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ORIGINAL ARTICLE

Changes in soil organic matter indices following 32 years of different wheat production management practices in semi-arid South Africa

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Abstract Soil organic matter (SOM) degradation is common in semi-arid regions due to frequent and intensive cultivation, removal of crop residues after harvesting and warmer environmental conditions. Therefore, we evaluated the effects of long-term wheat production management practices on organic matter content of a Plinthosol in semi-arid South Africa. The treatments included two methods of straw management (unburned and burned), three methods of tillage (no-tillage, stubble mulch and ploughing) and two methods of weeding (chemical and mechanical). Soil samples were collected in 2010 at various depths and analysed for soil organic carbon (SOC), soil total nitrogen (STN) and soil total sulfur (STS) as organic matter indices. Treatments where straw was not burned had greater STN and STS, but lower SOC levels than those where straw was burned. No-tillage had higher SOC levels than the stubble mulch and ploughing treatments only in the 0–50 mm soil layer. Below 100 mm soil depth, higher SOC levels were recorded in the ploughed plots. No-tillage and stubble mulch enhanced STN throughout the soil profile compared to ploughing. Ploughing and stubble mulch treatments had greater STS levels than no-tillage treatments in the upper 250 mm soil layer, and STS in the 0–450 mm soil layer was higher in mechanically weeded plots than in chemically weeded plots. Treatment combinations also showed some significant interactions on these indices, but lack of consistency made it difficult to single out the combination that was superior to others. However, to maintain or improve SOM of this Plinthosol priority should be given to no-tillage and stubble mulch management practices. Wheat grain yields over the 32 years trial period were significantly influenced by straw management and tillage methods, but not by weeding methods.

Keywords Conservation tillage · Conventional tillage · Soil organic carbon · Soil total nitrogen · Soil total sulfur

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Introduction

Soils in the arid and semi-arid regions are vulnerable to organic matter loss, especially when conventional tillage is practised regularly (Mills and Fey 2003; Kotzé and Du Preez 2007). More than 30 % reduction in soil organic C (SOC) with two decades of conventional tillage has been reported (Kotzé and Du Preez 2007). Warm conditions in combination with crop residue removal probably also contribute to SOC decline. South African soils are inherently low in SOC, ranging from <0.5 % to little more than 2 % (Du Preez et al. 2011a). Ross (1993) also pointed out that of 22–23 % global C in the tropical agroecosystems, only 2–3 % exists in the soil, which is likely to decline further if soil is continuously cultivated. Chen et al. (2009) have proposed that SOM can be maintained or improved in cropped landscapes by both increasing organic matter inputs and decreasing SOM loss and decomposition.

Conservation practices improve SOM, which plays a significant role in soil and water conservation, nutrient retention and provides considerable buffer capacity to the soil (Lal 2005; Kotzé and Du Preez 2007). According to Gattinger et al. (2011), these benefits are considered as a basis for improving food production and security in developing countries. Accumulation of crop residues near the soil surface coupled with minimal soil disturbance under these management practices slows down the rate of residue decomposition, and thereby reduces organic matter losses when compared to conventional tillage. Lemke et al. (2010) and Dalal et al. (2011) on the other hand suggest that, without N fertilizer in particular, no-tillage cannot improve SOM. Although continuous application of N fertilizers may lead to deleterious effects on the soil (e.g. Lemke et al. 2010), fertilization enhances plant biomass production, and thus organic matter inputs (Lemke et al. 2010; Dalal et al. 2011). Emerging evidence has shown that besides their beneficial effects on soil fertility, conservation tillage systems can be regarded as an essential tool to sequester C and mitigate emissions of greenhouse gases. However, Gattinger et al. (2011) suggest that reduced energy use is the principal way that conservation tillage reduces emissions of greenhouse gases. Even so, expensive inputs and implements still counterbalance the benefits of conservation practices. The use of chemical inputs (fertilizers to counteract microbial immobilization of nutrients and herbicides to control weeds) is not as widely practiced, or even possible, in developing countries compared to developed countries due to escalating prices, low incomes and limited credit availability to most farmers. As a result these inputs are rarely applied at recommended rates (Barnard and Du Preez 2004; Bakht et al. 2009). Yadvinder-Singh et al. (2005) however, highlight that immobilization of N in the surface-managed residues can transform soil N into slowly available forms, which may subsequently act as slow-release fertilizers. This enhances the N supplying capacity of soils as well as N use efficiency, and therefore application of N fertilizers could be unnecessary, or could be reduced (Yadvinder-Singh et al. 2005; Van Den Bossche et al. 2009). Subsequent crop growth can ultimately benefit due to N accumulation near the root zone (Yadvinder-Singh et al. 2005).

