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CHARACTERISATION OF SOIL PHYSICAL PROPERTIES AND RESISTANCE TO EROSION IN DIFFERENT AREAS OF SOIL ASSOCIATIONS

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ABSTRACT

Understanding the effects of soil physical properties on resistance to erosion is important for land use planning and soil erosion management. The objective of this study was to characterise the physical soil properties of areas of soil associations and determine the influence of litter source on aggregate stability and rates of soil loss in areas of soil association in the Ntabelanga area, Eastern Cape Province, South Africa. Soil was sampled from 21 randomly selected points in the areas of soil associations. Soil was incubated for 30 weeks after increasing the SOC to > 2% by adding *Vachellia karroo* leaves (low C/N) and *Zea mays* stover (high C/N) and rate of soil loss (t ha^{-1}) determined at 1, 3, 8, 14, 23 and 30 weeks of incubation. The soil physical properties, resistance to dispersion and aggregates distribution varied significantly ($P < 0.05$) across soils. All soils had significantly ($P < 0.05$) low (< 2%) SOC (%) and high (> 0.02)[(t ha h)·(ha MJ mm)$^{-1}$] K-factors indicating high erodibility. *Vachellia karroo* and *Z. may* organic matter significantly ($P < 0.05$) reduced soil loss from 1 to 8 weeks after incubation thereafter lost its effectiveness. Organic matter stabilised the soils, but only for a short period (8 weeks). It is recommended to minimise soil disturbance in the Ntabelanga area as this will exacerbates the problem of erosion.

Key Words: K-factors, *Vachellia karroo, Zea mays*

RÉSUMÉ

Il est important de comprendre les effets des propriétés physiques du sol sur la résistance à l'érosion pour la planification de l'utilisation des terres et la gestion de l'érosion du sol. L'objectif de cette étude était de caractériser les propriétés physiques du sol des zones d'associations de sol et de déterminer l'influence de la source de litière sur la stabilité d'agrégat de sol et les taux de perte de sol dans les zones d'association de sol dans la région de Ntabelanga, Province du Cap oriental, Afrique du Sud. Le sol a été échantillonné à partir de 21 points choisis au hasard dans les zones d'associations de sols. Le sol a été incubé pendant 30 semaines après avoir augmenté le COS à > 2% en ajoutant des feuilles de Vachellia karroo (faible C / N) et de la souche de *Zea mays* (C/N élevé) et le taux de perte de sol (t ha^{-1}) déterminé à 1, 3, 8, 14, 23 et 30 semaines d'incubation. Les propriétés physiques du sol, la résistance à la dispersion et la distribution des agrégats variaient considérablement (P <0,05) d'un sol à l'autre. Tous les sols avaient significativement (P <0,05) un SOC faible (<2%) (%) et élevé (> 0,02) [(t ha h).(ha MJ $mm)^{-1}$] facteur K indiquant une forte érodabilité. *Vachellia karroo* et Z.may peuvent considérablement réduire la perte de sol de 1 à 8 semaines après que l'incubation ait perdu son efficacité. La matière organique a stabilisé les sols, mais seulement pendant une courte période (8 semaines). Il est recommandé de minimiser la perturbation du sol dans la région de Ntabelanga car cela aggravera le problème de l'érosion.

Mots Clés: Facteurs K, *Vachellia karroo*, *Zea mays*

INTRODUCTION

Soil erosion is a complex process that depends on soil properties, ground slope, vegetation, and rainfall amount and intensity (Lal, 2001). Accelerated erosion, by water and wind, is a selective process and involves preferential removal of the light and small soil fraction (Bajrachrya *et al.*, 2000). Therefore, soils that easily disintegrate into light and small fractions under pressure are susceptable to erosion. Soil resistance is a measure of the capacity of the soil to absorb applied power without disruption or removal of soil from its original position. Soil physical properties are among the most sensitive to disturbance from soil working (Fu *et al.*, 2019; Ghanbarian and Daigle, 2015) and are known to influence soil erodibility (Andoh *et al.*, 2012; Tuo *et al.*, 2017). However, the effect of soil physical properties on soil resistance to erosion in areas of soil associations of the Ntabelanga area, Eastern Cape, South Africa is still sketchy.

South Africa (SA) is characterised by varying degrees of soil loss that are classified as moderate to high risk (where the average annual soil loss rate exceeds 12 t ha yr^{-1}) (Le Roux, 2010). The soils are characterised by a small (<2%) organic carbon content and are easily eroded (Parwada and Van Tol, 2016). The Eastern Cape Province, in particular has >56% of its total area under severe threat of erosion (Le Roux, 2007). Regardless of the high rates of erosion and unstable soils, the SA government proposed to construct a strategic dam in the Eastern Cape Province. The high rates of soil erosion in the proposed dam site pose a threat to the integrity of the dam. Large amount of sediments to be discharged into the dam will increase costs of maintenance and in the long run make it unusable for the purpose (Parwada and Van Tol, 2016). It is, therefore, prudent to characterise soil properties influencing erodibility in the proposed dam site. Furthermore, understanding the physical status of the soil will help with the control of soil erosion and ecological restoration.

Soil erodibility is a key parameter in assessing the soil's susceptibility to erosion; it is essential for predicting soil loss and evaluating its environmental effects (Panagos *et al.*, 2012). The most commonly utilised soil erodibility term is the soil erodibility factor (*K*) of the Universal Soil Loss Equation (USLE) (Wischmeier *et al.*, 1971). The K-factor was observed to vary between 0.7 for the most fragile soils, to 0.02 for the most resistant soils. De Oliveira *et al.* (2009) found values ranging from 0.12 in ferralitic soils on granite, to 0.2 in ferralitic soils on schist.

