Environ Dev Sustain
https://doi.org/10.1007/s10668-018-0089-z

Effects of litter quality on macroaggregates reformation and soil stability in different soil horizons

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Received: 18 May 2017 / Accepted: 18 January 2018

Abstract The resilience of soils under varying litter quality is unclear. Therefore, this study investigated the effects of different litter sources on soils with low (< 2%) initial organic carbon content on soil reaggregation and stability. Seven soils were incubated for 30 weeks at 25 °C after adding high-quality *Vachellia karroo* leaf litter ($C/N = 23.8$) and low-quality *Zea mays* stover ($C/N = 37.4$). Soil aggregation (SA) and stability were evaluated by measuring mean weight diameter (MWD), whole soil stability index (WSSI), percentage water-stable aggregates (% WSA) and distribution fractions of dry-sieved soil aggregates size (P_{ai}). Cumulative macroaggregates yields, MWD, % WSA and WSSI in litter-amended soils increased up to week 8 during incubation and thereafter declined gradually in all soils. Litter quality significantly ($P < 0.05$) enhanced macroaggregation and soil stability across soils but had insignificant ($P > 0.05$) effects within a soil type. An increase in macroaggregation increased MWD, WSSI values and large and small aggregates distribution. Aggregation was significantly higher in soils with higher clay content than sand content, suggesting that soil texture was highly influential to the litter effects on SA. We concluded that the rate of soil aggregate reformation was influenced by soil type × time interactions which determined the extent and dynamics of macroaggregation during the 30 weeks of incubation.

Keywords Aggregation · Decomposition · Dynamics · Soil texture · Stability indices

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Published online: 22 January 2018

1 Introduction

Accelerated soil erosion is a serious environmental problem that causes severe land degradation and threatens sustainable development of rural areas in particular (Tang 2004; Wang et al. 2013). The soil is easy to erode if poorly aggregated as soil particles are highly exposed to the erosive action of water and wind. A well-aggregated soil resists erosion, and water-stable aggregates in soil prevent erosion (Dinel et al. 1991). Six et al. (2004) noted that the aggregate size distribution (the amounts of large, medium and small macroaggregates (> 0.25 mm) and microaggregates (< 0.25 mm)) confers soil resistance to erosion through their influence on pore size and continuity. Similar observations were made by Elliott (1986) where the macroaggregates were found to contain more OM and less susceptible to erosion by creating larger pores for better water infiltration and aeration than microaggregates. This implies that a soil with more stable macroaggregates will be of a higher quality than a soil with less stable microaggregates. Soil aggregation is a process that depends on time, place, application and soil management (Seybold and Herrick 2001) because it is greatly influenced by the prevailing climatic conditions and soil management practices. Aggregates are considered as important physical properties, and their size distribution and stability are indices which show storage capacity of organic carbon and erosion potential (Diaz-Zorita et al. 2002). The macroaggregation is easily disrupted by impacts of rainfall and disturbances such as tillage and construction machinery (Six et al. 2004). A soil that promotes quick macroaggregation after manipulation is resilient and resists the erosive forces. Therefore, in order to alleviate the impact of soil erosion after soil disturbance, soil management practices like addition of organic matter (OM) that promotes reaggregation must be adopted. The addition of OM to soil has been advocated as a sustainable way for improving soil aggregation and stability, though the resilience of soils under different OM qualities is unclear (Helfrich et al. 2008; Castellano et al. 2015).

In soils where soil organic matter (SOM) is the major binding agent, the aggregates are formed in different stages with a different bonding mechanism for each stage (Six et al. 1998). Tisdall and Oades (1982) observed that the microaggregates (< 0.25 mm) join together to form macroaggregates (> 0.25 mm) where the binding agents are supposed to mainly young organic materials. However, according to Six et al. (2000), freshly added organic matter induces macroaggregate (> 0.25 mm) formation, while the decomposition of SOM within these macroaggregates results into stable microaggregates (Gale et al. 2000) and organomineral complexes. This was supported by the observation that soil aggregate stability increased with addition of low *C*/*N* litter (De Gryze et al. 2005; Abiven et al. 2007). This suggested that the chemical composition of litter has a strong control in the rate of litter decomposition (Heal et al. 1997). Litter material with a low *C*/*N* ratio (high quality) decomposes faster than those with higher *C*/*N* ratio (low quality). Jastrow (1996) and Six et al. (1998) found that water-stable macroaggregates are enriched in young organic matter compared to microaggregates, confirming that litter quality is a key factor determining the rate of OM decomposition (Bardgett and Shine 1999).

A number of soil aggregate indices have been proposed for assessing soil aggregation which include mean weight diameter (MWD), geometric mean diameter (GMD) and aggregate stability index (ASI) (Niewczas and Witkowska-Walczak 2003). These indices either lack clear differentiation between stable and unstable macroaggregates or apply only to a specific set of aggregate size and not the whole soil (Marquez et al. 2004) making them less appropriate for assessing soil aggregation. Recently, Nichols and Toro (2011) proposed the whole soil stability index (WSSI) as an improved method for assessing soil aggregation and its interaction with other soil functions which addresses the management impacts.

A good structure confers soil resistance to erosion (Alagoz and Yilmaz 2009), and one of its major indicators is the stability of soil aggregates in water, which is influenced by both the quality and quantity of OM in the soil (Piccolo 1996). Tisdall and Oades (1982) found positive effects of total OM, while Dutarte et al. (1993) indicated that the quality OM is responsible for aggregate stabilization. However, Abiven et al. (2009) noted that information on the effects of OM on soil structure is rather empirical and still poor, as is knowledge of the actual mechanisms by which OM acts in the soil. Abiven et al. (2009) also found some inconsistencies in the collected data on the relationship between the decomposition rates of OM and soil aggregate stability. The conflicting information on the role of OM in soil aggregation may be related to different mechanisms operating in the soil environment at different scales. Understanding the mechanisms involved in soil aggregate formation is important in the choice of suitable soil organic matter management practices.

Formation of macroaggregates leads to longer residence time of soil organic matter (SOM) due to the formation of smaller, more stable soil fractions with increasingly intimate association between organic matter and mineral surface (Poirier et al. 2005). De Gryze et al. (2005) noted that the turnover rate of microaggregates is slower relative to macroaggregates, meaning that there is increased stability with smaller size. Soil aggregates of different size and stability hold SOM of different nature and dynamics, and provide the physical protection for SOM from further biodegradation (Oades and Waters 1991). Stable macroaggregates (> 0.25 mm) are found to be richer in young and decomposable SOM than microaggregates.

