] for a severely gullied tropical soil support this assertion. This suggests that paying attention to soil texture, especially variations in silt content, may benefit microaggregate stability studies in relation to erodibility.

It is known that oxides which abound in many tropical soils are a major promoter of their colloidal stability. The role of particularly Fe oxides in microaggregate stability may not be limited to the promotion of microaggregate formation. A study conducted in a mediterranean environment revealed that Fe oxides also acted to decrease dispersion of clay [6]. The possibility of this phenomenon and the factors promoting it in Fe-oxide-rich soils in the core tropics need to be explored. This review reveals that there are conflicting reports on the effect of organic matter concentration on soil microaggregation and microaggregate stability of tropical soils. Forms of oxides in the soil can influence not only their aggregating potential but also that of organic matter [11], and this has been demonstrated specifically for microaggregation of tropical soils [28]. On the other hand, the chemical composition of organic matter and its distribution in the aggregate-size classes (whether it is physically protected within microaggregates or not) may also contribute to determining how it influences microaggregation in the soil. More studies are therefore suggested on the role of organic matter in microaggregate stability of tropical soils, with emphasis on soils differing in both contents and forms of oxides.

In erosion processes, field capacity is expected to be an important factor because of its direct link with infiltration and runoff. It has been shown that slaking potential of a soil decreases with an increase in its field capacity [8], suggesting that the tendency for dispersion may also decrease with an increase in field capacity. However, in severely gullied soils in eastern Nigeria showing silt content of not more than 1% and mean organic matter concentration of 0.18% (both on weight basis), CDR was shown to increase (i.e. decrease in colloidal stability) with an increase in field capacity [23]. Recently, Abrishamkesh et al. [1] reported higher field capacity under a condition of higher structural stability than lower structural stability in a temperate environment. Similarly, Obalum et al. [48] reported that the lower the structural stability of some coarse-textured tropical soils, the higher the pressure at which they attain field capacity. They attributed the observation to reduced dispersion and hence increased internal drainage of the soils as their stability increased. It appears therefore that the field capacity represents a structural index related to both dispersability and stability of soil aggregates. Research is needed to fully explore the relationships among field capacity, microaggregate stability and erodibility of tropical soils differing in degree of past erosion.

9. Conclusion

The majority of tropical soils show high microaggregate stability irrespective of their low organic matter concentration. This is due mainly to their high contents of Fe and Al oxides

which are known to promote microaggregation in soils of low organic matter concentration. However, there are some conflicting reports on the effects of the various players, especially oxides and organic matter, on microaggregation in tropical soils. So many natural and anthropogenic factors can lead to dispersion of the soils, but the factors tend to vary from study to study. A number of agricultural and environmental problems can arise from the dispersion of clay especially in sandy soils characterized by low concentration of organic matter [9], like the ones predominant in the tropics. The most important of these problems is soil erosion. Although only few studies have related soil erosion hazard (assessed either by soil erodibility or by soil loss) to selected indices microaggregate stability, these studies show that microaggregate stability is a useful tool for predicting erosion hazards in tropical soils. However, comparisons of results of erosion hazard prediction would be meaningful only when the same index of microaggregate stability is used. We suggest some areas for further research on microaggregation in tropical soils and the relationship between colloidal stability and soil erodibility.

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