In most cases, the K-factor is influenced by the quantity of soil organic matter (SOM) (Wang *et al.*, 2013). There are two possible approaches to improve soil resistance. These are, selecting the most resistant soil in an area for construction work and permanent cover of the most fragile soils (Ghanbarian and Daigle, 2015).

Organic matter (OM) is a major contributor to soil aggregate stability because it provides important biological binding agents, which decrease the breakdown of aggregates by slaking, swelling or even osmotic stress (Cosentino, 2006). Soil aggregation influences a range of soil properties, including water infiltration, hydraulic conductivity, water retention, soil porosity and compaction (Six *et al*., 2000); and the accumulation and long-term storage of soil organic carbon. In contrast, other studies have reported that the rate of OM input or soil characteristics (essentially C and clay contents) have no effect on aggregate stability (Abiven *et al*., 2009). The contribution of OM to soil erodibility, therefore, warrants more research.

Soil parameters such as mean weight diameter (MWD), and geometric mean diameter (GMD) have been mostly used to analyse aggregate stability (Kalhoro *et al*., 2017). Moreover, aggregate state (AS), aggregate degree (AD), and dispersion rate (DR) determine the ability of soil to resist disturbance, and can serve as indicators of soil structure (Tuo *et al*., 2017). The AS, AD and fractal dimension (D), are key determinants of soil particles and pore characteristics (like size, number, and geometry), and are commonly applied in soil classification and the estimation of various related soil properties, because of its relationship with soil water movement, structure, productivity and erosion (Zheng *et al*., 2018). Therefore, identifying changes in soil D, AS and AD provide useful information for further research regarding soil protection. It also give an insight on the recovery mechanisms and other soil science topics of areas of soil associations. State of aggregation (SA) gives the amount of naturally occurring discrete clusters or groups of soil particles that can only exist when the binding force exceeds the force between adjacent aggregates (Tobiasova *et al*., 2018). State of aggregation correlates with soil binding agents, and soils with high state of aggregation do not disperse easily (Thomas *et al.,* 2018).

Fractal dimension (D) is also a powerful tool that can be used in characterising aggregate-sized distributions applied to monitor the soil structure (Ghanbarian and Daigle, 2015). Zheng *et al*. (2018) found that MWD and GMD increased, while fractal dimension decreased when the fractal method was used to estimate soil structural changes under practices in conventional tillage/no tillage rotation.

Literature provides a general explanation on the relationship between the soil physical properties and soil erodibility, ignoring the specificity of erosion on soil type (Le Roux, 2010; Zheng *et al*., 2018). The generalisation results in ineffective planning and failure of soil erosion controlling measures (Parwada and Van Tol, 2016). Form and rates of soil erosion are site specific to the prevailing conditions. Soil erosion control requires a quantitative evaluation of potential soil erosion on a specific location. Few studies have examined at the effects of soil physical properties, quantification of soil loss and aggregate size distribution in areas of soil associations.

The objective of this study was to characterise the physical soil properties of areas of soil associations and determine the influence of litter source on aggregate stability and rates of soil loss in areas of soil association in the Ntabelanga area, Eastern Cape Province, South Africa.

MATERIALS AND METHODS

The study site. The experiment was carried out in the soil physics laboratory at the University of Fort Hare (UFH), South Africa. Soil was collected from the Ntabelanga area in the Eastern Cape Province, South Africa. The Ntabelanga area is located between 31° 7’ 35.9" S and 28° 40’ 30.6" E. The South African Government has proposed to construct a multi-purpose dam in the Ntabelanga area; however, the soils are unstable and highly erodible due to their low (< 2%) soil organic carbon content (Parwada and Van Tol, 2016). High sediment discharge will shorten the dam's lifespan, hence, the need to check the rates of soil erosion.

Soil sampling. Soil samples were taken from six dominant areas of soil associations, that exist in the Ntabelanga area. Soils in an area of soil association are likely to behave alike to a certain treatment (Parwada and Van Tol, 2017). The areas of soil associations were: shallow, wet, melanic, semi-duplex, apedal and duplex (Table 1). At least three samples were taken per area of soil association, basing on seven naturally occurring soil horizon profiles in the areas of soil associations. A total of 21 samples were collected. The naturally occurring soil horizon profiles varied in depths as; the melanic A, red apedal B and G-horizon were > 300 mm, and the orthic A, pedocutanic B and prismacutanic B were < 300 mm and a saprolite with an unweathered rock exposed on the surface (Parwada and Van Tol, 2016). Soil texture was determined by the hydrometer method as described by Okalebo *et al.* (2000) and the SOC analysed by the wet acid digestion of the Walkley-Black method (Nelson and Sommers, 1996). Resistance to hydraulic dispersion indices and soil structure dispersion under condition of immersion were calculated according to the procedure outlined in Table 1.

Soil sample preparation. Soil samples were air-dried and large clods fragmented manually. They were then sieved through a 5 000 µm pore size. Visible organic materials and debris were discarded. The soil was then oven-dried at 40 °C for 24 hr, and aggregate stability was measured according to Le Bissonnais (1996). Briefly, 5 g of soil was immersed in 50 mL deionised water for 10 minutes and then the water was sucked off using a pipette. The material was transferred to a 50 µm sieve previously immersed in ethanol. The sieve was then gently moved up and down in ethanol,

TABLE 1. Descriptive statistics of K-factor and soil organic carbon (SOC) content of the areas of soil associations prior to incubation

Soil association	Horizon	Surface soil structure class	Permeability class	SOC (%)	K-factor (t ha h)·(ha MJ mm)$^{-1}$
Shallow	Orthic A (ot.s)	(3) very coarse	(2) moderate fast	0.6	0.78
Wet	G-horizon (gh)	(1) very fine granular	(6) very slow	0.5	0.67
Melanic	Melanic A (ml.s)	(1) very fine granular	(6) very slow	0.4	0.34
Semi-duplex	Pedocutanic B (vp)	(1) very fine granular	(2) moderate fast	0.4	0.40
Apedal	Red apedal B (re)	(2) fine granular	(4) moderate slow	1.4	0.78
Duplex	Prismacutanic B (pr)	(4) blocky	(4) moderate slow	0.7	0.88
Shallow	Saprolite (so)	(3) very coarse	(2) moderate fast	1.2	0.54
	LSD			0.4	0.23

The saprolite (so) was found on the surface. The numbers in brackets on the surface soil structure and permeability classes represents the class five times to separate < 50 µm from those > 50 µm fragments. The remaining > 50 µm fraction was also oven-dried at 105 °C for 24 hr and gently sieved by hand on a stack of sieves of 2000, 1000, 500, 250, 100 and 50 µm pore size.