The capacity to recover from perturbations is an important and inherent attribute of a soil (Blanco-Canqui and Lal 2010). Any soil possesses an inherent regeneration capacity which in interaction with proper management can reverse degradation. Use of organic matter has been advocated as a sustainable management practice in soil conservation against erosive forces (Whitbread et al. 2003). The addition of OM in soils is known to enhance aggregation of soil particles (Six et al. 1998; Whitbread et al. 2003); however, there is little understanding on the effects of different litter sources in soil aggregation dynamics especially after soil manipulation (Helfrich et al. 2008). This information will be very important in planning soil conservation strategies after land development projects like road or dam construction. The effect of litter quality on the rate of reaggregation following disturbance has not been sufficiently investigated to date (Podrazsky et al. 2015).

The aim of this study was therefore to assess the ability of OM (*Vachellia karroo* leaf and *Zea mays* stover litter) additions to initiate water-stable macroaggregate reformation in soils with differing primary particle size distributions. We hypothesized that the reformation of water-stable aggregates in a structurally broken soil (< 0.25 mm aggregates) occurs within a shorter time under *V. karroo* than under *Z. mays* litter and soils that quickly reform water-stable aggregates are resilient.

2 Methodology

2.1 Description of the study area

A laboratory experiment was conducted at the University of Fort Hare (UFH), South Africa, using soils collected from the Ntabelanga area in the Eastern Cape Province, South Africa. The Ntabelanga area is located about 380 km southeast of the UFH and lies between 31°7′35.9″S and 28°40′30.6″E. The Ntabelanga area falls within the South Eastern Uplands Aquatic Ecoregion and the Mzimvubu to Kieskamma Management Area which is in the sub-escarpment Grassland and sub-escarpment Savanna Bioregions (Mucina and Rutherford 2006). The Ntabelanga area receives a mean annual rainfall total of about 749 mm, with most of it failing in December and January. The lowest (15 mm) average rainfall is received in June and the highest (108 mm) in January. The sub-humid grasslands in the Ntabelanga area suffer from severe gully erosion, even with their dense grass cover (Sonneveld et al. 2005; Van Tol et al. 2014), suggesting that the causes of high erosion rates in the study area are influenced more by erodibility than erosivity factors. The area is characterized by highly unstable soils that are prone to erosion as evidenced by extensive areas of severe gully erosion on the inter-fluvial areas adjacent to stream channels (Parwada and Van Tol 2016).

2.2 Soil sampling and analysis

Twenty-one soil samples were collected from nine randomly selected points generated from a geographical position system (GPS). The nine selected points represented areas of soil associations in a proposed Ntabelanga dam catchment (Parwada and Van Tol 2016). At each sampling point, we collected at least one soil sample depending on the naturally existing soil horizon profiles. Some of the sampling points were severely eroded and lacked the A horizon, and others were rocky just below the A- horizon. The soil was initially characterized for properties that influence erodibility (Parwada and Van Tol 2016) and then compounded to seven samples according to the naturally existing soil horizon profiles representing the areas of soil associations in the Ntabelanga area (Van Tol et al. 2014). The compounded soils were reanalyzed for the primary particle size distribution and soil organic carbon (SOC) before incubation. The existing soil horizon profiles in the Ntabelanga area were the orthic A, melanic A, pedocutanic B, red apedal B, prismacutanic B, G horizon and saprolite (Table 1).

The soils were analyzed for primary particle size distribution by the hydrometer method as described by Okalebo et al. (2000), and total soil organic carbon was determined through the wet acid digestion Walkley–Black method (Nelson and Sommers 1996). Soil structural index (SI) was estimated according to Reynolds et al. (2007) as:

Table 1 Descriptive statistics of mean soil particle size distribution, initial soil organic carbon (SOC) content of the soil horizons used in the incubation experiments

Soil association	Horizon	Sand (%)	Clay (%)	Silt (%)	SOC (%)	Clay ratio	SI (%)
Shallow (4)	Orthic A (*ot.s*)	57.8 (0.7)	23.6 (0.2)	18.6 (0.6)	0.81 (0.1)	3.2 (0.4)	3.3 (0.2)
Wet (3)	G horizon (*gh*)	47.5 (0.5)	27.5 (1.0)	25 (0.2)	0.53 (0.2)	2.6 (0.3)	1.7 (0.2)
Melanic (3)	Melanic A (*ml.s*)	18.0 (0.7)	62.5 (0.7)	19.5 (0.3)	0.39 (0.4)	0.6 (0.3)	0.8 (0.1)
Semi-duplex (3)	Pedocutanic B (*vp*)	17.0 (0.6)	63.0 (0.5)	20.0 (0.5)	0.39 (0.3)	0.6 (0.3)	0.8 (0.1)
Apedal (3)	Red apedal B (*re*)	60.5 (0.8)	25.5 (0.6)	14.0 (0.7)	1.35 (0.1)	2.9 (0.2)	5.9 (0.3)
Duplex (4)	Prismacutanic B (*pr*)	36.0 (0.6)	38.0 (0.5)	26.0 (0.6)	0.70 (0.2)	1.6 (0.1)	1.9 (0.2)
Shallow (1)	Saprolite (*so*)	33.7 (0.6)	44.5 (0.7)	21.8 (0.5)	1.61 (0.3)	1.2 (0.2)	4.2 (0.1)

The number after soil associations indicates frequency of sampling and (± se)

$$SI = \left(\frac{1.724 \times \%\,OC}{\%\,silt + \%\,clay}\right) \times 100 \tag{1}$$

