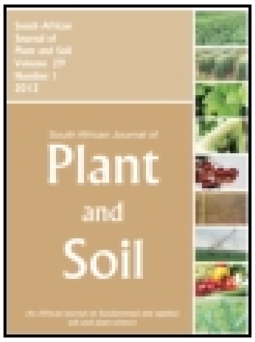

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Effects of long-term grazed crop and pasture systems under no-till on organic matter fractions and selected quality parameters of soil in the Overberg, South Africa

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There is limited soil research on semi-arid, grazed no-till crop and pasture systems. The long-term (10 years) effect of three grazed no-till dryland crop and pasture rotation systems, and perennial lucerne pasture were assessed on soil carbon (C) and nitrogen (N) stocks, soil organic matter functional pools and selected soil quality parameters in the Overberg, South Africa. The largest soil C and N stocks (0–30 cm) were found in crop–pasture systems containing wheat and medic/clover (70.2–74.9 Mg C ha^{-1} and 8.3–8.4 Mg N ha^{-1}), compared with perennial lucerne pasture (63.4 Mg C ha^{-1} and 7.7 Mg N ha^{-1}) or cropping-only systems (54.7–58.9 Mg C ha^{-1} and 6.3–6.7 Mg N ha^{-1}). Significantly higher labile C and N (free particulate organic matter fraction) contents were observed in crop–pasture systems (1.37–1.74 g C kg^{-1} and 0.107–0.110 g N kg^{-1}) than in continuous cropping systems (0.9–1.0 g C kg^{-1} and 0.042–0.045 g N kg^{-1}), attributed to higher annual C and N inputs and lower extent of soil disturbance. Significant positive correlations were found between soil C and N functional pools and soil quality parameters (soil respiration, effective cation exchange capacity and aggregate stability) and wheat yields. The results show the importance of the medic/clover pasture and wheat rotations in enhancing soil quality in the Overberg region.

Keywords: conservation agriculture; crop rotation; soil C stocks; soil organic matter functional pools; soil quality

Introduction

Conservation agriculture (CA) contributes to soil quality through improvement of soil structure, increase in soil water content and an increase in soil organic matter (SOM) content (FAO 2007). Although integrated crop and pasture-based livestock production systems under no-till present challenges for ‘ideal’ CA systems, similar benefits can be achieved by ensuring well-managed pasture phases and effective rotational grazing (Lilley and Moore 2009; Kirkegaard et al. 2014). The SOM benefits of a pasture phase rotation in rain-fed cropping systems are well established (Dalal and Chan 2001). In the semi-arid grain-producing areas of the Overberg, South Africa, dry-land crop and sheep production are the most important agricultural production enterprises. Integrated crop and pasture livestock production systems under no-till are widely implemented in this region. Limited local and international research has been conducted on the long-term effect of grazed no-till crop and pasture systems on SOM and soil quality in semi-arid climates, necessitating the need to quantify soil carbon (C) and nitrogen (N) stocks and the distribution of different SOM functional pools.

Soil organic matter plays an important role in several soil physical (e.g. soil water-holding capacity and aggregate stability), chemical (e.g. cation exchange capacity and nutrient supply) and biological (e.g. microbial activity and biomass) properties (Lal 2011). However, SOM consists of different functional pools (fractions), each with unique functional characteristics and different rates of turnover (von Lützow et al. 2007). These pools, reflecting key functions of organic matter, play an important role in optimising soil quality and crop production (Freixo et al. 2002; Krull et al. 2004; Haynes 2005). Furthermore, isolation of total SOM into a labile fraction that is more responsive to management practices is important as it provides an earlier indication of the effects of changes in current soil management and cropping systems practices than total soil organic carbon (SOC) (Gregorich et al. 1994; Plaza-Bonilla et al. 2014). Vital factors controlling the amount of SOM stored are the quantity and quality (such as C:N ratio) of SOM input (Wright and Hons 2005) and the rate of decomposition (Conant et al. 2011). In general, no-till practices have been observed to contribute to the accumulation of C in soils by decreasing the decomposition rate of organic matter, especially in the surface soil. Several authors (West and Post 2002; Chen et al. 2009; Huang et al. 2010) attributed the decrease in decomposition to a higher soil aggregate stability as a result of less physical disturbance. However, no-till as an isolated system may not always produce the positive results as expected in terms of accumulation of SOC. According to Sisti et al. (2004) and Conceicão et al. (2013), the type of crop rotation adopted is as important. Therefore, the use of diversified and high C input cropping systems, which include legumes, has to be considered as a management strategy together with no-till to enhance C sequestration. Plant roots represent a significant, but poorly understood, source of C inputs (van Vleck and King 2011). Much of the C found in soils has been found to be derived from belowground inputs (plant roots and rhizosphere) as it is retained in soils much more efficiently (Rasse et al. 2005), especially in grazed systems.

Three major SOM functional pools are generally recognised (Sohi et al. 2001; Cerli et al. 2012): (1) the free particulate organic matter (fPOM) fraction, defined as the intermediate fraction between plant residues and humified organic matter; (2) an occluded particulate organic matter (oPOM) fraction that is contained within soil aggregates; and (3) a heavy mineral-bound organic matter (MOM) fraction, comprised of microbially transformed organic material tightly bound or sorbed to clay minerals. The fPOM fraction represents a major portion of labile SOC and consists of a heterogeneous mixture of recent crop residues and microbial residues in different stages of decomposition (Gregorich et al., 1994). The fPOM fraction is a key attribute of soil quality (Gregorich et al. 1994; Haynes 2005). It is unprotected by soil minerals and is therefore an easily mineralisable SOM fraction that has an important role in microbial activity, nutrient availability and formation of water-stable aggregates (Haynes 2005). The oPOM and specifically the MOM fractions represent the large background of stable SOC that contributes a major proportion to soil C sequestration in the medium to long term (Haynes 2005). Recalcitrant black C can also occur in any of the three isolated pools, especially in the fPOM fraction if the soils were subject to frequent burning (Leifeld et al. 2015).

Therefore, the objectives of this study were (1) to examine the long-term (10 years) effect of different grazed crop and pasture rotation systems on the soil C and N stocks and SOM functional pool fractions; (2) to determine the role of the belowground root biomass of the crop and pasture systems on the soil C and N content; and (3) to examine the relationship between the SOM fractions and soil quality parameters.