The samples were replicated three times per sample. The weight of each fraction was then measured. The weight of the soil fraction < 50 µm was calculated as the difference between the initial weight and the sum of the weight of the other six fractions and expressed as the mean weight diameter (MWD).

Soil incubation experiments. The soil was passed through a 2000 µm sieve to homogenise the soil aggregate sizes (<2000 µm), and then air-dried. Low (>2%) SOC was noted to be the major factor influencing soil erodibility in the Ntabelanga area (Parwada and Van Tol, 2016). Basing on that, study organic matter (OM) from two sources was added to the soil in order to raise the SOC to > 2%. *Vachellia karroo* (Hayne) Banfi and Galasso leaves (low C/N) and maize (*Zea mays*) stover (high C/N) were the OM sources. The *V. karroo* leaves were collected from the Ntabelanga area, Eastern Cape Province, South Africa at the start of 2014 winter season (early May), and the *Z. mays* stover was from a 2013/2014 season harvested crop.

The OM were oven-dried at 60 °C for 24 hr to homogenise the moisture and then ground to pass through a 2000 µm sieve. The organic materials were added to the soil according to the calculated C/N ratios of the *V. karroo* and *Z. mays* matter (Parwada and Van Tol, 2018a). The organic materials and soils were mixed as described by Parwada and Van Tol (2018b). Briefly, 600 g of each soil was put in a 1000-mL jar and then organic materials were applied at a rate of 2.28 g per 100 g soil and 2.43 g per 100 g soil for the *V. karroo* and *Z. mays* stover, respectively.

Sixty-three jars in total, including a no organic materials were added (control) for each soil were used (Parwada and Van Tol, 2018b).

In the incubator, jars were arranged as a 7 × 3 factorial in a completely randomised design (CRD) with three replicates. Water holding capacity (WHC) of the soils was adjusted to 60 % and incubated at 25 °C for 30 weeks (Parwada and Van Tol, 2017).

Erosion resistance and mechanical stability of macroaggregates. At sampling time only ninety grammes of soil was taken out leaving some soil in the jar at 1, 3, 8, 14, 23 and 30 weeks of incubation. Macroaggregates of > 250 µm which are sensitive to external forces and mechanical stability were randomly chosen and calculated as the cumulative mass percentage of aggregate > 250 µm under dry sieving (Six *et al*., 2002).

The dried soil was also wet-sieved through a set of sieves 2000, 1000, 500, 250, 100 and 50 µm, following a procedure described by Six *et al* (2002). To determine aggregate > 250 µm resistant to hydraulic dispersion, six indices were measured: water-stable macroaggregate (WSA), mean weight diameter (MWD), geometric mean diameter (GMD), percentage of aggregate destruction (PAD), fractal dimension (D) and erodibility factor (K). Water-stable aggregates (%) refers to the cumulative mass percentage of aggregates > 250 µm under wet sieving (Kihara *et al*., 2011). The MWD and GMD were calculated as follows:

$$\mathrm{MWD} = \sum_{I=1}^{n} x_i\, w_i \quad \text{Eq. 1}$$

The higher the MWD values the higher proportion of macroaggregates in the sample and, therefore, better stability.

$$\mathrm{GMD} = \exp\left(\sum_{i=1}^{n} w_i\, \log_{10} x_i\right) \quad \text{Eq. 2}$$

Where:

n is the number of aggregate fractions under wet sieving (n = 6 with the fractions being >2000, 1000-500, 500-250, 250-100, 100-50 and < 50 µm), x_i is the mean diameter (mm) of aggregate fraction i under wet sieving, equaling to 2000, 1000, 500, 250, 100 and 50 µm respectively and w_i is the mass proportion of aggregate fraction under wet sieving. PAD was calculated as:

$$\text{PAD} = \frac{\text{MSA}_{>250} - \text{WSA}_{>250}}{\text{MSA}_{>250}} \times 100\%$$

.... Eq. 3

Where:

PAD is the percentage of aggregate destruction, $MSA_{>250}$ = mass fraction of aggregates > 250 µm after dry sieving; and $WSA_{>250}$ = mass fraction of aggregates > 250 µm after wet sieving.

Fractal dimension (D) was used to express mass and size information about aggregates and was calculated as:

$$\frac{M\ (r < R)}{M_T} = (\frac{R}{R_L})(3 - D)\ \ldots\ldots \quad \text{Eq. 4}$$

Where:

M (r<R) is the cumulative mass of aggregates with size *r* smaller than a comparative size *R* under wet sieving, i.e., as *R* is 1000 µm, *M (r<R)* refers to the mass of aggregates < 250 µm and 250 – 500 µm under wet sieving; M_r is the total mass of aggregates under wet sieving, is the sieve size opening equaling to 2000, 1000, 500, 250, 100 and 50 µm, respectively; R_L is the maximum aggregate size defined by the largest sieve size opening, equaling to 2000 µm.

