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Review

Litter quality effects on soil stability and erodibility of selected South African soils

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Literature on soil erosion in South Africa, classifies soils in Eastern Cape (EC) Province as dispersive and highly unstable to erosion due to low (< 4%) soil organic matter (SOM) content. Many traditional strategies in controlling soil erosion are failing in EC, suggesting need for alternatively different strategies. Addition of organic matter (OM) to increase SOC maybe a solution. SOC threshold levels of SOC in soil aggregation have been extensively studied but little on synergistic effects of quality and soil stability. A well aggregated soil is stable and resists erosive forces hence low rates of soil erosion. This review was to get an insight on the role of SOC and its corresponding quality in stabilizing soils against erosion. Literature suggested that SOC content has to be high (> 2%) in stable soils and quality influenced the resident time (RT) of SOC in the soil. High quality SOC (C: N < 24) is fast lost through decomposition than low quality (C: N > 24). This can be concluded that under same soil, slow decomposable SOC has prolonged effects in soil stabilization than fast decomposing high quality SOC. Different sources of OM can be used to enhance soil aggregation but relationship between OM quality and aggregation is yet to be studied. A better understanding of the spatial variability of OM is important for refining soil conservation management practices and improving sustainable land use. The generated information can assist in formulating soil erosion policies and erosion control strategies in EC and South Africa at large.

Keywords: unstable soils, litter quality, stabilization, synergistic, quantity

INTRODUCTION

In South Africa, about 80% of the land is threatened by soil erosion (van Rensburg, 2008; Paterson *et al.*, 2011) and each year several arable lands are rendered unusable due to erosion (Reinks *et al.*, 2000). Compared to Australia, the average predicted soil loss (12.6 t.ha⁻¹.yr⁻¹) (Le Roux *et al.*, 2010) for South Africa is three times as much as that estimated (4.1 t.ha⁻¹.yr⁻¹) by Lu *et al.* (2003). Soil erosion not only involves the loss of fertile topsoil and reduction of

soil productivity, but is also coupled with serious off-site impacts related to increased mobilization of sediments and delivery to rivers and dams. Flugel *et al.* (2003) states that eroded soil material leads to sediment load in streams which affects water use and ecosystem health. For instance, the storage capacity of the Welbedacht Dam near Dewetsdorp in the Free State, South Africa was rapidly reduced by more than 86% from its original storage capacity within 20 years since its completion in 1973 (DWA, 2011). Soil erosion increases the water crisis in South Africa (Le Roux *et al.*, 2010). The soil erosion problem is exacerbated by the inherent erodibility of the

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parent materials in South Africa that give rise to erodible soils (Laker, 2004; Paterson *et al.*, 2013). The soil erosion problem may get worse in the future due to population and climatic changes (Le Roux *et al.*, 2008). Considering the increasing threat of sedimentation of water bodies, it is important to identify source areas and key processes of sediment transport from field to the reservoirs.

Although the present soil erosion rates in South Africa are still poorly understood, Eastern Cape (EC) Province is the most severely affected (where the average annual soil loss rates exceeds $12 \text{ t.ha}^{-1}.\text{yr}^{-1}$) (Le Roux *et al.*, 2007). The data on the rates of soil erosion in South Africa were obtained at large scale in a spatial context using geographical information systems (GIS) and remote sensing techniques (Le Roux *et al.*, 2007). The data generalize site properties and therefore the soil erosion management and control options. However soil erosion depends on many site properties like soil erodibility, topography and rain erosivity all which are known to change over short distances. This means that the causes of soil erosion are largely site specific and therefore should not be generalized for effective control of soil erosion.

Generalizing the causes of soil erosion results in wrong choices of controlling options that would ineffectively curb the problem. Local soil and water conservation (SWC) measures have been widely believed to be effective in controlling soil erosion (Mwango *et al.*, 2015a,b), however, Laker (2004) noted a failure of these traditional controlling measures in the EC Province, suggesting that there could be unique soil properties influencing soil erodibility. The techniques used over-parameterize and have misleading parameter values in the local context and lack of verification data therefore tends to give only a general understanding of soil erosion in spatial context. Furthermore, these techniques only detect severely eroded bare areas but cannot identify the nature of erosion and intrinsic soil properties influencing the erosion (Pretorius and Bezuidenhout, 1994). Regardless of a lot of money and human resources channelled towards management and controlling soil erosion in the EC Province, sound soil erosion mitigatory measures are still elusive. In terms of soil erosion management intervention it is especially important to highlight areas that are intrinsically susceptible to erosion.