Materials and methods

Description of study site

Long-term field experiments investigating different pasture and crop rotation systems under no-till were initiated in 2002 at the Tygerhoek Research Farm of the Western Cape Department of Agriculture, near Riviersonderend, Overberg, Western Cape, South Africa. Prior to this trial, the site was under wheat monoculture and conventional tillage (mouldboard tillage). The dominant soil type at the study site is classified as a Leptic Cambisol Skeletic (IUSS Working Group WRB 2006), which is locally classified as a Glenrosa soil form (Soil Classification Working Group 1991). The soils are typically very shallow (30–40 cm deep), derived from weathered Bokkeveld shale, with a loamy texture and high content of coarse fragments. General soil characteristics are given in Table 1. The dominant clay minerals identified in the soil clay fraction using X-ray diffraction were kaolinite and illite. The Köppen-Geiger climate classification for this region is BSk (cool semi-arid climate). The long-term average annual rainfall is 450 mm, which predominantly falls in the winter months, and the long-term average annual temperature is 17.5 °C. In 2012, when soil sampling and yield data were collected, the average rainfall and temperature were 690 mm and 16.8 °C, respectively (ARC-ISCW 2013).

Most of the crops are planted in May and harvested in mid-October to November as the climatic conditions are suitable for grain production in the winter period. Six-year crop and pasture rotations are typically practised in the Overberg region.

The field trial consisted of a randomised complete design with three replications of each treatment. Each experimental plot was 20 m × 25 m. The treatments in this study included crop and pasture systems ranging from 100% pasture to 100% crops with the following plant species: lucerne (*Medicago sativa*); burr medic *(Medicago polimorpha*), clover *(Trifolium michelianum*), wheat (*Triticum aestivum*), canola (*Brassica napus*), lupin (*Lupinus luteus*) and barley (*Hordeum vulgare*). The treatments that were applied were: (1) perennial lucerne (100% perennial pasture), two crop–pasture systems; (2) medic/clover–medic/clover–wheat (MMW) (67% annual pasture, 33% crop); (3) medic/clover–medic/clover–wheat–wheat (MMWW) (50% annual pasture, 50% crop); and (4 and 5) 100% cash-crop cycle (continuous cropping) in two different phases, consisting of wheat–barley–canola–wheat–barley–lupin (WBCWBL1 and WBCWBL4). The numbers '1' and '4' in the 100% cash-crop cycle refers to the first and fourth crop planted in the cropping sequence, i.e. wheat planted directly after lupin and wheat planted directly after canola, respectively. The underlined crop (wheat) in the rotation code represents the crop that had been planted at the time of soil sampling (2012). The two WBWCWBL treatments were selected to see the immediate effect of wheat planted after lupin (legume) or canola on SOC fractions. Wheat was selected as the crop phase in each rotation as it is a common crop and the yields could be compared. Adjacent natural, undisturbed vegetated soil (500 m from the experimental site) covered with indigenous renosterveld fynbos, consisting of predominantly renoster bushes (*Dicerothamnus rhinocerotis*), was also sampled for comparison (Table 1). It was later discovered that the clay content of the undisturbed natural site was much lower than that of the cultivated sites (Table 1), which could negatively affect its C storage potential, thus it could not be used as a reference soil. However, it was decided to keep the natural veld treatment in the present study, as it was useful for comparing the distribution of C in the functional pools. Trial management protocols included N, phosphorus (P) and micro-element applications with agricultural lime applied every 3–4 years as necessary (if soil pH dropped below 5 in 1 M KCl) according to recommended management practices for the Overberg crop production region. Nitrogen application for wheat was adjusted based on the previous season's crop, with 40 kg N ha^{-1} after medic/clover, 50 kg N ha^{-1} after lupin, 60 kg N ha^{-1} after canola, and all treatments received 15–20 kg P ha^{-1}. Crops were chemically protected against weeds, diseases and insect pests, and harvested using standard farming machinery. The application of pest control measures differed yearly, but similar crops received similar applications. Planting was performed with a no-till Ausplow, fitted with knife-openers

Table 1: Soil pH, effective cation exchange capacity (ECEC), aggregate stability, respiration, bulk density and particle size distribution of pasture and crop treatments and natural vegetated soil at 5–10 cm depth. The SE is presented in parenthese (n = 3)

Treatment	pH (H_2O)	ECEC ($cmol_c$ kg^{-1})	Aggregate stability (%)	Soil respiration (g C m^{-2} d^{-1})	Bulk density (g cm^{-3})	Sand (%) (2.00–0.05 mm)	Silt (%) (0.05–0.002 mm)	Clay (%) (<0.002 mm)
Lucerne	6.87 (0.06)	8.7 (0.1)	43.0 (1.3)	1.09 (0.11)	1.437 (0.049)	37.2 (2.3)	39.4 (0.8)	23.5 (1.6)
MMW	6.90 (0.10)	9.1 (0.3)	48.2 (1.9)	1.30 (0.10)	1.485 (0.065)	46.1 (1.4)	32.5 (1.0)	21.4 (1.5)
MMWW	7.13 (0.08)	12.1 (0.6)	47.8 (1.1)	1.25 (0.05)	1.341 (0.034)	32.9 (2.7)	40.6 (1.2)	26.5 (1.6)
WBCWBL4	6.94 (0.20)	8.8 (0.5)	39.1 (1.6)	1.04 (0.04)	1.313 (0.024)	32.5 (1.8)	43.6 (0.8)	23.9 (1.0)
WBCWBL1	7.25 (0.09)	10.1 (0.2)	44.8 (1.2)	0.96 (0.09)	1.382 (0.051)	34.9 (2.2)	43.2 (1.5)	22.0 (1.7)
Natural	6.83 (0.17)	7.4 (0.8)	64.7 (5.5)	1.68 (0.12)	1.448 (0.079)	59.0 (3.1)	26.7 (1.3)	14.0 (1.5)

and presswheels, disturbing the top 10 cm of the soil. Medic/clover is suppressed in the years that wheat is planted, and in the following year it spontaneously regrows from the soil seed bank. Sheep were stocked on medic/clover pastures from May to November and then moved to the crop residues of the cropping systems for as long as the residues are of value to them, while the lucerne pastures were grazed on a rotational basis of one week every six weeks during the year. Stocking rates were the same in the lucerne and medic/clover pastures.