The K-factor was determined as described by Parwada and Van Tol (2016) using a modified erodibility nomograph proposed by Wischmeier *et al.* (1971). Five soil parameters (texture, organic matter content, course fragments, surface structure, and permeability) were used in the computation of the erodibility factor as follow:

$$K = \left[\frac{(2.1 \times 10^{-4} \times M^{1.14}(12 - OM) + 3.25(s-2) + 2.5(p-3))}{100}\right] \times 0.1317$$

.... Eq. 5

Where:

M is the textural factor = $(m_{silt} + m_{vfs}) \times (100 - m_c)$, m_c = [%] clay fraction content (< 0.002 mm) m_{silt} = [%] silt fraction content (0.002- 0.05 mm), m_{vfs} = [%] very fine sand fraction (0.05- 0.1), OM= [%] the organic matter content, s = soil structure class, p = permeability class

Primary particle size distribution was analysed by the hydrometer method as described by Okalebo *et al.* (2000), and organic matter content (OM%) and organic colloid were determined by the potassium dichromate-external heating method (Sato *et al.*, 2014). The soil structural classes were assigned according to the method proposed by Rawls *et al* (1983).

Microaggregates (< 250 µm) stability. Aggregates of < 250 µm, were used to indicate the structure and dispersion of soil under condition of immersion, aggregate state (AS), aggregate degree (AD) and dispersion rate (DR were calculated as follows:

$$AS = w_{(50-250)} - w_{mc\ (50-250)}$$

.... Eq. 6

$$AD = \frac{AS}{w_{(50-250)}} 100\%$$ .... Eq. 7

$$DR = \frac{w_{<50}}{w_{mc\ (<50)}} \times 100\%$$ .... Eq. 8

Where:

$w_{(50\text{-}250)}$ is the mass proportion (%) of microaggregate (50 – 250 µm), $w_{mc\ (50\text{-}250)}$ is the mass proportion (%) of soil mechanical composition (50 – 250 µm), $w_{<50}$ is the mass proportion (%) of microaggregate (< 50 µm), $w_{mc\ (<50)}$ is the mass proportion (%) of soil mechanical composition (< 50 µm), and all were measured through the pipette method described by (Kemper and Chepil, 1965).

The clay moisture equivalent ratio (CMER), erosion ratio (ER), clay ratio and stability index were also obtained as follows:

Clay moisture equivalent ratio (CMER) =

$$\frac{\%\text{clay}}{\%\text{ moisture equivalent}}$$ .... Eq. 9

$$\text{Erosion ratio (ER)} = \frac{\text{Dispersion ratio}}{\text{Clay moisture equivalent ratio}}$$

.... Eq. 10

$$\text{Clay ratio} = \frac{\%\ (\text{sand} + \text{clay})}{\%\ \text{clay}}$$ .... Eq. 11

Stability index = Cd-Wd .... Eq. 12

Where:

Cd = % calgon dispersable (silt + clay) and Wd = % water dispersable (silt + clay)

The soils with DR > 0.15, ER > 0.1 and CMER < 1.5 were regarded as erodible (Igwe and Agbatah, 2008).

Soil resistance to erosion by raindrop splash during incubation. K-factor is a quantitative description of the inherent erodibility of a particular soil; it is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff. Therefore, we equated the K-factor to rate of soil loss under a simulated single storm during the incubation period. High rates of soil loss corresponded to the inherent high K-factor of the soil.

Soil loss was estimated at 1, 3, 8, 14, 23 and 30 weeks of incubation and soil aggregates classification in different sizes as described in Equations 1 and 2 was also done in the same weeks. Briefly, the rainfall was applied as an 8-min single rainstorm (SR), using a rainfall simulator (LUW, Eijelkamp Equipment, 6897 ZG Giesbeck, Netherlands). Three runs of rainfall simulations were done for each soil sample. The simulator has 49 capillary tubes that uniformly apply raindrops of 5.9 mm in diameter. A splash cup was filled with soil and saturated with distilled water from below.

After saturation, the soil was subjected to simulated rainfall at an intensity of 360 mm hr^{-1} (approximately 60 mm hr^{-1} natural rainstorm with time-specific energy of 1 440 J/ ($m^2 \cdot h$). High rainfall intensity was to compensate for the short falling distance (0.4 m), which was used during calibration of the rainfall simulator. After the rainstorm, the splashed sediments were collected from the splash plate and washed into a jar, oven dried at 105 °C for 24 hr and weighed. The oven dried soil was weighed and soil loss in tonnes per hectare calculated as follows:

$$S = \frac{D_{t2} - D_{t1}}{t_2 - t_1} A$$ .... Eq. 13

Where:

S = the splash rate of a given rainfall period (g/ (minû0m^2)); D_{t1}, D_{t2} = the total detachment after time t_1, t_2, respectively (g); t_1, t_2, represent the rainfall duration (min); A represents the area of splash plate (0.07 m^2).

Data analysis

Sampling during incubation was non-destructive. A subsample (90 g) was taken using a stainless steel spatula from the each jar at 1, 3, 8, 14, 23 and 30 weeks of incubation. A repeated measures analysis of variance (ANOVA) was carried out to compare soil loss of the soils during the pre-incubation and incubation periods. Correlations between soil physical properties and soil loss was also done. The residuals of each analysis were checked for normality and homoscedastity. The data were analysed with JMP version 11.0.0 statistical software (SAS Institute, Cary, NC, USA).

RESULTS AND DISCUSSION

All the six areas of soil associations had < 2 % SOC, which is a threshold for sustaining soil quality (Parwada and van Tol, 2019). The soils had an average SOC and K-factor of 0.74% and 0.69 t ha h ha^{-1} MJ^{-1} mm^{-1}, respectively (Table 1). The higher (> 0.02 t ha h ha^{-1} MJ^{-1} mm^{-1}) the K-factor, the higher the rate of erosion (De Oliveira *et al*., 2009). All the areas of soil associations had K-factor >0.02 t ha h ha^{-1} MJ^{-1} mm^{-1}, which indicates that they were susceptible to erosion (Wang *et. al*., 2013).