Paterson *et al.* (2011) suggested that the severe soil erosion South Africa is due to incorrect land management and scant vegetation cover. Use of local soil and water conservation measures such as tree planting (Mwango *et al.*, 2014a, b) in such cases could be ideal to curb the erosion, however Sonneveld *et al.*, (2005) noted severe gullying even under dense grass cover in parts of sub-humid grasslands in EC province. This suggests that the high rate of soil erosion in the EC province is more related to the soil properties than the scant of vegetation cover. Du Preez *et al.* (2011) observed that the soils have less than 1.1% organic carbon which is considered as the critical

carbon concentration for structural stability in most soils, hence being highly unstable to soil erosion. Addition of organic matter (OM) in such soils could be a solution in stabilizing against soil erosion but there are some grey areas that required attention when using OM to control soil erosion. Literature clearly states the quantity of SOM required by a soil to resist detachment but is silent on its quality. More so the roles of different OM fractions along the continuum of decomposition is still sketchy.

In general, it is agreed that SOM enhance aggregation through bonding of primary soil particles into aggregates. Nonetheless, information on corresponding SOM quality in soils with different properties is still limited. Furthermore, the exact role of SOM in the process of chemical stabilization and the mechanisms of interactions that occurs between the SOM and soil particles is also not yet fully understood (Huygens *et al.*, 2005). Explaining the role of SOM in soil particle aggregation, Kemper and Koch (1966) found an increase in aggregate stability with increase in the SOM. The SOM helps to stabilise and arrange primary particles into architectural units. The level of stability in a soil architectural unit influences soil erosion (Young and Crawford, 2004). The ability of a soil to resist erosion depends on the stability and architectural arrangement of soil particles.

Soils with poor architectural arrangement are more detachable, unstable, and susceptible to compaction, have low water infiltration and high runoff rates (Young and Crawford, 2004). The SOC is one of the biotic factors that interacts with abiotic solids in improving soil architectural units. De Jonge *et al.* (2009), defined soil particle architecture as the pore and particle networks and their interfaces which are created by interactions between biotic and abiotic solids, water and solutes and influenced by man during soil use and management. A good soil architectural unit should therefore allow free water infiltration and air movement. A good soil architectural unit is stable and can resist erosive forces thereby more protected from soil erosion (Young and Crawford, 2004) while a poor soil architectural unit restricts water infiltration and is unstable under erosive forces thus being highly sensitive to soil erosion.

The soil particle architecture results from the rearrangement, flocculation and cementation of particles (Six *et al.*, 2004) and is mediated by clay particles, bacteria, inorganic (Fe/Al oxides, CaCO_3 , Silica) and soil organic matter (SOM). The SOM quality can be synergistic or disruptive to aggregation (Six *et al.*, 2004). The organic stabilizing agents can be grouped into three based on the age and degradation of organic matter: transient, temporary and persistent (Tisdall and Oades, 1982). This shows that the quality of decomposing matter has a significant effect on the aggregation. The role of SOM in stabilizing and soil aggregates formation is well documented (Six *et al.*, 2004) and theories on aggregate formation have been derived. The theory of aggregate

hierarchy concept by Tisdall and Oades (1982) is commonly used to explain the role of SOM in binding soil particles into aggregates. The theory was slightly modified by Oades (1984). Recent research has now extensively corroborated Oades' modification (Six *et al.*, 2004) and its use in understanding soil particle architecture.

Factors influencing soil erosion in the Ntabelanga area

Soil characteristics have a major influence on erodibility, with soils from the Tarkastad and Molteno formations in northern parts of the Eastern Cape Province being associated with duplex soils (Land Type Survey Staff, 1972-2008) that are highly erodible with widespread gully erosion (Le Roux *et al.*, 2010). Furthermore, in the Eastern Cape a distinction can be made between erodible soils developed on the silts and mudstones of the Beaufort Series which give rise to fine textured dispersive soils and the dolerites which form well-structured clay soils with a lower erodibility (Garland *et al.*, 2000). Various authors state that geology is probably the most dominant factor controlling the inherent erodibility of soils in South Africa (Laker, 2004; Rowntree *et al.*, 2008) and not the climate and slope gradient as frequently determined in the USA and Europe (Vanmaercke *et al.*, 2011). Soil properties such as clay dispersibility are also a key factor and significant evidence in understanding how it influences erodibility of soils in SA (Buhmann *et al.*, 1996). While it is generally agreed that soils in the Eastern Cape Province are highly erodible (Garland *et al.*, 2000; Laker, 2004; Le Roux *et al.*, 2008), soil erodibility within a spatial context is as yet poorly understood and needs further investigation (Le Roux, 2012).