Clay ratio was calculated using percentages of the particle sizes obtained per horizon as follows:

$$\text{Clay ratio} = \frac{\%\,sand + \%\,silt}{\%\,clay} \tag{2}$$

2.3 Laboratory soil incubation

To determine the rate of soil aggregate reformation (> 0.25 mm aggregates) in different soils, we conducted a soil incubation experiment with organic litter of different quality. Soil from the seven horizons collected in Ntabelanga area was passed through a 2-mm sieve and air-dried. The soil was then ground to destroy all macroaggregates (> 0.25 mm). After macroaggregate destruction, the samples were sieved to pass a 0.25-mm sieve to achieve aggregate homogeneity, and then the fractions > 0.25 mm (macroaggregates) were discarded. High-quality *V. karroo* leaf (*C*/*N* = 23.8) and low-quality *Z. mays* stover litter (*C*/*N* = 37.4) both collected from the Ntabelanga area were used in the incubation. The *V. karroo* leaves were harvested at the beginning of winter season (May 2014), and *Z. mays* stover was from a harvested crop at the end of 2013/2014 season. The plant materials were cut into very small segments and oven-dried at 60 °C. After drying, the litter was ground to pass through a 2-mm sieve. Then, the litter was carefully mixed with the soil avoiding further breaking of the aggregates using hands. The quantities of OM to be added in a soil jar were calculated according to *C*/*N* ratios of the litters. Sixty-three 1000-mL jars were filled with 600 g of soil each, and the litter applied at a rate of 2.28 g OM/100 g soil and 2.43 g OM/100 g soil for *V. karroo* leaves and *Z. mays* stover, respectively. The mixture was to constitute at least 2% SOC (threshold SOC content for aggregate stability) (Kay and Angers 2000) since the initial SOC content of the seven horizons ranged from 0.39 to 1.61% (Table 1). A control treatment with no litter amendment was included. In the incubator, jars were arranged in 7 × 3 factorial laid in completely randomized design (CRD) with three triplicates. The amended soil moisture content was adjusted to 60% water holding capacity and a temperature of 25 °C and incubated for 30 weeks. The soil moisture levels in the jars were adjusted to 30% water holding capacity for 2 days per week to create a dry condition during soil incubation. The soil macroaggregation and stability were determined by measuring some sieve size fraction indices from the incubated soils.

2.4 Measurement of soil aggregates and stability indices

A subsample (90 g) was taken from each jar at 1, 3, 8, 14, 23 and 30 weeks of incubation, and mean weight diameter (MWD), aggregate size distribution (P_{ai}) and water-stable aggregation (WSA) were measured. After determining the aggregate size distribution and water-stable aggregation, the whole soil stability index (WSSI) was then calculated for each respective sampling week during incubation.

Aggregate size distribution (P_{ai}) was measured on dry-sieved aggregates in three aggregate size classes (> 2, 0.25–2 and 0.053–0.25 mm) as described by Six et al. (2000). Briefly, dry sieving consisted of placing the soil atop a screen with the size equal to the size of the largest aggregates in the size class, tapping the sides at least 50 times with the palm of the hand to pass the soil through the screen, collecting the soil passing through the screen on piece of filtering cloth, and pouring it onto a screen equal to the smallest aggregates in the size class followed by tapping. Each aggregate size class was collected individually from largest to smallest. The weight of aggregates in each size class was measured and used to calculate the proportion of aggregates in each size class relative to the whole soil. Soil on top of the 2-mm sieve and below the 0.053-mm sieve was collected and weighed as part of the summed total weight (W_T).

The proportion of dry-sieved aggregates in each size class was according to Six et al. (2000) as:

$$P_{ai} = \left[\frac{W_A - \left[\left(\frac{W_C}{W_O} \right) \times W_A \right]}{W_T} \right] \tag{3}$$

where P_{ai} = proportion of dry-sieved aggregates ith size class, W_A = weight of total material in the ith size class, W_C = weight of material measured during wet sieving for ith size, W_O = weight of aggregates placed on the sieve prior to wet sieving size i and W_T = summed total weight of all the aggregate size classes plus the soil from above 2-mm sieve and below the 0.053-mm sieve.

The stability of soil aggregates to forces of water was estimated using wet sieving method as modified by Kemper and Rosenau (1986). About 50 g of the < 2 mm aggregates was placed on the top most sieve in a stack with size of 2, 0.25 and 0.053 mm. The samples were first immersed in distilled water and then sieved by moving the sieve set vertically. The soil retained by each sieve was dried at 105 °C for 24 h, weighed and corrected for sand particles to obtain the proportion of water-stable aggregates. The mean weight diameter (MWD) (mm) as an index of soil structural stability to water erosion was then calculated according to Unger 1997 as:

$$\text{MWD} = \sum_{i=1}^{n=3} w_i x_i \tag{4}$$

where x_i = the mean diameter of the ith class size range (mm) and w_i = the proportion of the ith size class range with respect to the total mass of sample.

The water-stable aggregation (WSA) from each aggregate size class (> 2, 2–0.25 and 0.025–0.053 mm) was also measured according to a modified Kemper and Rosenau (1986) method. In brief, aggregates (4 g for the > 2 mm, 2 g for the 0.25–2 mm and 1 g for the 0.053–0.25 mm) were placed onto 0.0132-mm sieve size (¼ of the smallest size) and capillary-rewetted for 10 min. Stable aggregates were separated manually as described by Cambardella and Elliott (1992). Then, the WSA for each size class was calculated according to Six et al. (2000) as:

$$\text{WSA}_i = \left[(W_a - W_c) \div W_O \right] \times 100 \tag{5}$$

where WSA_i = water-stable aggregation for size class i, W_a = weight of material on the sieve after wet sieve size i, W_c = weight of coarse material in sieve size i and W_O = weight of aggregates placed on the sieve prior to wet sieving size i.

The dry aggregate size distribution and WSA calculated as in Eqs. 3 and 5 were used to get the whole soil stability index (WSSI) according to Nichols and Toro (2011) as:

$$\mathrm{WSSI} = \left[\frac{\sum_i^n \left[(1) \times (P_{ai}) \times ((\mathrm{WSA}_i) \div 100) \right]}{n} \right] \quad (6)$$

where is the WSSI = whole soil stability index ($0 \leq \mathrm{WSSI} \geq 1$): 0 means all the aggregates are unstable, and 1 means 100% aggregates are stable, n = the number of the aggregate size classes $i = n$ and decreases by an increment of 1 from the largest to the smallest aggregate sizes class, WSA_i = water-stable aggregation for size class i, and P_{ai} = proportion of dry-sieved aggregates for size class i.

2.5 Statistical analyses

Sampling during incubation was not destructive to the whole incubated soil (600 g in a jar), but only subsampling was done during data collection. The observations were independent of each other; data followed a normal distribution and homoscedasticity, and thus, the repeated measures analysis of variance (ANOVA) test was run to compare treatment means among the whole soil stability index (WSSI), mean weight diameter (MWD), aggregate size distribution and percentage water-stable aggregates (% WSA). Where sphericity assumptions could not be met, the Greenhouse–Geisser correction of P was used. Means were separated using the Tukey test ($P < 0.05$). All data were analyzed using JMP version 11.0.0 statistical software (SAS Institute 2010).