Our results did not show a direct relationship between SOC content and erodibility (Table 1). Low (< 2%) SOC content was not necessarily correspond to the high K-values (Table 1). This observation disagrees with Idah *et al.* (2008), who noted high erodibility factors in soils with less than 2% organic matter. Morgan (2001) also noted that soil K- factor decreases linearly with increasing organic content over the range of 0 to 10%.

High soil organic matter promotes aggregation of soil particles and thereby confers resistance against erosion. However, high K-factors in the areas of soil associations could have been influenced by other soil properties apart from the low (<2%) SOC content (Table 1). The apedal had significantly (P < 0.05) the highest (1.4 %) SOC; while the melanic and semi-duplex had significantly the least (0.4%) SOC content (Table 1).

Highest (0.88 t ha h ha^{-1} MJ^{-1} mm^{-1}) and lowest (0.34 t ha h ha^{-1} MJ^{-1} mm^{-1}) K-factor were observed in the duplex and melanic, respectively (Table 1). The K-factor is an estimate of the ability of soil to resist erosion based on the physical characteristics of each soil (Harris *et al.,* 2012). De Oliveira *et al*., (2009) found that soils with faster infiltration rates, higher levels of organic matter and improved structure had a greater resistance to erosion. However, in some cases, soil with relatively low erodibility factor may show signs of serious erosion. This is because soil erosion is a function of many factors other than the K-factor as stated in the Universal Soil Loss Equation (USLE) (Wang *et. al*., 2013). In such cases, factors such as rainfall erosivity index, topographic factor, cropping factor or conservation practices other than the K-factor will be having a major influence on the rate of erosion.

The primary particle size distribution varied significantly (P < 0.05) across the seven soil horizons and was found to be in the following order; sand > silt > clay in most of the soil horizons except in the melanic A and pedocutanic B (Table 2). We can conclude from the texture classification that the soil texture varied under the seven soil horizons. Soil particle size influenced the rate of erosion by water since soil erodibility was increasing with an increase in the size of soil separates (Table 1). This is because soils with greater sand in their distribution have more macropores and less flocculating agents, which permits more water, increases their tendency to detach from each other and be

TABLE 2. Descriptive statistics of mean soil particle size distribution, clay ratio and structural stability indices of the soils used in the incubation experiments

Soil horizon profile	Sand	Clay	Silt	PAD	DR	AD	AS	Clay ratio	ER	CMER	Stability index
	— — — — — — — % — — — — — — —										
Orthic A (ot.s)	57	24	19	46	55	60	25	3.00	1.10	0.050	1.5
G-horizon (gh)	48	28	24	51	68	57	28	2.60	1.28	0.053	2.1
Melanic A (ml.s)	18	62	20	86	81	43	38	0.70	0.92	0.088	5.6
Pedocutanic B (vp)	17	62	21	78	90	40	36	0.71	1.03	0.087	5.4
Red apedal B (re)	51	25	24	55	73	58	27	2.92	1.43	0.051	2.4
Prismacutanic B (pr)	38	36	26	30	96	53	21	3.21	1.52	0.063	1.3
Saprolite (so)	45	33	22	54	60	48	29	1.23	1.00	0.060	3.1
±SD	8.1	5.3	7.1	9.7	6.2	9.2	3.0	0.81	0.93	0.02	0.52

transported by water (Six *et al*., 2000). It is the reverse in the case of soils with higher clay proportion with smaller particle sizes and yet tightly bonded to one another. This could explain the observed high rates of soil loss in the prismacutanic B and low rates in the melanic A (Fig. 1). Most soils had high sand content (17 to 57 %), except in the melanic A and Pedocutanic B which indicates that most of the soils were highly erodible. The clay particles provide bondage between the varying soil particles, resulting in the formation of more stable aggregates, which makes them less susceptible to erosion. However, soil erodibility could be high even in clay soils if they have dispersion tendencies. Clay dispersion reduces the tendency of soil particles to bind together and form aggregates, thereby becoming susceptible to the shearing force of flowing water, and subsequently to soil erosion.

The AS, AD, DR, and PAD varied to some degree among the seven soil horizons (Table 2). The prismacutanic B had lowest PAD (30%), AS (21%) and stability index of 1.3. High values of AS, AD and PAD (Table 2) indicated low rates of soil erosion. High values of AS, AD and PAD are associated with well aggregated, balanced macro- and micro-pore spaces and high SOM contenting allowing easy water infiltration, thereby reducing rates of erosion (Tuo *et al*., 2017). The results are similar to those of Tuo *et al*. (2017). We also found that the Melanic A had the highest PAD (86%), AS (38%) and stability index of 5.6 (Table 2) that corresponded to lowest rates of soil loss (Table 4). The melanic A had the lowest (0.70) clay ratio, while the prismacutanic B had the highest (3.21) clay ratio (Table 2).

The soil horizons had an ER > 0.1, DR > 0.15 and CMER < 1.5 (Table 2), therefore are highly erodible. All of the soils had DR values of > 0.15 (Table 2), which suggests that they were all dispersive soils. Igwe and Agbata (2008) noted that soils with DR > 0.15 were more erodible; while soils with DR < 0.15 were less erodible. Igwe (2005) earlier reported that soils with DR > 0.5 were highly dispersive, DR = 0.3 to 0.5 moderately dispersive, DR from 0.15 to 0.3 slightly dispersive and DR < 0.15 non dispersive. In both cases, our study showed DR values above these values; hence, we concluded that the Ntabelanga soils were dispersive.