Soil and plant sampling

Soil samples were collected in June 2012, shortly after the first rains and the emergence of the wheat. Composite soil samples were taken at four depths (0–5, 5–10, 10–20 and 20–30 cm) at all sites. At each of the 18 plots (6 treatments × 3 replicates) approximately 25 cores (diameter 40 mm) per depth were taken. All soil cores were bulked (3.5 kg of soil), and thoroughly mixed with a soil splitter. The samples were air dried and sieved through a 2-mm sieve. Unsieved soil was also preserved for aggregate stability determination. The soda-lime method (Keith and Wong 2006) was used to determine the cumulative soil CO_2 respiration efflux of bare soil from the different treatments for a period of four weeks shortly after soil sampling had taken place.

The experimental design made it possible to collect plant residues (above- and belowground) for C and N determination of all the crop and pasture treatments directly after crop harvest (spring 2012) as there are replications for each phase in each of the rotation systems at the trial site. Representative above- and belowground residues were sampled at three plots for each crop. The medic/clover pasture was sampled compositely as it was difficult to distinguish between the individual plant species due to dense mixed planting. Root samples were taken from the four depths using a soil corer (diameter 40 mm). At each plot, a core was taken within a row, while the other two were taken in-between the rows and the samples were bulked together. Five representative subsamples were taken from each of the composite samples and the roots and coarse sand particles were separated from the fine sand particles, clay and silt using a gentle water stream through a 0.25 mm mesh sieve (Samson and Sinclair 1994; Crawford et al. 1997). The coarse sand particles and roots remaining on the sieve were separated using density fractionation. After cleaning the roots, they were oven-dried at 40 °C for 48 h and weighed to calculate root mass density (Singh et al. 2014).

Soil and plant characterisation

The soil total C and N contents, soil bulk density, and coarse fragment content and density were determined on all soil samples taken at all four depth increments. Dry combustion was used to determine total C and N using a EuroVector CNH elemental analyser (EuroVector, Milan, Italy). Soil bulk density (BD) was measured using the clod method (Grossman and Reinsch 2002), while coarse fragment density was measured using a pycnometer. Given the relatively high (24%–55%) and variable content of coarse fragments in the soil at the site, which was not a function of crop treatment, the soil BD was corrected for coarse fragment content, as it is <2 mm soil fraction where C and N is measured and stored in the soil. The BD of the <2 mm soil fraction was calculated as follows:

$$[\text{Soil BD (clod method)} - (\text{Coarse fragment fraction} \times \text{BD of coarse fragments})/(1- \text{coarse fragment fraction})].$$

The following formula was used to calculate soil C or N stocks per soil depth:

$$\text{Stocks (kg ha}^{-1}\text{ depth}^{-1}) = \text{Soil C or N (kg kg}^{-1}) \times <2 \text{ mm BD (kg m}^{-3}) \times 10\,000 \text{ m}^2 \times \text{depth (m)}$$

The respective C or N stocks per depth were then added to calculate the total soil C or N stocks in each treatment to a depth of 30 cm (total soil depth).

Although the soil pH was relatively neutral (Table 1), it was found to contain no free carbonates using a concentrated-HCl laboratory test, as no visible effervescence was observed. Therefore, the measured total C content was assumed to be equivalent to the organic C content. The 5–10 cm depth soil samples were used for the fractionation of total SOM into different functional pools and for soil properties (pH, Total C and N, cation exchange capacity, aggregate stability, particle size analysis). This depth increment was selected as the top 10 cm soil increment is believed to be most sensitive to changes due to crop rotation and no-till practices and avoids the highly variable 0–5 cm litter-rich soil layer. The 5–10 cm depth increment was also used by Freixo et al. (2002) and Alvaro-Fuentes et al. (2008) in their respective studies.

Soil pH was measured in distilled deionised water at a 1:2.5 soil to solution ratio. The effective cation exchange capacity (ECEC) of the soil samples was calculated from the sum of exchangeable basic cations extracted using 1 M

NH_4OAc (pH 7.0) and exchangeable acidity was extracted using 1 M KCl (Thomas 1982). The sand, silt and clay contents of the soil were determined using wet sieving and the pipette method (Gee and Bauder 1986). Aggregate stability of the aggregates (<0.25 mm) was determined using the wet sieving technique (Kemper and Rosenau 1986) using a Wet Sieve Apparatus (Eijkelkamp Agrisearch Equipment, Giesbeck, The Netherlands). Oven-dried crop residue samples were ground using a mortar and pestle to ensure a homogeneous sample for dry combustion C and N analysis using an EuroVector CNH elemental analyser.

Soil organic matter fractionation

The SOM functional pool fractionation method used was based on the physical density fractionation procedures described by Sohi et al. (2001) and Cerli et al. (2012). Three SOM fractions were isolated, namely the fPOM, oPOM and MOM fractions. Briefly, 5 g soil and 25 mL sodium iodide solution at a density of 1.6 g cm^{-3} were used. A sonicator (ultrasonic processor) (Qsonica Sonicators, Newton, CT, USA), fitted with a probe tip immersed to a depth of 15 mm in suspension, was used to disrupt the aggregates at an energy level of 200 J mL^{-1} and attain the intra-aggregate organic matter. The solid sample residue (MOM fraction) was dialysed in cellulose dialysis tubing with a molecular cut-off of approximately 14 000 Da (Sigma Aldrich, St Louis, MO, USA). All fractions were oven-dried at 40 °C for 72 h. A five-decimal digital micro-scale was used to determine the mass of each of the three isolated fractions, and then the C and N contents of each fraction were determined by dry combustion using an EuroVector CNH elemental analyser.

Statistical analysis

All results were expressed as an average of three replicates with standard error. Data were statistically analysed by analysis of variance using the Statistica 13 software package (StatSoft, Tulsa, OK, USA). Differences among means were separated by Fisher's least significant difference (LSD) test at the 0.05 probability level. Correlations between parameters were assessed using Pearson's correlation analysis at the 0.05 probability level.