3 Results and discussion

Orthic A and red apedal B had most particles in > 0. 002-mm size range. Melanic A and the pedocutanic B had the highest clay content and lowest sand particles as shown by the low clay ratio values (Table 1). The soil organic carbon for the seven horizons ranged from 0.39 to 1.61%. The saprolite was found on the surface, and this could be the reason for the noted higher SOC percentages (Table 1).

Considering the structural stability index (SI) values of 5% < SI < 7% and < 5% indicates a high degrading risk and structurally degraded soils, respectively (Reynolds et al. 2009). The *re* indicated a high degrading risk (SI = 5.9), while the other six soil horizons were structurally degraded (SI < 5%) (Table 1). The low SI could be attributed to the sub-optimal levels of SOC (< 2%) observed in all the soils. According to the Soil Classification Working Group (1991), the *ot* is a rocky horizon such as Lithocutanic B as second horizon, *gh* is characterized by a subsoil horizon, and the *ml* is a pedocutanic B. The *vp* has a moderate degree of structure in the subsoil horizon, while the *pr* has a sandy topsoil on clayey prismacutanic B subsoil horizon. The *re* has an apedal subsoil horizon (Fey and Gilkes 2010) (Table 1).

Mean weight diameter (MWD) and whole soil stability index (WSSI) exhibited soil horizon × litter × time interactions (Table 2). Water-stable aggregate (WSA) in the large macroaggregates (> 2 mm) and small macroaggregates (0.25–2 mm) showed soil horizon × litter × time interactions, while WSA in the microaggregates (0.053–0.25 mm) was significantly influenced by the soil horizon × litter interactions (Table 2).

The proportion of dry-sieved aggregates (P_{ai}), large macroaggregates (> 2 mm), small macroaggregates (0.25–2 mm) and microaggregates (0.053–0.25 mm) were significantly ($P < 0.05$) influenced by soil horizon × litter and litter × time interactions, while soil

Table 2 Repeated measures analysis of variance (ANOVA) for MWD, WSSI and WSA during 30 weeks of incubation

Source of variation	MWD	WSSI	WSA (mm)		
			> 2	0.25–2	0.053–0.25
Between subjects					
Horizon (*H*)	*	**	**	**	**
Litter (*L*)	**	**	**	**	**
$H \times L$	**	**	**	**	ns
Within subjects					
Time (*T*)	**	**	**	**	**
$H \times T$	**	**	*	**	ns
$L \times T$	**	**	ns	**	ns
$H \times L \times T$	**	**	**	**	ns
CV (%)	30	15	36	18	21

**, * and ns mean statistical significance at < 0.01 and 0.05 and non-significant

Table 3 Repeated measures analysis of variance (ANOVA) for the proportion of dry-sieved aggregates (P_{ai}) during the 30 weeks of incubation

Source of variation	Aggregate class sieve size (mm)			
	> 2	0.25–2	0.053–0.25	< 0.053
Between subjects				
Horizon (*H*)	**	**	**	ns
Litter (*L*)	**	**	**	*
$H \times T$	**	**	**	*
Within subjects				
Time (*T*)	**	*	**	ns
$H \times T$	ns	ns	ns	ns
$L \times T$	**	*	*	ns
$H \times L \times T$	ns	ns	ns	ns
CV (%)	13	25	21	16

**, * and ns mean statistical significance at < 0.0001 and 0.05 and nonsignificant

horizon, litter and time insignificantly ($P > 0.05$) influenced mineral fractions (silt + clay) (< 0.053 mm) (Table 3).

Mean weight diameter (MWD) (mm) varied across the soil horizons and was influenced by soil horizons × litter source × time interactions. The MWD was statistically ($P > 0.05$) the same per soil horizon under both the *V. karroo* and *Z. mays* and lowest in the control (Table 4). Mean weight diameter increased from 1 to 8 weeks of incubation and reached maximum at week 8 in all soil horizons and thereafter decreased ($P < 0.05$) up to week 30 in the *ot.s*, *gh*, *pr* and *so* except in *vp*, *re* and *ml.s*, where the decline began after 23 weeks of incubation (Table 4). The mean weight diameter was generally observed to be highest ($P < 0.05$) in the *vp*, *re* and *ml.s* and lowest in *pr* on soils amended with litter the entire incubation period (Table 4).

Mean weight diameter is related to aggregate stability (Nimmo and Perkins 2002) as higher MWD values correspond to higher aggregate stability (Le Bissonnais 1996). Le Bissonnais (1996) suggested five classes of stability, with a MWD < 0.4 mm classified as very

Table 4 Tukey test changes in the mean weight diameter (mm) with time of litter incubation