The mean weight diameter (MWD) of the seven soil horizons ranged from 0.44 to 2.56 mm and 0.39 to 2.13 mm under dry and wet sieving, respectively (Table 3). The geometry mean diameter (GMD) ranged from 0.18 to 1.02 mm under dry sieving; and from 0.07 to 0.41 mm under the wet sieving (Table 3). Prismacutanic B (pr) had significantly ($P < 0.05$) the least MWD and GMD under both dry and wet sieving. The melanic A had significantly ($P < 0.05$) the highest MWD and GMD in both dry and wet sieving (Table 3).

Basing on Le Bissonnais (1996)'s classification of soil susceptibility to erosion, using the MWD, the soils ranged from being unstable (Prismacutanic B, Orthic A, Saprolite, and G-horizon) to very stable (Melanic A and Pedocutanic B) under dry sieving. The orthic A, G-horizon and prismacutanic B were very unstable under wet sieving. Our results showed that the orthic A, prismacutanic B and G-horizon, saprolite were prone to both wind and water erosion because they had the lowest MWD_d and MWD_w. Any soil disturbance in wet or dry condition will therefore increase the rate of erosion in these soil horizon profiles.

Largest (4.92) and smallest (3.11) fractal dimension (D) were observed in the prismacutanic B and pedocutanic B, respectively (Table 3). The value of D was inversely proportional to that of MWD and GMD. Larger D values corresponded to proportionally small values of MWD and GMD (Table 3). The observed D and AD (Table 2) values were relatively low compared to those reported in other studies (Igwe and Agbatah, 2008). However, they agree with the report by Cheng *et al.* (2007), who observed that soil physical properties such as fractal dimension in soil originating from granite were lower than that of the soil from other parent materials. In this study, low D values in melanic A and pedocutanic B corresponded well to improved soil conditions, thereby reducing erodibility. Soil management should, therefore, aim at lowering the fractal dimension through practices that increase soil organic matter. The clay particles provide bondage between the varying soil particles, resulting in the formation of more stable aggregates which makes them less susceptible to erosion.

TABLE 3. Fractal dimension (D) and distribution of dry and wet sieved mean weight diameter (MWD) and geometry mean diameter (GMD) of the Ntabelanga soil associations used in the incubation experiments

Soil horizon profile	D	MWD_d	MWD_w	GMD_d	GMD_w
		mm			
Orthic A (ot.s)	4.64	0.60	0.48	0.28	0.11
G-horizon (gh)	4.14	0.54	0.45	0.24	0.10
Melanic A (ml.s)	3.20	2.56	1.11	1.02	0.41
Pedocutanic B (vp)	3.11	2.31	1.13	0.92	0.37
Red apedal B (re)	4.73	0.88	0.50	0.32	0.13
Prismacutanic B (pr)	4.92	0.53	0.34	0.25	0.10
Saprolite (so)	4.32	0.63	0.39	0.18	0.07
LSD (0.05)	1.2	0.34	0.25	0.21	0.08

The MWD and GMD are crucial indicators of aggregate stability (Thomas *et al*., 2018). The MWD reflects the proportion of macro aggregates (Tobiasova *et al*., 2018), while the GMD estimates the size of the most frequent aggregate size class (Tuo *et al*., 2017). The MWD_w indicate the proportions of macro aggregates in a soil structure as influenced by factors by like raindrop impact; it is directly proportional to structural stability (Zheng *et al*., 2018). Higher MWD_d than MWD_w values usually indicate lower stability of soil (Torri *et al.,* 1998) of which most soils except the melanic A and pedocutanic B were unstable. The results agree observations with Le Bissonnais (1996). The MWD and GMD in fast wetting treatment had lower values than those in the dry-sieving (Table 3). Results indicated that fast wetting that imitates the natural rainfall scenario more closely, was better in defining the treatment-difference than the dry aggregates. This suggests that the fast wetting is idea in studying soil erosion by water.

The prismacutanic B (pr) had the highest ($P < 0.05$) soil loss (t ha^{-1}) at pre-incubation and during soil incubation (Fig. 1). These results confirm the role of SOC in reducing rates of soil erosion. Soil organic matter (0.7%) content in the prismacutanic B was below the threshold level (< 2%) prior-incubation, therefore could have minimised the rate of macroaggregate formation, hence, high soil loss. Similar results were observed by Parwada and Van Tol (2018a) whereby they noted a low rate of macroaggregate reformation under low (<2%) SOC content. The melanic A (ml.s) had significantly ($P < 0.05$) low rates of soil loss both prior to and during incubation, suggesting the importance of clay content in increasing resistance to detachment by water.