Results and discussion

Soil carbon and crop root distribution with depth

The largest differences in soil total C content between the different cultivated treatments were observed in the top 0–10 cm of soil (Figure 1), emphasising the significance of the first few centimetres of the soil under no-till practices. The C content of the MMWW system at 0–5 and 5–10 cm was significantly higher compared with all other cultivated treatments (Figure 1). The 0–5 cm C content of the MMWW treatment did not differ statistically from the natural vegetated site (Figure 1). However, unlike the MMWW treatment, the natural site C content declined to the lowest C content of all sites at 5–10 and 10–20 cm depths (Figure 1). This dramatic change in SOC distribution at the natural site is likely due to the fact that the site has never been physically disturbed. The general decrease in SOC below 20 cm in the cultivated treatments can be attributed to aboveground crop residues that accumulate on the soil surface in no-till systems, and because most of the roots (67%) were typically concentrated in the 0–10 cm depth (Figure 2). Crop roots are considered a major source of C input in soil (Rasse et al. 2005; Cong et al. 2015), especially in no-till systems that are exposed to grazing, which results in lower aboveground inputs. Generally, the lucerne pasture had the highest root density throughout the soil profile, whereas barley had the lowest (Figure 2). At 5–10 cm depth, medic/clover (6.2 kg m^{-3}) and lucerne (7.3 kg m^{-3}) pastures had significantly higher root densities compared with those of the other crops (4.2–4.9 kg m^{-3}) (Figure 2). Lucerne has a deeper rooting system in comparison with annual species such as the medic/clover pastures used in this study (Hakl et al. 2011). Both lucerne and medic/clover have similar taproot systems with branching lateral roots. It is important to consider that the medic/clover pastures dieback completely in summer and then re-establish in winter from the soil seed bank, forming completely new roots again, unlike the perennial lucerne pasture. Therefore, annual C inputs from the medic/clover roots should be higher compared with lucerne roots, despite the higher root density of lucerne (Figure 2). Comparing the root densities

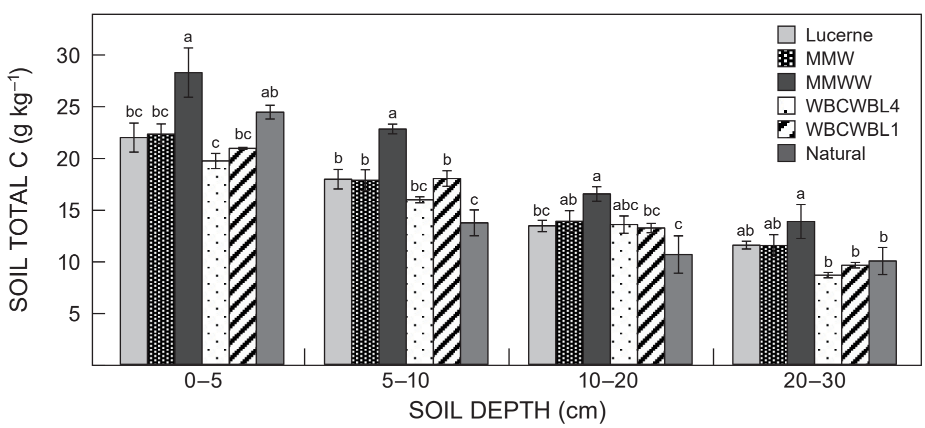

Figure 1: Depth distribution of carbon (C; g kg^{-1}) in the pasture and cropping treatments and natural vegetated site at 0–5, 5–10, 10–20 and 20–30 cm soil depth intervals. Error bars represent the SE ($n = 3$). The same lower-case letters above bars indicate lack of significant differences according to Fisher's LSD test ($P < 0.05$)

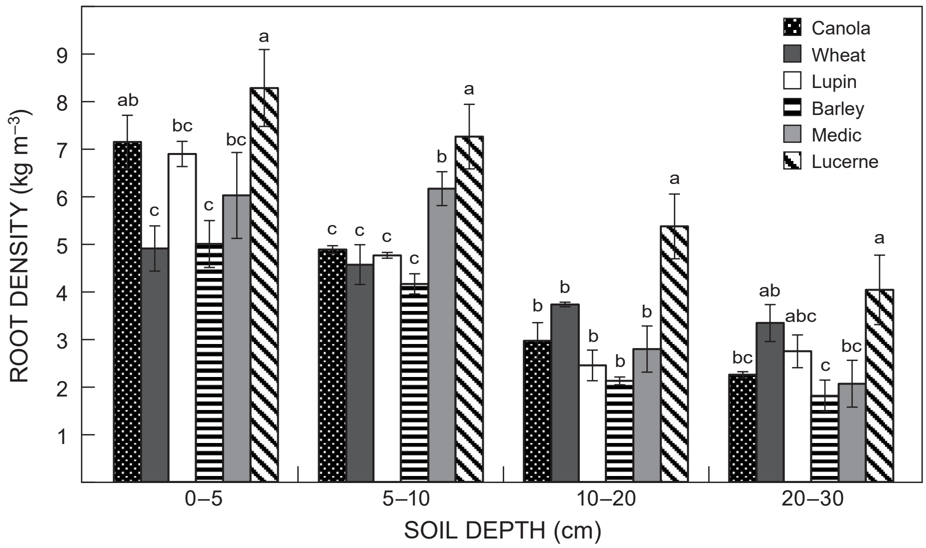

Figure 2: Depth distribution of the root density (kg m^{-3}) of each crop used in the pasture and cropping treatments in the 0–5, 5–10, 10–20 and 20–30 cm soil depth intervals. Error bars represent the SE (n = 3). The same lower-case letters above bars indicate lack of significant differences according to Fisher's LSD test ($P < 0.05$)

in the subsoil (10–20 and 20–30 cm), it can be seen that the wheat roots were the second-most dense compared with lucerne (Figure 2) and would also be subject to annual turnover, thus providing higher inputs in the subsoil.