Similarly to C and N, most of soil sulfur (S) is in organic form. However, despite the importance of this nutrient in growth and physiological functioning of plants, S has received relatively little attention for many years because of its presence in common fertilizers and atmospheric deposits (Scherer 2001; Itanna 2005; Eriksen 2009). However, with the reduction in S in fertilizers over the last two to three decades (Eriksen 2009) S deficiency has become more widespread and a threat to crop production. Yadvinder-Singh et al. (2005) stated that the decreasing use of organic manures, disposal (burning or removal) of crop residues after harvesting and sulfate leaching are also the major precursors to S deficiency in agricultural soils. Residue incorporation into the soil can retard losses of S due to leaching (Yadvinder-Singh et al. 2005), and maintain S fertility of soils since crop residues contain appreciable quantities of S (Itanna 2005). However, the incorporation of crop residues by tillage may have only short-term beneficial effects on soil S, because of the accelerated S mineralization following tillage (Houx et al. 2011). In general, a decline in SOM due to intensive cultivation would rapidly offset S reserves in soils (Itanna 2005; Du Preez et al. 2011b).

Despite the potential beneficial effects of reduced or no-tillage combined with residue retention, substantial accumulation of crop residues on the soil surface can hinder planting operations and seedling establishment, harbour pests and diseases and increase weed infestations (Kumar and Goh 2002; Mandal et al. 2004; Yadvinder-Singh et al. 2005; Bhupinderpal-Singh and Rengel 2007) and so farmers may opt to burn or remove crop residues after harvesting. However, burning or removing crop residues destroys the residue layer at the soil surface and reduces the amount of organic materials expected to recharge pools of SOM (Chan and Heenan 2005).

Stubble burning may give short-term N supply benefits to the succeeding crop, but a long-term negative impact on overall N fertility and soil quality (Yadvinder-Singh et al. 2005). Residue burning directly and indirectly reduces microbial activity and diversity, thereby reducing microbial immobilization of N and S, resulting in short-term availability of these nutrients (Bhupinderpal-Singh and Rengel 2007). Conversely, large quantities of C, N and S from aboveground plant biomass are lost during and after burning (Sharma and Mishra 2001; Heard et al. 2006). Eventually only small amounts are returned to the soil as ash, which can still be lost mostly through leaching (Menzies and Gillman 2003). Kumar and Goh (2002) therefore concluded that straw burning cannot be recommended as an option to farmers due to its deleterious effects on soil N. Chan and Heenan (2005) also pointed out that even though the negative impact of straw burning on SOC was relatively smaller than that of tillage, stubble burning has a potential for continual loss of SOC, and possibly soil total N (STN) and soil total S (STS). Therefore farmers who continuously dispose of crop residues after harvesting need demonstration of the benefits of recycled crop residues on SOM levels and ultimately on crop productivity (Bakht et al. 2009).