The melanic A had highest (62%) clay content which could have promoted cohesion

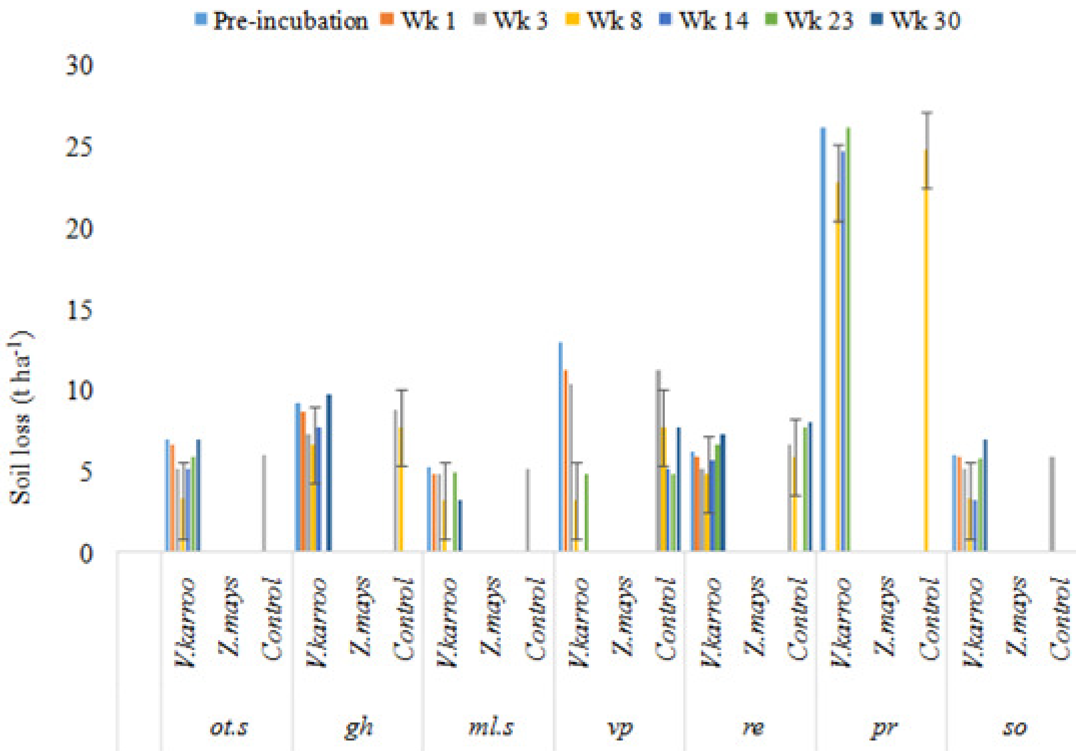

Figure 1. Soil loss (t ha^{-1}) under a single rainfall storm during the 30-week incubation period.

of soil particles, thereby stabilising soil against the raindrop impact prior the incubation. During incubation, the low rate of soil loss experienced in melanic A could be due to synergetic effects of both the high clay content and organic matter. Usually, clay soils would repel organic matter since both are negatively charged.

Previous study on the same soils, observed that the exchangeable Ca^{2+} and Mg^{2+} dominated the exchange complexes of the soils (Parwada and Van Tol, 2016). The adsorbed cations (Ca^{2+} and Mg^{2+}) on the clay particles resulted to loss of negativity, and hence the clay attracted the negatively charged organic matter and increasing aggregation using the Bronsted and Lewis acid mechanism. The rate of soil loss was higher at pre-incubation than at 1 to 8 weeks during incubation. The soil loss increased from 14 to 30 weeks during incubation in all the soil horizons (Fig. 1).

Results showed that OM had a significant ($P < 0.05$) effects on soil loss regardless of the source (Fig. 1). The added OM effectively reduced soil loss in 1 to 8 weeks of incubation (Table 4), thereafter lost its effectiveness up to week 30. The results agree with those of Six *et al.* (2000), who observed that SOM was an essential but transient component of the soil that controls many physical, chemical and biological properties of the soil. Fu *et al.* (2019) reported that the quantity of the residue had a larger effect on splash detachment, shear strength and aggregate stability than residue type.

Soil aggregation is essential for the resistance of soil to erodibility, and it influences the capacity of soils to remain productive (Guo, *et al.*, 2019). The added organic matter residues reduced the soil's erodibility by increasing soil aggregate stability, shear strength and resistance to splash detachment (Parwada and Van Tol, 2018a). It was therefore import to add organic matter to the areas of soil associations in order to enhance soil stability and resistance to erosion.

The proportion of aggregates > 250 µm and aggregates < 250 µm size fractions significantly ($P < 0.05$) varied across the soil horizons (Table 4). The proportion of wet sieved aggregate fractions significantly ($P < 0.05$) influenced soil loss rate (Table 4). The highest (10.3 t ha^{-1}) and lowest (2.5 t ha^{-1}) were recorded in the control treatment of the red apedal (re) and OM added melanic A, respectively (Table 4). The proportion and distribution of aggregate class size in a soil was influenced by the quantity of OM. The OM influenced macroaggregation, thereby, balancing the quantity of macroaggregates and microaggregates in the soil. Soil horizons with near balanced (1:1) macroaggregates to microaggregates ratios had low rates of soil loss (Table 4). Similar results were noted by Six *et al.* (2002) who found that the aggregate size distribution (the amounts of large, medium and small macroaggregates (> 250 µm) and microaggregates (< 250 µm)) confers soil resistance to erosion through their influence on pore size and continuity.

Soil loss was significantly ($P < 0.05$) and directly proportional to the ratio of macroaggregates (> 2000 and 250- 2000 µm): microaggregates (50 – 250 µm) plus mineral fractions (< 50 µm) weights. High macroaggregates: microaggregates fractions ratios had significantly ($P < 0.05$) low rates of soil loss and vice versa (Table 4). The controls (no organic matter added) had more total microaggregate than macroaggregate, and the highest rates of soil loss compared to soils amended with organic matter (Table 4).

The results suggest that organic matter is influential in macroaggregation as earlier observed by Six *et al.* (2002) who found that macroaggregates contained more OM and less susceptible with erosion. Soil with a balanced proportion of macroaggregates and microaggregates can resist erosion more than soil with extremely high content of either macroaggregates or microaggregates (Parwada and Van Tol, 2018a). The orthic A had more

TABLE 4. The average proportion of wet-sieved aggregate fractions (% by weight) and average soil loss among the soil horizons under different litter sources during 30 weeks of incubation