Total soil organic carbon and nitrogen stocks

Higher total C and N stocks (0–30 cm) were observed in crop–pasture rotations containing medic/clover (70.2–74.9 Mg C ha^{-1} and 8.3–8.4 Mg N ha^{-1}), compared with perennial lucerne pasture (63.4 Mg C ha^{-1} and 7.7 Mg N ha^{-1}), continuous cropping (54.7–58.9 Mg C ha^{-1} and 6.3–6.7 Mg N ha^{-1}) or natural vegetated soil (60.5 Mg C ha^{-1} and 6.4 Mg N ha^{-1}) (Figure 3a and b). Carbon stocks in crop–pasture systems (MMWW and MMW) were significantly higher than those of all other systems, whereas N stocks were significantly higher than both continuous cropping systems or natural vegetated soil (Figure 3). These results show that crop–pasture treatments are more effective for C and N sequestration compared with perennial lucerne pasture and continuous cropping under Overberg soil and environmental conditions. Similarly, Chan et al. (2011) demonstrated in a long-term (23 years) study that inclusion of a mowed clover (*Trifolium subterraneum*) pasture phase in no-till wheat production in a year-round rainfall region of Australia significantly enhanced soil C stocks (48.0 t ha^{-1}, 0–30 cm) compared with no-till cropping-only system with wheat and lupins (40.5 t ha^{-1}, 0–30 cm). The soils in the Chan et al. (2011) study were much deeper (over 1 m depth) compared with the shallow soils (30 cm) in the present study, thus root growth was more concentrated to 0–30 cm depth in the present study compared with that in the Chan et al. (2011) study.

The higher C stocks observed in the crop–pasture systems in the present study are mainly attributed to the higher annual inputs from the medic/clover roots in the top 10 cm and wheat roots below 10 cm (Figure 2), as well as the lower extent of physical soil disturbance due to annual

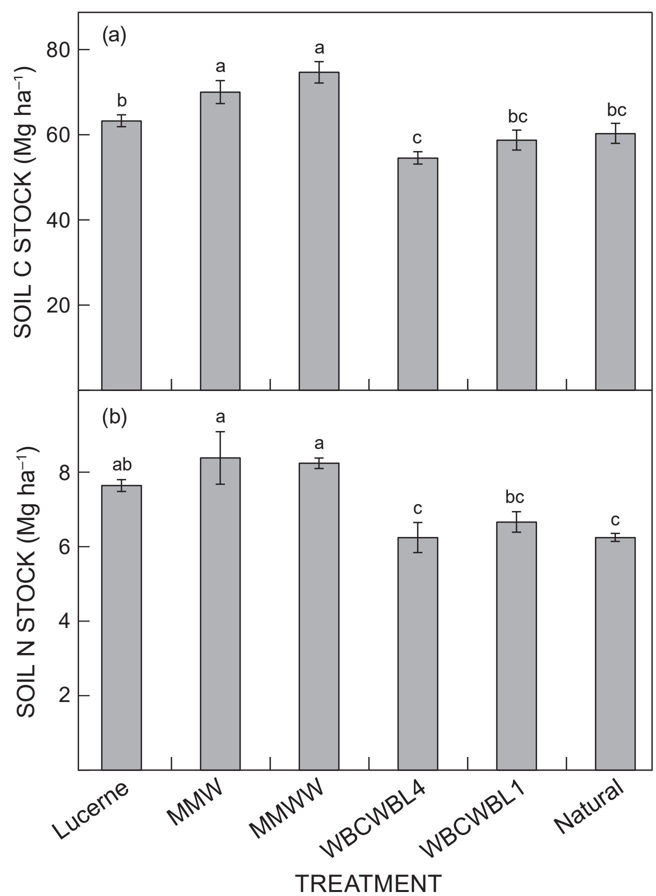

Figure 3: Total soil (a) carbon (C) and (b) nitrogen (N) stocks (0–30 cm depth) in the pasture and cropping treatments and natural vegetated soil. Error bars represent the SE (n =3). The same lower-case letters above bars indicate lack of significant differences according to Fisher's LSD test ($P < 0.05$)

mechanical planting, as previously discussed. Chan et al. (2011) also attributed the significantly higher C stocks of the no-till clover–wheat system compared with a wheat–lupin system to enhanced root inputs of dense clover pasture. Given the wider C:N ratio of wheat above- and belowground residues (Table 2), it is also likely that they decompose more slowly and remain in the soil for longer compared with the medic/clover residues (Brady and Weil 2014). The higher N stocks in the medic/clover and lucerne pastures are attributed to the significantly higher N content of the legume residues compared with that of other crops (Table 2). Carbon stocks obtained in the continuous cropping systems also compared well with those of Sombrero and Benito (2010) (53 Mg C ha^{-1}) under similar management (no-till and cereal cropping), clay content, soil depth and climatic conditions. The significantly lower C and N stocks of the natural site compared with the medic/clover rotations could be due to the lower residue inputs of the perennial fynbos vegetation at the site, as well as the lower clay content of the soil (Table 1), which would negatively affect soil C storage potential (Brady and Weil 2014).

Soil organic matter carbon and nitrogen functional pools

The percentage of C recovered in the functional pool fractions ranged between 85% and 99% of total SOC with an average recovery of 93% (Table 3), similar to previous studies that employed this method (Freixo et al. 2002; John et al. 2005). Under-recovery of soil total C is mainly ascribed to soil material loss (during the density fractionation procedure) or due to experimental error in soil total C determination. In all treatments, the C:N ratio of the MOM fraction was significantly the lowest compared with the other fractions and ranged between 8:1 and 9:1 (Figure 4), indicating the ability of clay minerals to adsorb and stabilise microbial products (Golchin et al. 1994). The C:N ratio of the fPOM fraction was significantly higher in the cropping treatments (21:1–22:1) and natural vegetated soil (22:1), whereas it was significantly lower in the treatments containing legume pastures (13:1–15:1) (Figure 4), corresponding to the higher N content of lucerne and medic/clover residues (Table 2). The higher C:N ratio of the fPOM fraction signifies the dominance of more labile, less decomposed plant components (Gregorich et al. 2006). The C:N ratios of the oPOM fraction were generally lower than those observed for the fPOM fraction, except for the undisturbed lucerne pasture and natural soil (Figure 4). The general decline in C:N ratio observed from the fPOM to the oPOM fractions suggests a stronger contribution of microbial biomass to the oPOM fraction as microbial products are rich in N (Brady and Weil 2014). The decreasing C:N ratio in the order fPOM > oPOM > MOM also indicates an increasing degree of degradation and humification of the organic matter (Baisden et al. 2002; John et al. 2005).