Soil architecture/ structure

The terms *soil architecture* and *soil structure* are synonymous, and both reflect the state of the soil from nano to pedon scale (de Jonge *et al.*, 2009). **Soil structure** has many definitions. Letey (1991) gave a more comprehensive definition as "the size, shape and arrangement of the solid particles and voids which is highly variable and associated with a complex set of interactions between mineralogical, chemical and biological factors", while Dexter (1988) defined soil structure as the spatial heterogeneity of different components or properties of the soil. These two soil structure definitions focus on the internal arrangement of the components of structure with little attention on how it is impacted by external factors. Most recently, de Jonge *et al.* (2009) defined soil architecture to include the impact of human activities. They defined **soil architecture** as "the pore and particle networks and their interfaces which are created by interactions between biotic and abiotic solids, water and solutes, and influenced by man during soil use and management".

Soil structure/architecture can be considered from four different fundamental aspects; form, stability, resiliency and vulnerability (Kay, 1998). The term "architectural form" encompasses the soil mineral fraction occupying the solid space and the heterogeneous arrangement of voids (pores) therein. To fully understand how the solid fraction influences soil functions, the fractions of the individual components (mineral matter) as well as their distribution should be considered. The clay fraction in soils is probably the most active component of the mineral fraction, and can be considered as the base-level structural element in the conceptual hierarchical organization of soil structure (Dexter, 1988). However, the fractions of silt and sand determine how the clay fraction is arranged in the soil matrix, underlying the importance of also considering the distribution rather than just clay content. At low clay content (< 10 %), the soil matrix is formed mainly by sand and silt, with the clay deposited in the pores between the sand grains. When clay content increases from 10 to 20 %, the clay particles coat the sand and silt particles. At higher clay content (> 20 %), the clay particles completely coat the structural units of sand and silt and clay bridges dictate the arrangement of the soil matrix (Dalrymple and Jim, 1984).

Soil organic matter

Soil Organic Matter (SOM) is the most important indicator for soil quality improvement because it regulates water movement and holding capacity, and controls soil structural stability by affecting the quantity of macro- and micro-aggregates (Handayani *et al.*, 2010). Soil organic matter is the total organic fraction of the soil. It contains living microbial biomass and a complex and heterogeneous mixture of organic compounds and minerals, including plant and soil microbial derived residues at various stages of decomposition and stabilization degrees (Rodeghiero and Cescatti, 2005). SOM promotes formation of soil aggregates and thereby influences soil physical properties and soil moisture (Allison *et al.*, 2010). Well-aggregated soils possess a larger pore space, a higher infiltration rate and are more resistant to erosion than poorly aggregated soils. Therefore it is important to maintain high levels of SOM (> 4%) in soils.

Particulate organic matter fractions

Particulate organic matter (POM), which is soil organic matter between 53-2000 μm in size (Cambardella and Elliot, 1992) is an intermediately available fraction of organic C and N and more sensitive to the land management changes compared to total soil organic matter (Cambardella and Elliott, 1992; Parton *et al.*, 2007). The term form is generally used to describe measurable organic matter components whereas the term pool is used