Horizon	Litter	Aggregate size class (μm)				Soil loss (t ha^{-1})
		> 2000	250-2000	50-250	<50	
ot.s	*V. karroo*	15	10	30	45	8.7
	Z. mays	29	7	22	42	9.5
	Control	5	14	23	58	9.6
gh	*V. karroo*	6	26	38	30	7.4
	Z. mays	8	28	35	29	5.2
	Control	6	17	22	55	9.8
ml.s	*V. karroo*	27	31	37	5	3.6
	Z. mays	28	31	37	4	3.4
	Control	10	19	31	40	2.8
vp	*V. karroo*	30	34	28	8	2.5
	Z. mays	30	34	28	8	2.8
	Control	9	18	25	48	3.7
re	*V. karroo*	7	39	11	43	5.8
	Z. mays	7	37	11	45	6.1
	Control	15	17	21	47	10.3
pr	*V. karroo*	19	8	41	32	6.3
	Z. mays	19	8	41	32	6.1
	Control	5	2	15	78	10.9
so	*V. karroo*	10	24	18	48	5.1
	Z. mays	13	30	46	9	5.0
	Control	2	10	32	56	8.4
LSD (0.05)			3.87			

ot.s = orthic A, ml.s = melanic A, vp = pedocutanic B, re = red apedal B, so = saprolite, gh = G horizon and pr = prismacutanic B.

of microaggregates than macroaggregate, and had the highest rate of soil loss; whereas, the melanic A had the lowest rate of soil loss, but with more macroaggregates than microaggregates. A balance in the aggregate fraction size distribution gives a soil enough pores space for water movement, thereby reducing chances of crusting. The prediction of potential erosion hazards in soils would also be explained by the relative influence of organic matter on macro- and microaggregate stability.

The macroaggregates are generally considered more sensitive to soil organic matter concentrations and hence are less stable than microaggregates (Parwada and Van Tol, 2018a). The response of macroaggregates being more sensitive to SOM concentrations than microaggregates is still debatable to-date, and more studies are needed. A study by Six *et al.* (2002) showed that the relationships between aggregate stability indices and OM concentrations in tropical soils was generally weak mainly due to the relatively lower organic matter status of the soils. Increasing the SOM in areas of soil association is an ideal practices as it will promote macroaggregation thereby resisting erosion.

The *V. karroo* and *Z. mays* organic matter contributed to the formation and stability of large macroaggregates through different aggregate fractions and had a positive effect on the soil structure over time, primarily increasing the macroporosity and reducing the soil bulk and particle density in soil horizons (Table 4). Similar results were obtained by Cosentino (2006) in Alfisol soil of sub-humid tropics. The soil aggregates also influence other mechanisms such as runoff generation and soil surface sealing. The current results showed that the ratio of the macroaggregates to microaggregates was paramount in soil resistance to erosion in the areas of soil associations. This suggests that soil management practices that promote macroaggregation should be implemented in the areas of soil associations.

Soil loss was significantly ($P < 0.05$) negatively correlated to AD, AS, CMER and stability index (Table 5), but positively correlated with fractal dimension (D), percentage of aggregate destruction (PAD), dispersion rate (DR) and erosion ratio (ER) (Table 5). Various significant ($P < 0.05$) correlations were observed between other physical soil parameters in the soil horizons (Table 5). The AD, AS, CMER values and stability index has to be increased and the D value, DR and ER reduces, hence addition of SOM and minimal soil disturbance are necessary in the Ntabelanga area in order to lower the rate of soil loss.

Results showed that the fractal dimension (D), percentage of aggregate destruction (PAD), aggregate state (AS) and aggregate degree (AD), which were measured to indicate resistance of macroaggregates > 250 μm, to hydraulic action, significantly ($P < 0.05$) influenced detachment by splash (Table 5). Most of the soil parameters (DR, ER, CMER and stability index) used to determine

TABLE 5. Correlation between soil loss and some physical soil properties the Ntabelanga area, Eastern Cape Province in South Africa

	Soil loss	PAD	DR	AD	AS	Clay ratio	D	ER	CMER	Stability index
Soil loss	1									
PAD	0.651*	1								
DR	0.649*	0.123	1							
AD	-0.673*	0.451	0.231	1						
AS	-0.652*	0.547*	-0.641*	0.634*	1					
Clay ratio	-0.345	0.413	0.124	0.112	0.321	1				
D	0.686*	-0.312	-0.213	0.255	0.345	0.246	1			
ER	0.874**	-0.513*	0.512*	0.131	-0.815**	0.423	0.232	1		
CMER	-0.645*	-0.416	0.415	0.512*	0.517*	0.341	0.456	0.611*	1	
Stability index	-0.743*	-0.653*	0.745*	0.514*	0.656*	0.612*	-0.513*	-0.754*	-0.633*	1

microaggregate (<250 µm) stability had a significant (P <0.05) influence on soil loss. This suggests that microaggregate stability is important in decreasing soil loss in the studied areas of soil associations.

A number of studies tend to support the view that erosion in the soils is related more to microaggregate stability than to macroaggregate stability (Igwe, 2005; Igwe and Agbatah, 2008; Guo *et al*., 2019).

Igwe and Agbatah (2008) studied the predictability of soil loss by selected macro- and microaggregate stability indices for some soils. They observed that all microaggregate stability indices predicted soil loss better than their macroaggregate stability counterparts. However, some researchers reported weak correlations between soil erodibility and macroaggregate stability indices for some soils (Six *et al*., 2002; Igwe 2005; Igwe and Agbatah 2008).

CONCLUSION

It is concluded that different areas of soil associations with different physical properties such as density, particle size distribution, and organic matter content, vary significantly in resistance to erosion. The soils in the Ntabelanga area are highly erodible with K-factor values of > 0.02. Therefore, it may not be recommended to carry any form of soil disturbing activity unless some soil stabilising mechanism are simultaneously applied. Addition of OM to the soils increase the MWD, GMD, AS and AD hence reducing the rates of soil loss. More macroaggregates (>250µm) than microaggregates (< 250 µm) confer soil resistance to raindrop detachment. Addition of *V. karroo* and *Z. mays* organic matter reduces soil loss in 1 to 8 weeks of incubation; thereafter it loses its effectiveness. Therefore there is need to reapply fresh OM after the 8 weeks to sustain the effectiveness. It is recommended to minimise the soil disturbance in the areas of soil associations as this will exacerbate the problem of high erodibility.

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