The C isolated in the different fractions ranged between 0.9–1.74, 0.07–0.31 and 11–18.7 g C kg^{-1} for the fPOM, oPOM and MOM fractions, respectively, at the 5–10 cm soil depth (Figure 5). The MMWW treatment (1.74 g C kg^{-1}) and natural vegetated soil (1.69 g C kg^{-1}) contained significantly higher fPOM-C than the lucerne (1.16 g C kg^{-1}) or WBCWBL4 and WBCWBL1 treatments (1.00 and 0.90 g C kg^{-1}, respectively) (Figure 5a). The MMW treatment (1.37 g C kg^{-1}) also contained much higher fPOM-C compared with the continuous cropping treatments (Figure 5a). According to Haynes (2005), increases in particulate organic matter usually reflect greater above- and belowground inputs, which is then expected to be translated into higher SOM contents in the long term. Thus the higher fPOM-C of the crop–pasture systems would

Table 2: Carbon (C) and nitrogen (N) contents and C:N ratio of the above- and belowground biomass of each crop used in the different pasture and crop rotation systems. The same superscript lower-case letters indicate lack of significant differences according to Fisher's LSD test ($P < 0.05$)

Crop	Aboveground			Belowground		
	C (%)	N (%)	C:N	C (%)	N (%)	C:N
Canola	42.2^{ab}	0.3^{c}	162^{a}	42.8^{a}	0.4^{b}	113^{a}
Wheat	42.9^{ab}	0.3^{c}	165^{a}	39.0^{a}	0.8^{b}	70^{b}
Barley	41.0^{b}	0.6^{c}	73^{b}	38.5^{a}	0.8^{b}	58^{b}
Lupin	42.9^{ab}	0.6^{c}	71^{b}	42.0^{a}	1.0^{b}	49^{bc}
Medic/clover	42.9^{ab}	2.5^{b}	19^{c}	40.6^{a}	1.8^{a}	26^{cd}
Lucerne	43.7^{a}	3.9^{a}	11^{c}	41.9^{a}	2.1^{a}	20^{d}

Table 3: Average percentage carbon (C) recovered in density fractionation procedure of soil total C in pasture and cropping treatments and natural vegetated site at 5–10 cm depth. The SE is presented in parentheses ($n = 3$)

Treatment	C recovered of total soil C (%)
Lucerne	96.6 (3.0)
MMW	88.0 (2.7)
MMWW	90.4 (2.7)
WBCWBL4	99.2 (2.7)
WBCWBL1	84.5 (2.6)
Natural	95.0 (4.0)

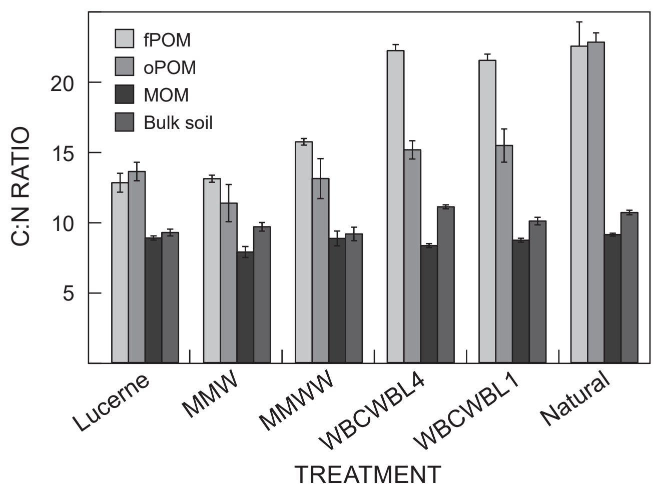

Figure 4: The carbon:nitrogen (C:N) ratio of the free particulate organic matter (fPOM), occluded particulate organic matter (oPOM) and mineral-bound organic matter (MOM) fractions and bulk soil (5–10 cm depth) of the pasture and crop treatments and natural vegetated soil. Error bars represent the SE ($n = 3$)

likely have contributed to the highest total SOC content in these treatments in the long term. The higher fPOM-C in the crop–pasture systems at 5–10 cm is mainly attributed to higher annual belowground inputs through medic/clover roots (Figure 2), as aboveground inputs were somewhat limited by grazing. The lucerne pasture residues had the lowest C:N ratio (Table 2), which would enhance the residue mineralisation rate, whereas the wheat–medic/clover rotations also include high C:N crop residues (wheat) besides the low C:N legume residues (medic/clover), which would contribute to slower residue decomposition rates. Furthermore, each time a crop (wheat, canola, barley or lupin) is planted using the no-till Ausplow planter, the top 10 cm of the soil is physically disturbed, enhancing mineralisation of the more labile fPOM fraction and disrupting soil aggregates.

The fPOM-N and oPOM-N contents (Figure 6a) followed a similar trend to the C fraction results. However, the fPOM-N was significantly higher in the MMW and MMWW (0.111 g kg^{-1} and 0.107 g kg^{-1}, respectively) and lucerne (0.092 g kg^{-1}) treatments compared with the WBCWBL4 and WBCWBL1 (0.045 and 0.042 g kg^{-1}, respectively) treatments (Figure 6a), which is attributed to the higher N content of the legume residues (Table 2).

The oPOM-C content of the natural vegetated soil was significantly higher (0.31 g C kg^{-1}) compared with the cultivated treatments (Figure 5a) and corresponded with the highest aggregate stability (Table 1). Among the cultivated treatments, the crop–pasture rotations (MMW and MMWW) contained significantly higher oPOM-C content (0.15–0.20 g kg^{-1}) than the lucerne (0.07 g C kg^{-1}) and WBCWBL4 (0.07 g C kg^{-1}) treatments (Figure 4a). The oPOM-N contents in the crop–pasture rotations (MMW and MMWW) were significantly higher than the lucerne pasture or cropping systems (Figure 6a), following a similar trend to the oPOM-C results (Figure 5a). These oPOM-C results can also be attributed to the extent of physical soil disturbance of the different treatments, as well as the respective fPOM-C and -N contents, which would encourage aggregation by stimulating microbial decomposition and the production of microbial biochemical adhesive agents.