to refer to theoretically separated, kinetically delineated components of SOM (Wander, 2004). Current conceptual models differentiate functional SOM forms into active, intermediate and passive fractions (Amundson, 2001) on the basis of their different turnover rates, or equivalently, their residence times. In order to understand the dynamics of SOM and to gain insight into stabilization and destabilization mechanisms, it is essential to identify, isolate and characterize functional SOM forms, without altering any of their properties that might be relevant to their function in the soil. This can be accomplished using methods such as physical fractionation (Christensen, 2001; von Lutzow and Kogel-knaber, 2009). These include fast degrading fractions (months to a few years) mainly composed of carbohydrates identified in the O-alkyl region; an intermediate degrading fraction (10 – 100 yr) composed by aliphatic and aromatic compounds identified in the alkyl region; and the recalcitrant fraction (> 100 yr) mainly composed of charcoal, a highly condensed and aromatic POM fraction identified in aryl C region (Gleixner *et al.*, 2001; Skjemstad *et al.*, 2001). Despite the variation in POM turnover expected by its composition, the actual rate at which the organic fractions are decomposed depends also in the degree of protection by the soil matrix (Baldock and Skjemstad, 2000), as well as temperature, aeration and water content that influence microbial activity.

The fractionation of POM into relevant forms with different turnover rates is based on its composition and degree of physico-chemical stabilization. These extraction procedures attempt to isolate fractions that respond to land management and use and that represent a significant proportion of POM (Olk and Gregorich, 2006). Physical fractionations segregate POM forms as a function of their association to soil minerals and position within the architecture of soil aggregates. This suggests that different POM forms have different roles in soil aggregation.

Effects of litter quality on decomposition

Fresh plant residues are considered as the soil litter fraction and can be an important component of the active fraction and is the primary source of all POM (Skjemstad *et al.*, 2001). However, the processes of litter decomposition and POM stabilization are often considered separate (Sollins *et al.*, 1996). Litter decomposition research has focused on the effects of litter quality on short-term mineralization and nutrient release (Parton *et al.*, 2007), whereas POM stabilization research has focused on organomineral interactions that slow POM turnover relative to total POM due to physicochemical protection by mineral association and microaggregate occlusion (Six *et al.*, 2002; von Lutzow and Kogel-knaber, 2009; Stewart *et al.*, 2008). Recent studies suggest high-quality litters hasten short-term aggregate turnover (Chivenge *et al.*, 2011; Puttaso *et al.*, 2013). However, longer duration studies find that litter quality has little effect on microaggregate-occluded POM

fractions (Chivenge *et al.*, 2011; Puttaso *et al.*, 2013). High-quality (C/N <24) litters increase microbial biomass, and microbial residues are widely considered to be an important contributor to the amount of microaggregate-occluded POM (Guggenberger *et al.*, 1999; Ludwig *et al.*, 2015).

The rate of litter decomposition is influenced by a number of factors including climate (temperature and moisture), litter quality and the nature and abundance of the decomposing organisms (Melillo *et al.*, 1982). According to Melillo *et al.* (1982), the two most important factors are climate and the chemical nature of the litter. Several studies have indicated that the chemical and biochemical quality of litter affects mass loss during decomposition (Chivenge *et al.*, 2011; Puttaso *et al.*, 2013). The addition of higher quality substrate (lower C/N ratio of < 24 and lower lignin content) resulted to increased POM mineralization compared to the addition of lower quality (C/N ratio > 24) substrate (Potthast *et al.*, 2010). Since the organisms that decompose residues need N (and other essential elements) as well as C, if there is little N in the residue, decomposition is slow. Chivenge *et al.* (2011) found that when immature legumes are ploughed into the soil that had lower dry matter but higher N concentration and low C/N, decomposition was faster. On the other hand, the high cellulose, hemicellulose and lignin contents of legumes ploughed in at a matured age reduced the speed of decomposition. The C/N ratio in plant residues is highly variable and increases with maturity. An ideal substrate material was found to have C/N ratio = 24 to satisfy the N requirement of microbes. If the C/N ratio of residue > 24, available soil N is consumed by microbes and this retards decomposition rate.

There is debate in the literature as to whether the rate of SOC increase is dependent entirely on the amount of organic carbon applied or dependent on the form of organic carbon. A number of authors have reported linear increases in SOC related to the amount of organic matter applied (Dick and Gregorich, 2004; Bhogal *et al.*, 2006 & 2007), whilst others, have reported that the rate of SOC accumulation is dependent on the source of organic carbon (Potthast *et al.*, 2010). This greatly suggests that litter quality is a major control factor of organic carbon content in various soils. Nevertheless, less is known about litter quality and soil organic carbon (SOC) stabilization in different soils (Gentile *et al.*, 2011).