Horizon	Litter source	Week 1	Week 3	Week 8	Week 14	Week 23	Week 30
ot.s	*V. karroo*	0.53^{c}	1.36^{b}	2.05^{a}	1.36^{b}	1.22^{b}	0.99^{bc}
	Z. mays	0.47^{c}	1.35^{b}	2.08^{a}	1.50^{b}	1.23^{b}	0.95^{bc}
	Control	0.42^{c}	0.54^{c}	0.55^{c}	0.46^{c}	0.46^{c}	0.45^{c}
gh	*V. karroo*	0.59^{c}	1.35^{b}	1.95^{a}	1.41^{b}	1.21^{b}	0.89^{bc}
	Z. mays	0.57^{c}	1.36^{b}	1.99^{a}	1.36^{b}	1.22^{b}	0.90^{bc}
	Control	0.48^{c}	0.53^{c}	0.58^{c}	0.49^{c}	0.42^{c}	0.42^{c}
ml.s	*V. karroo*	0.77^{bc}	1.58^{ab}	2.22^{a}	1.76^{a}	1.35^{b}	0.98^{bc}
	Z. mays	0.87^{bc}	1.59^{ab}	2.27^{a}	1.74^{a}	1.38^{b}	0.96^{bc}
	Control	0.48^{c}	0.51^{c}	0.55^{c}	0.47^{c}	0.43^{c}	0.42^{c}
vp	*V. karroo*	0.82^{bc}	1.36^{b}	2.36^{a}	1.69^{a}	1.39^{b}	0.89^{bc}
	Z. mays	0.85^{bc}	1.37^{b}	2.32^{a}	1.73^{a}	1.37^{b}	0.99^{bc}
	Control	0.47^{c}	0.43^{c}	0.48^{c}	0.43^{c}	0.42^{c}	0.42^{c}
re	*V. karroo*	0.89^{bc}	1.53^{b}	2.38^{a}	1.77^{a}	1.36^{b}	0.94^{bc}
	Z. mays	0.88^{bc}	1.36^{b}	2.37^{a}	1.68^{a}	1.38^{b}	0.96^{bc}
	Control	0.46^{c}	0.57^{c}	0.56^{c}	0.53^{c}	0.53^{c}	0.47^{c}
pr	*V. karroo*	0.43^{c}	0.55^{c}	0.97^{bc}	0.57^{c}	0.40^{d}	0.35^{d}
	Z. mays	0.42^{c}	0.59^{c}	0.86^{b}	0.54^{c}	0.41^{d}	0.35^{d}
	Control	0.37^{d}	0.41^{d}	0.88^{b}	0.46^{cd}	0.39^{d}	0.29^{d}
so	*V. karroo*	0.47^{c}	1.34^{b}	2.01^{a}	1.38^{b}	0.87^{bc}	0.86^{bc}
	Z. mays	0.46^{c}	1.36^{b}	2.04^{a}	1.35^{b}	0.88^{bc}	0.85^{bc}
	Control	0.42^{c}	0.48^{c}	0.49^{c}	0.43^{c}	0.43^{c}	0.43^{c}

Means with different letter superscripts were significantly different at $P = 0.05$

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

unstable, 0.4–0.8 mm unstable, 0.8–1.3 mm medium, 1.3–2.0 mm stable and > 2.0 mm very stable. Therefore, the soils were unstable (Le Bissonnais 1996) at week 1 and under the control treatment in all the soil horizons. The soils were stable at week 3 and very stable at week 8 in most soil horizons except in G horizon. The soil aggregate stability started to decrease gradually in week 14 to medium at week 30 (Table 4). These results confirm that regardless of litter quality, the addition of litter to soil enhanced aggregation stability and the MWD correlated with time after litter application. Initially, the MWD increased with an increase in time of litter incorporation up to 8 weeks of incubation and thereafter decreased. The results agree with findings of Tisdall and Oades (1982) that indicated OM is closely related to the formation and stability of soil aggregates. Thus, the amendment of organic residues can improve soil structure and increase aggregate stability (Hati et al. 2008), and this could explain increase in MWD observed as from week 3 of incubation. The lack of litter quality impact on MWD within the same soil horizon suggests similarities in terms of the *C*/*N* ratios of the litter material used. These results are contrary to observations by Conde et al. (2005), Guenet et al. (2010) and Potthast et al. (2010) where addition of higher-quality substrate (lower *C*/*N* ratio of < 24 and lower lignin content) resulted to a greater soil aggregation and high MWD than the addition of lower quality (*C*/*N* > 24) substrate. The quality of the *V. karroo* leaf compared to *Z. mays* stover in this study can be classified as intermediate quality and associated with just a balance of immobilization and mineralization. The overly low MWD (Table 4) and amount of large

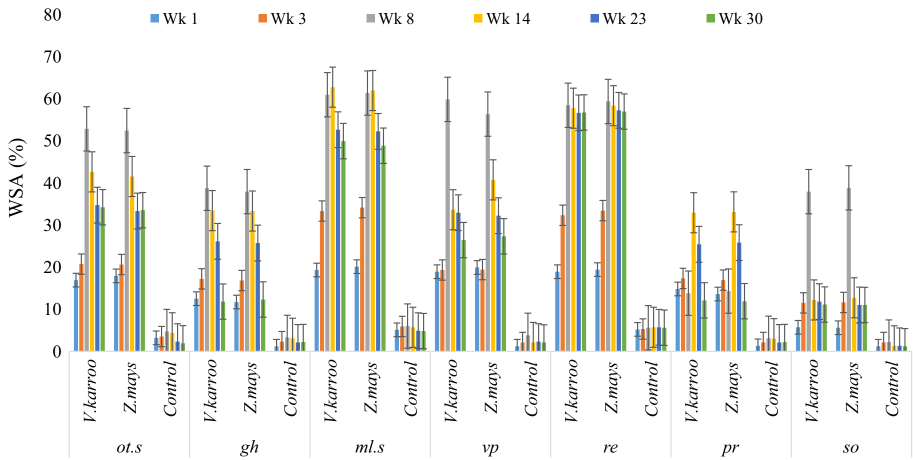

Fig. 1 Water-stable aggregates (WSA) in large macroaggregates (> 2 mm) size class for the soil horizons under different litter sources following 30 weeks of incubation

water-stable (WS) aggregates (> 0.25 mm) (Figs. 1, 2) at week 1 probably resulted from the fact that all macroaggregates originally present in the soils were destroyed by sieving < 0.25 mm before incubation and that the added OM had not decomposed well yet to affect the binding of soil particles.

The mean weight diameter (Table 4) and large WS aggregates (> 0.25 mm) (Figs. 1, 2) were observed to decline as from 14 to 30 weeks which could be due to gradual loss in litter effectiveness with time through decomposition as litter was applied once throughout the incubation period. Similarly, Coppens et al. (2006) found that a single application of fresh organic matter resulted in small and short-term effects in soil aggregation. Thus, the results enlighten the processes of new macroaggregate formation under the influence of plant litter decomposition and characterize the distribution of aggregate size fractions in the soil horizons. The decline in the MWD starting from 14 to 30 weeks of incubation suggested the need to reincorporate fresh organic matter to maintain high MWD in the soil horizons. These results agree with Helfrich et al. (2008) who also found that the effects of organic matter on soil aggregation declined as time after application increased. Differences in MWD as from 3 to 30 weeks of incubation across the seven soil horizons could be due to different decomposition rates of litter caused by the contrasting texture (Table 1) observed in each horizon. The results agreed with Heal et al. (1997) and Six et al. (1999) who observed that soil properties greatly influenced decomposition rates and binding of organic matter and clay minerals.