The MOM-C in the MMWW treatment (18.7 g C kg^{-1}) was significantly higher than the MMW (14.1 g C kg^{-1}), WBCWBL1 (14.2 g C kg^{-1}) and natural treatments (11.0 g C kg^{-1}) (Figure 5b). The lucerne and WBCWBL4 treatments contained 16.0 and 14.7 g C kg^{-1}, respectively (Figure 5b). There were fewer statistically significant differences in MOM-N means between treatments (Figure 6b). Only the natural vegetated soil had significantly lower MOM-N compared with the cultivated sites. The MOM-C forms the backbone of stable SOC and is important for long-term C sequestration (Freixo et al. 2002; John et al. 2005). It is

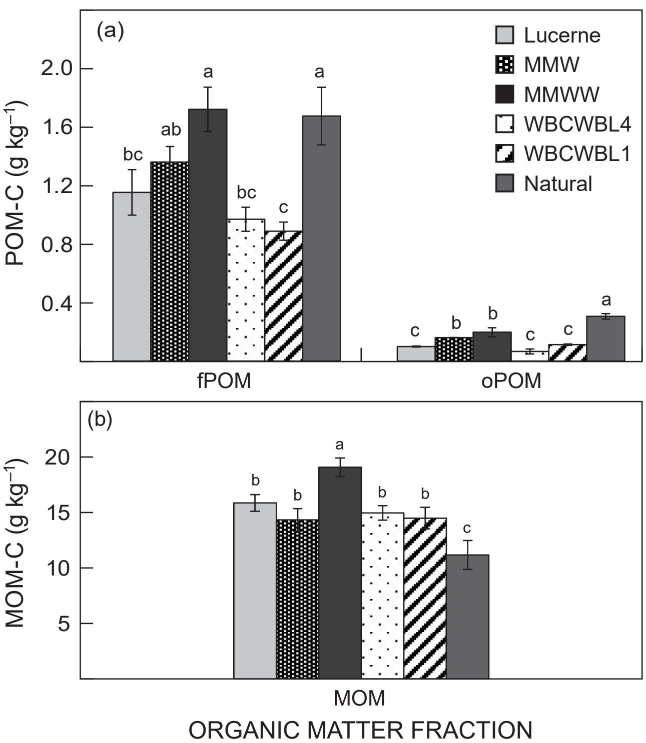

Figure 5: The soil carbon (C) content in the (a) free particulate organic matter (fPOM) and occluded particulate organic matter (oPOM) and (b) mineral-bound organic matter (MOM) fractions (5–10 cm depth) of the pasture and crop treatments and natural vegetated soil. Error bars represent the SE (n = 3). The same lower-case letters above bars indicate lack of significant differences according to Fisher's LSD test ($P < 0.05$)

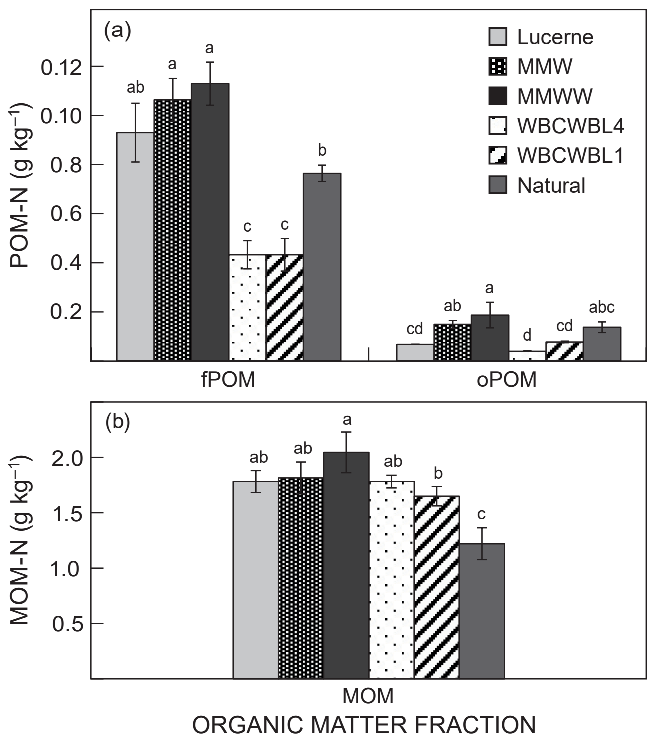

Figure 6: The soil nitrogen (N) content in the (a) free particulate organic matter (fPOM) and occluded particulate organic matter (oPOM) and (b) mineral-bound organic matter (MOM) fractions (5–10 cm depth) of the pasture and crop treatments and natural vegetated soil. Error bars represent the SE (n = 3). The same lower-case letters above bars indicate lack of significant differences according to Fisher's LSD test ($P < 0.05$)

less affected by management practices than the fPOM and oPOM fractions and changes will only occur in the long term because the turnover rates are much slower. Clay content plays a very important role in the mineral-C as sorptive organic-mineral interactions are a very important stabilising mechanism (Baldock and Skjemstad 2000); this was confirmed by a strong positive correlation (r = 0.86, $p < 0.05$) between clay content and MOM-C across all sites. In the cultivated treatments at 5–10 cm depth, the majority of the SOC (90%–93%) was associated with the MOM fraction, whereas 6%–9% and 0.4%–1.0% of SOC was associated with the fPOM and oPOM fractions, respectively. The natural vegetated site contained relatively less C in the MOM fraction (85%) than the cultivated treatments, which could be attributed to the lower soil clay content (Table 1).

Soil quality and wheat yields and quality

The SOM functional pools contribute differently to various soil functions and can be seen as fine indicators of soil quality (Baldock and Skjemstad 1999; Haynes 2005). Soil respiration was significantly positively correlated with fPOM-C for all cultivated treatments (r = 0.86, $p < 0.05$) (Figure 7a). This is consistent with the findings of Janzen et al. (1992) signifying that the fPOM fraction is a useful indicator of labile SOC activity. The oPOM fraction correlated most strongly with aggregate stability of the soils (r = 0.89, $p < 0.05$) (Figure 7b), an important measure of soil quality and resistance to erosion (Haynes 2005). The MOM-C fraction correlated most strongly with the effective cation exchange capacity (ECEC) of the soils (r = 0.74, $p < 0.05$) (Figure 6c). The contribution of humus to ECEC is critical in these soils dominated with low-activity clay minerals. Non-significant weak correlations were observed between ECEC and the fPOM-C and oPOM-C fractions, thus confirming the view of Krull et al. (2004) that each pool contributes differently to various soil functions.