Role of litter in soil aggregate stability

Aggregate stability is often measured on a specific aggregate size class which is not a measurement of whole soil structure (Six *et al.*, 2004). Soil organic matter levels, soil biological activity and soil functions (such as water infiltration, water holding capacity and aeration) are related to soil aggregation (Chivenge *et al.*, 2011). Soil dry aggregate (DA) and water-stable aggregate (WSA)

amounts and size distributions affect the soil quality. The soil organic matter (OM) concentration is an indicator of soil quality (Bhogal *et al.*, 2006) and influences aggregate amount and size. Angers *et al.* (2008) noted a linear relationship between OC concentrations and water-stable aggregates from various soils. However, Perfect and Kay (1990) noted that there was no relationship between an increase in water-stable aggregates and total OC. This suggests that some components of soil organic matter forms are more actively involved in soil aggregate stabilization than others.

Soil organic matter influences many other soil physical, chemical and biological properties. Hence knowledge of soil aggregate and organic carbon relationships is important in evaluating effects of soil management practices. Aggregation is a key to maintaining soil structure stability and an effective means of controlling erosion (Cambardella and Elliot 1992; Angers *et al.*, 2008). Soil aggregation is usually determined by a wet sieving method (Kemper and Rosenau, 1986). Soil aggregation has been conceptualized as a hierarchical system of primary particles forming microaggregates (< 0.25 mm), which then become the foundation for formation of macroaggregates (> 0.25 mm) of varying sizes (Tisdall and Oades, 1982). The formation of macro- and micro-aggregates is a dynamic process involving soil physical, chemical and biological process (Juma, 1993; Monreal *et al.*, 1995). Microaggregates are cemented by persistent, aromatic humic material in association with amorphous Fe and Al and polyvalent metals. The binding agents holding together macroaggregates can be transient or temporary (Tisdall and Oades, 1982). The interrelationship between SOM and the stability of topsoil aggregates has been well established. Several mechanisms are involved in soil susceptibility to particle detachment, and they are mainly related to soil erodibility. It is difficult to measure soil erodibility, given the complex interactions between soil properties and time-related conditions that make soil erodibility a dynamic (rather than a constant) property (Roose, 2003).

Problem statement

If the application of organic matter (OM) to soil can stabilize soil against soil erosion and the effects of OM quality on soil stabilization are explored, OM could contribute significantly in land restoration in South African degraded areas. It is agreed that SOC values of 2% (equivalent to 3.4% SOM) is the upper threshold below which most soils are prone to structural destabilization (Howard & Howard, 1990; Janzen *et al.*, 1992). However, these values are based on SOC quantity and say nothing on quality. As a potential solution to the highly unstable soils, there is interest in research to determine the synergistic effects of litter quality and the architecture of soil particles on soil erosion. The present review

summarises up-to-date information on litter quality effects in soil stabilization. It identifies information gaps in regard to litter quality with the aim of guiding future research programs in soil conservation through addition of OM. This review was guided by the question "Can any type of organic matter be used in stabilizing soil against soil erosion?"

CONCLUSION AND RECOMMENDATIONS

A comprehensive, up-to-date review on synergistic effects of organic matter/litter quality and soil aggregation on soil erosion has hitherto been unavailable. In this review, scientific studies on soil erosion status in SA and role OM in soil stabilization against soil erosion have been discussed to explore information gaps towards the feasibility of using OM to conserve soil. High rates of soil erosion are due to unstable soils that have low (< 2%) SOC content. Soil erodibility is influenced by many factors such as chemical, physical and biological soil properties but was shown to decrease when SOC content is at least 2% and where the soils can resist erosive forces. Sources of OM influenced the rate at which SOC is lost in soils, high quality (C/N < 24) decomposes faster than low quality (C/N > 24). The soil organic matter (SOM) quality influenced the resident time (RT) of the organic carbon in soils. High quality organic matter sources promote faster soil aggregation but with shorter RT than low quality sources. Therefore low quality organic matter has more prolonged effects in soil aggregation than high quality matter because as they decompose slowly. Whilst any OM source can be used to enhance soil aggregation and stability, a major drawback is on ensuring selection of OM with clear and prolonged soil stabilizing effects. Different OM may have different effects on soil erodibility depending on properties of the soil in question. Therefore, to maximize the benefits of OM in soil conservation, there was need to explore effects of various OM sources in stabilizing soils of different properties.

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Competing interests

The authors declare that they have no competing interests

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