Water-stable (WS) large macroaggregate size class distribution varied according to soil horizons × time × litter interactions (Fig. 1). The WS large macroaggregate across the 7 soil horizons increased from week 1 to 8 and thereafter significantly ($P < 0.05$) decreased. At week 8 of incubation, *ml.s*, *vp* and *ot.s* yielded most WS large macroaggregates and lowest in the *pr* under both *V. karroo* and *Z. mays* (Fig. 1).

The effect of *V. karroo* and *Z. mays* litter on WS large macroaggregates yield was statistically ($P < 0.05$) the same in most soil horizons (Fig. 1).

Vachellia karroo and *Z. mays* litter significantly ($P < 0.05$) improved yields of %WS large macroaggregates, small macroaggregates and microaggregates in comparison with the control (Figs. 1, 3, 5).

Whole soil stability index (WSSI) varied with time in soil horizons under the different litter sources (Fig. 2). The WSSI for the WS large macroaggregates across the 7 soil horizons increased from week 1 to 8 and thereafter significantly ($P < 0.05$) decreased. At week 8 of incubation, *ml.s*, *vp* and *re* significantly ($P < 0.05$) had the highest WSSI and lowest in the *pr* under both *V. karroo* and *Z. mays* (Fig. 2).

The WSSI was lower at 1 and 30 weeks of incubation in most soil horizons under *V. karroo* and *Z. mays* except in G horizon where no statistical ($P < 0.05$) differences were observed from 1 to 23 (Fig. 2).

Water-stable (WS) small macroaggregates (0.25–2 mm) were statistically ($P < 0.05$) highest in the *ml.s*, *vp* and *re* at week 3 of incubation and lowest in the *pr* under *V. karroo* and *Z. mays* litter (Fig. 3). The effect of *V. karroo* and *Z. mays* litter on the yield of small macroaggregates per soil horizon was insignificantly ($P > 0.05$) different from 1 up to 30 weeks of incubation.

The whole soil stability index (WSSI) for the WS small macroaggregates varied with time in soil horizons under the different litter sources (Fig. 4). Whole soil stability index for the WS small macroaggregates generally showed increase from 1 to 8 weeks in all the 7 soil horizons. At week 8 of incubation, the WS small macroaggregates were significantly ($P < 0.05$) highest in the *ml.s* and *vp*, and lowest in the *pr* under both *V. karroo* and *Z. mays* (Fig. 4).

The WSSI was lower (0.1) in the control in all the soil horizons and at 1 and 30 weeks of incubation in most soil horizons under *V. karroo* and *Z. mays* except in *ml.s* and *re*, where the WSSI was statistically ($P < 0.05$) higher from 1 to 30 weeks (Fig. 4).

Yield of microaggregates (0.053–0.25 mm) showed variations at different times of sampling across the soil horizons under *V. karroo* and *Z. mays*. The yield of microaggregates per soil horizon was statistically ($P < 0.05$) the same in all the 7 soil horizons from 1 to 8 weeks and was highest at week 14 of incubation (Fig. 5). *Vachellia karroo* or *Z. mays* litter influence on yield of microaggregates was statistically ($P < 0.05$) constant per soil horizon from 1 to 30 weeks of incubation (Fig. 5). Microaggregates yield was significantly

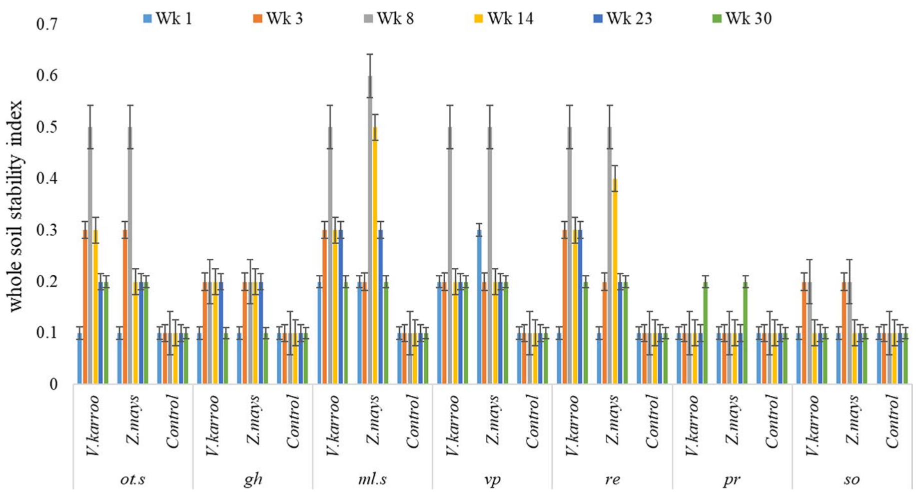

Fig. 2 Whole soil stability index (WSSI) for large macroaggregates (> 2 mm) size class among the soil horizons under different litter sources following 30 weeks of incubation

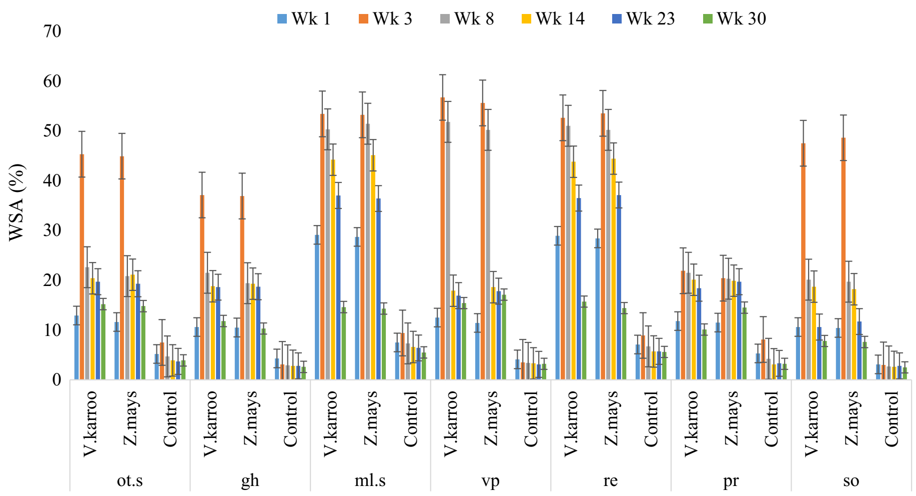

Fig. 3 Water-stable aggregates in small macroaggregates (0.25–2 mm) for the soil horizons under different litter sources following 30 weeks of incubation