In 2012, the wheat yield of the MMWW rotation system (5 955 kg ha^{-1}) was, on average, 37% higher than the yields obtained in the WBCWBL4 (4 300 kg ha^{-1}) and WBCWBL1 (4 400 kg ha^{-1}) rotation systems. The MMW rotation produced the second-highest yield of 4 900 kg ha^{-1}. The medic/clover systems achieved the highest wheat yields, despite the fact that the wheat in these rotations received 10–20 kg N ha^{-1} less mineral N fertiliser compared with the cropping systems. The protein content of the wheat in the crop–pasture rotations (12.6%–13.2%) was also higher compared with those of the continuous cropping systems (10.3%–10.6%). Positive legume rotation effects on subsequent cereal yields have also been reported by Burle et al. (1997). The higher wheat yield and quality obtained in the medic/clover–wheat rotation systems can be attributed to the higher total C and N stocks (Figure 3) and also, importantly, the higher N content in the fPOM fraction (Figures 4 and 6). The crop–legume pasture systems contained the highest fPOM and oPOM contents among the cultivated systems (Figure 5), which also positively correlates with two critical soil quality parameters, soil respiration and aggregate stability (Figure 7). According to García-Préchac et al. (2004), better soil quality is one of the main reasons for higher crop yields in crop–legume pasture rotations compared with continuous cropping systems.

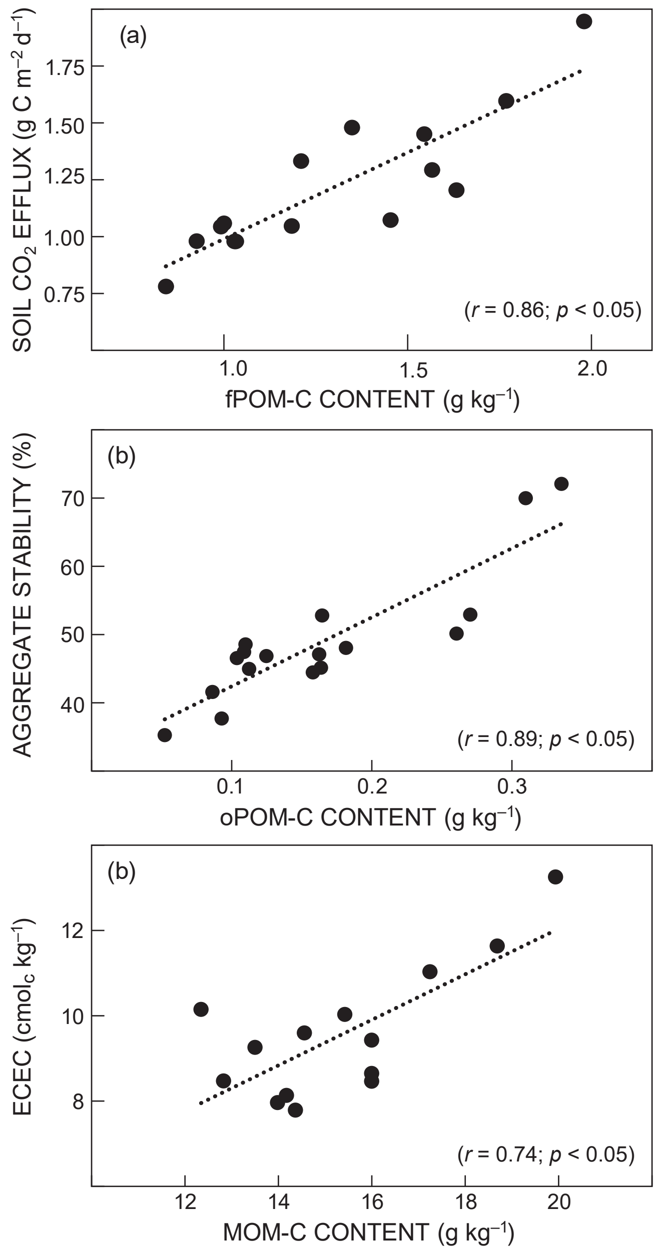

Figure 7: Relationships between soil organic matter functional pools and soil quality indicators. (a) Free particulate organic matter carbon content (fPOM-C) and soil CO_2 efflux, (b) occluded particulate organic matter carbon content (oPOM-C) and aggregate stability, and (c) mineral-bound organic matter carbon content (MOM-C) and effective cation exchange capacity (ECEC). Pearson correlations are shown

Conclusions

After 10 years, grazed no-till crop–pasture rotation systems containing wheat and medic/clover resulted in significantly higher soil C stocks (70.2–75.0 Mg ha^{-1}) compared with no-till continuous crop-only rotation systems (54.7–58.9 Mg ha^{-1}) and perennial lucerne pastures (63.4 Mg ha^{-1}). Furthermore, among all the studied systems, the crop–pasture rotation systems contained the highest average N stocks, as well as higher fPOM and oPOM C and N contents. This is attributed to both the higher annual belowground C inputs of the medic/clover and wheat roots, and the slightly wider C:N ratio of the root inputs compared with the perennial lucerne pasture. The no-till continuous crop-only rotation systems had the lowest C stocks overall, which can be attributed to the greater extent of soil disturbance in the 0–10 cm soil depth due to annual mechanical planting and lower belowground C inputs. Significant positive correlations were observed between C functional pool fractions and soil quality parameters (respiration, ECEC and aggregate stability) and wheat yields. The results of this study demonstrate the long-term beneficial effect of the medic/clover pasture and wheat rotations in enhancing soil quality in the Overberg grain production region.

Geolocation information

Tygerhoek Research Farm: 34°09′32″ S, 19°54′30″ E.

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Disclosure statement

The authors declare that they have no conflicts of interest.

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