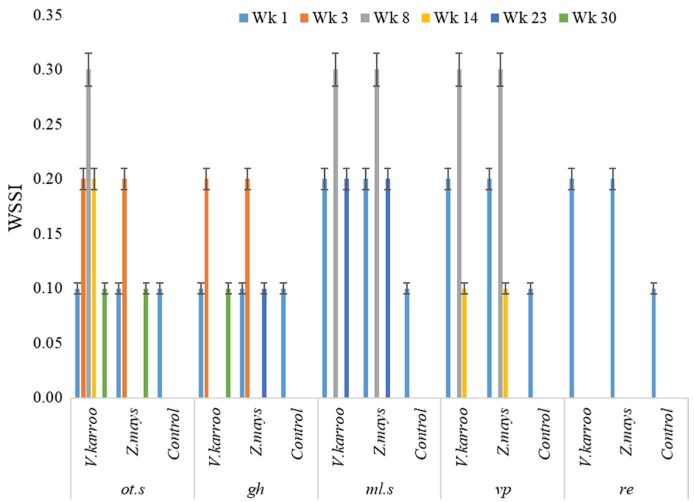

Fig. 4 Whole soil stability index (WSSI) in small macroaggregates (0.25–2 mm) for the soil horizons under different litter sources following 30 weeks of incubation

($P < 0.05$) highest in *ml.s* and *re*, and lowest in the *so* under both *V. karroo* and *Z. mays* litter (Fig. 5).

The whole soil stability index (WSSI) for the microaggregates varied with time in soil horizons under the different litter sources (Fig. 6). Whole soil stability index within a soil horizon was statistically ($P < 0.05$) the same under both *V. karroo* and *Z. mays* litter from 1 to 30 weeks of incubation (Fig. 6).

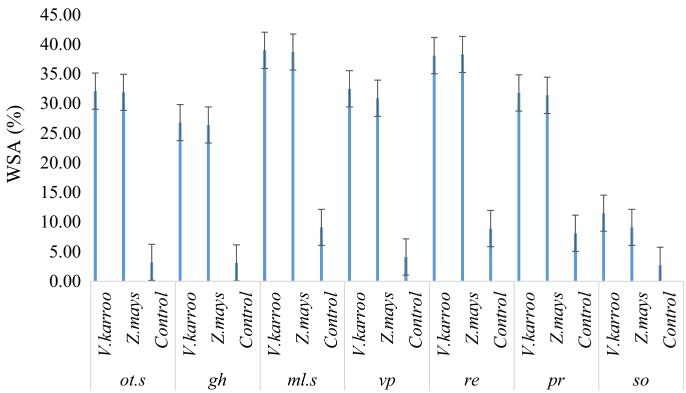

Fig. 5 Water-stable aggregates (WSA) in microaggregates (0.053–0.25 mm) for the soil horizons under different litter sources during 30 weeks of incubation

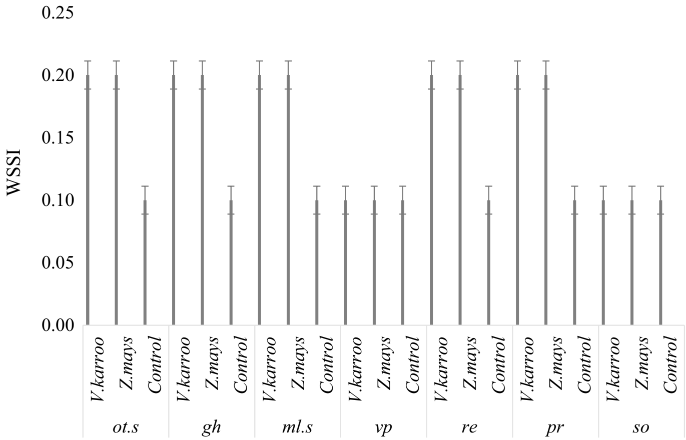

Fig. 6 Whole soil stability index (WSSI) in microaggregates (0.053–0.25 mm) for the soil horizons under different litter sources during 30 weeks of incubation

The large WS macroaggregate (large and small) formation was greater in litter-amended than unamended soils. This is consistent with previous studies showing enhanced macroaggregates formation after organic matter was added in low OM soil (Kimetu and Lehmann 2010). The large WS aggregates had the highest whole soil stability indices compared to the microaggregate size class (Figs. 2, 4, 6). Soil aggregation varies in time and space as a function of soil horizon and quantity of organic matter.

Our study showed that largest aggregate formation took place within the 3rd to 8th week of incubation. This agrees with Helfrich et al. (2008) who found high yield of macroaggregates in early stages of incubation when investigating the aggregate formation in a silt loam from a long-term wheat cropping. The soil was incubated after macroaggregates (> 0.25 mm) destruction for 84 d where they observed that a single application of maize leaves led to a short-term effect on soil macroaggregates. These findings suggest that macroaggregate formation is a rapid process and takes place within first days of incubation.

The rate of water-stable large and small macroaggregate formation was highest with the first 8 weeks of incubation, but the process was still proceeding in all the 7 soil horizons under both *V. karroo* and *Z. mays* litter (Figs. 1, 3). This is in contrast with the findings of De Gryze et al. (2006) who found no significant changes in aggregate formation after 17 days of incubation. De Gryze et al. (2006), Helfrich et al. (2008) noted a decrease in macroaggregate content just after 2 weeks of incubation; however, in this study we noted a decrease in macroaggregates content staring at 8 weeks of incubation. This suggests that the macroaggregates form before microaggregates during the soil aggregation which is contrary to Six et al. (1998)'s observations.

The effect of time on the proportion of dry-sieved aggregates (P_{ai}) was insignificant ($P < 0.05$) across the 7 soil horizons and litter sources. The proportion of dry-sieved aggregates varied across the soil horizons and between litter sources (Table 5). The proportion of dry-sieved aggregates were statistically ($P < 0.05$) the same across the soil horizons under both *V. karroo* and *Z. mays* litter and lowest in the mineral fractions (silt + clay) (< 0.053 mm) (Table 5).

All the 7 soil horizons were highest in the macroaggregate (> 2 and 0.25–2 mm) and lowest in mineral fraction (< 0.053 mm) aggregate class sizes (Table 5). The *gh* and *ml.s* had most dry aggregates in the microaggregate (0.053–0.250 mm) than other horizons. A

Table 5 Tukey test proportion of dry-sieved aggregates (P_{ai}) among the soil horizons under different litter sources during 30 weeks of incubation

Horizon	Litter	Aggregate size class (mm)			
		> 2	0.25–2	0.053–0.25	< 0.053
ot.s	*V. karroo*	0.40^{d}	0.60^{c}	0.20^{ef}	0.12^{f}
	Z. mays	0.41^{d}	0.49^{c}	0.31^{e}	0.11^{f}
	Control	0.04^{f}	0.01^{f}	0.03^{f}	0.11^{f}
gh	*V. karroo*	0.51^{cd}	0.49^{c}	0.74^{b}	0.10^{f}
	Z. mays	0.56^{c}	0.62^{b}	0.75^{b}	0.12^{f}
	Control	0.05^{f}	0.24^{d}	0.25^{d}	0.11^{f}
ml.s	*V. karroo*	0.60^{b}	0.70^{b}	0.83^{a}	0.12^{f}
	Z. mays	0.65^{b}	0.73^{b}	0.86^{a}	0.11^{f}
	Control	0.03^{f}	0.12^{f}	0.13^{f}	0.12^{f}
vp	*V. karroo*	0.61^{b}	0.46^{c}	0.18^{ef}	0.11^{f}
	Z. mays	0.62^{b}	0.47^{c}	0.18^{ef}	0.12^{f}
	Control	0.04^{f}	0.23^{e}	0.15^{f}	0.11^{f}
re	*V. karroo*	0.62^{b}	0.58^{c}	0.16^{ef}	0.13^{f}
	Z. mays	0.68^{b}	0.56^{c}	0.17^{ef}	0.11^{f}
	Control	0.03^{f}	0.04^{f}	0.02^{f}	0.12^{f}
pr	*V. karroo*	0.60^{b}	0.47^{c}	0.28^{d}	0.13^{f}
	Z. mays	0.61^{b}	0.48^{c}	0.29^{d}	0.11^{f}
	Control	0.01^{f}	0.04^{f}	0.03^{f}	0.12^{f}
so	*V. karroo*	0.41^{d}	0.10^{f}	0.16^{ef}	0.13^{f}
	Z. mays	0.43^{d}	0.12^{f}	0.15^{f}	0.11^{f}
	Control	0.05^{f}	0.04^{f}	0.05^{f}	0.11^{f}

Means with different letter superscripts were significantly different at $P = 0.05$

ot.s orthic A, *ml.s* melanic A, *vp* pedocutanic B, *re* red apedal B, *so* saprolite, *gh* G horizon, *pr* prismacutanic B decline of aggregates size from the microaggregates to large macroaggregate was observed in the *ml.s* (Table 5). The *vp, re, pr* and *so* had most of the dry aggregates in the large macroaggregate (> 2 mm) class and the quantities of the subsequent aggregates statistically ($P < 0.05$) declined with class size (Table 5). The ot.s and gh had lower quantities of large macroaggregates (> 2 mm) but more of small macroaggregates (0.25–2 mm) and microaggregates (0.053–0.250 mm). The proportion of large and small aggregates (> 2 and 0.250–2 mm) in the investigated soil horizons decreased in the following order: *ml.s* > *re* > *vp* > *pr* > *gh* > *ot.s* ≥ *so*. Addition of litter is known to affect the soil aggregates size distribution. In this study, investigated soil horizons responded differently to same quantity and quality of litter; this suggested that soil properties of the original soils horizons such as the primary particle size distribution could have been influential. These results are similar to Blagodatskaya and Kuzyakov (2008) when they found varying decomposition behavior due to soil properties.

The increasing fractions of the macroaggregates (> 2 and 0.250–2 mm), which consequently increased the MWD in the soils amended with *V. karroo* and *Z. mays* observed in our study, were likely due to the increased cohesive interaction caused by the increased soil microbial activities induced by the organic matter (Milne and Haynes 2004). In particular, organic matter was more easily encrusted within aggregates in *ml.s* and *vp* than the other soil horizons and hence more macroaggregates formation, which was consistent with the previous finding (Jones and Worrall 1995). The results suggest that clay fraction in soils is the most active component of the mineral fraction and can be considered as the base-level structural element in the conceptual hierarchical organization in soil aggregation (Six et al. 2004). The soil aggregation indices were lower in soil horizons with low clay than with high clay content. This could be because the added organic matter was adsorbed to clay surface and coated with the clay particles (Ingram and Fernandes 2001). High clay content (> 60%) in the *ml.s* and *vp* promoted the bonding of the organic matter to the surface of clay particles; therefore, the high MWD, WSA % and WSSI were observed in these soil horizons. In a recent study by Fissore et al. (2016), the clay mineralogy was shown to be more influential on mineralization of the soil than just the amount of clay in general. However, this study did not look at the effects of clay mineralogy and therefore may be a limitation to the findings, and this opens a void for further studies.

4 Conclusion and recommendations

The added litter, regardless of its quality, improved the MWD, WS aggregates, WSSI and distributions of dry-sieved aggregates from 3 to 8 weeks and was maximum at week 8 of incubation thereafter. Highest effects of the organic matter (OM) were observed in soil horizons with highest (> 60%) clay content, meaning that the clay influenced the effect of OM in soils. The effects of OM were more pronounced in the large macroaggregates (> 2 mm) and small macroaggregates (0.25–2 mm) than in the microaggregates (0.053–0.25 mm), suggesting that the macroaggregates are formed first during soil aggregation. Reformation of the macroaggregates was an ongoing process for the 30 weeks of incubation with highest rates observed within the first 8 weeks. The quantity of aggregates class size was directly proportional to the MWD, WSSI and dry-sieved aggregate size distribution. The effect of litter quality on the macroaggregates reformation was the same within a soil horizon but varied across the studied soil horizons. In order to maintain high rates of aggregates formation after 8 weeks of litter application, fresh litter had to be reapplied. The study concluded that not all litter is equally suitable to enhance soil aggregation in soils. Furthermore, what and how soil properties affected the stabilization of SA were unclear from this study. Again, since the formation and stabilization processes of SA structures can affect the soil carbon dynamics, further researches on SA structures, especially stabilization mechanisms related to application of soil organic matter, are needed.

Acknowledgements The authors gratefully acknowledge the Agricultural Research Council for funding the study as well as the Water Research Commission for financial support to the first author.

Compliance with ethical standards

Conflict of interest There are no conflict of interests regarding the publication of this paper.

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