Studies on the influence of different residue management practices on soil fertility of a Plinthosol have been conducted in a long-term wheat trial at the Agricultural Research Council (ARC) Small Grain Institute near Bethlehem in the Eastern Free State, South Africa since 1979. Although the treatments, particularly conservation practices, were expected to have beneficial effects on soil fertility, about 31 % of STN and 38 % of SOC were lost from the cultivated area in the first 10 years compared to the native pasture (Wiltshire and Du Preez 1993). After 20 years of the trial higher SOC and lower STN were recorded in the burned rather than unburned treatments (Kotzé and Du Preez 2007). In other studies elsewhere it has been shown that since changes in soil fertility and crop yields may only be evident after several years (10 years or more), long-term studies are required in order to develop sound management systems (Yadvinder-Singh et al. 2005; Bhupinderpal-Singh and Rengel 2007; Govaerts et al. 2009). Govaerts et al. (2009) also raised what seems to be a worldwide concern that despite the benefits of conservation practices, adaptation rates of these practices by farmers are slow. In the past, conventional tillage was the common practice among the wheat producers in South Africa. However, according to Derpsch and Friedrich (2009), conservation practices seemed to gain popularity in South Africa since the 2005 World Congress on Conservation Agriculture that was held in Nairobi. From their report it is obvious that lack of proper communication on the benefits of conservation agriculture between researchers and extension officers or farmers in South Africa resulted in the slow adaptation rates, and they believe that great efforts should be made to propagate these management practices and their benefits to farmers. It is against this backdrop that this study was conducted to further evaluate the effects of different wheat production management practices on organic matter content of this semi-arid Plinthosol after 32 years have elapsed.

Materials and methods

A trial was established in 1979 at the ARC-Small Grain Institute (28°9′S, 28°17′E; 1,680 m above sea level) near Bethlehem in the Eastern Free State of South Africa to study the effects of some wheat management practices on soil fertility and crop productivity. Prior to acquisition of the site by the institute it was conventionally tilled for at least 20 years, but other management details are unknown. The mean annual rainfall in this area is 743 mm and the mean annual class-A pan evaporation is 1,815 mm, resulting in a mean annual aridity index of 0.41. Most of the rain (82 %) falls from October to March, with mean daily temperatures ranging from 7.1 °C in July to 20.3 °C in January.

According to the Land Type Survey Staff (2001), the trial is on land type Ca6n that occupies 420,000 ha. This land type is defined as a plinthic catena which, in upland positions, has margalitic and/or duplex soils derived from Beaufort mudstone, shale, sandstone and grit, with dolerite sills in places. The trial is laid out on a terrain unit 3 with a 2–3 % north facing slope. According to the USDA system, the soil would fall under the great group Plinthustalfs (Soil Survey Staff 1987). This Plinthosol (FAO 1978) consists of three diagnostic horizons: an orthic Ap (0–300 mm), yellow brown apedal B1 (300–650 mm) and soft plinthic B2 (>650 mm), containing 18, 23, and 36 % clay, respectively. The parent material comprises a mixed deposit of aeolian and colluvial nature on shale that increases with depth from 750 to 900 mm.

The experiment is laid out across a north-facing slope using a randomized complete block design with three blocks serving as replicates. Each block comprises 36 field treatments: two straw management treatments (burned and unburned), three tillage methods (ploughing, stubble mulch and no-tillage), two weed control methods (mechanical and chemical) and three levels of nitrogen fertilization in a factorial arrangement. Nitrogen levels were 20, 30, and 40 kg N ha^{-1} until 2002, and thereafter 30, 40 and 60 kg N ha^{-1}. For purposes of comparison with the previous studies, soil samples were taken, as in the past, only from the intermediate N level plots. This intermediate N rate, both before and after 2002, reflects common farmer practice in this region. Plots are 6 m × 30 m with 10 m borders and are cropped annually with winter wheat (*Triticum aestivum* L.) without any rotation or replacement with a summer crop. However, in 1990, 1991 and 2010, oats (*Avena sativa* L.) was used as a substitute crop, as a way to reduce soil-borne diseases (Take-all, *Gaeumannomyces graminis*) that occurred in some treatments. A fallow period of 5 months is maintained in this trial to restore soil water between harvesting and seeding, during which most of the rainfall events are expected.

Immediately after harvesting in December, wheat straw in the relevant no-tilled, mulched and ploughed treatments is burned or left unburned. In the ploughed treatments, just after burning a two-way offset disc is used to incorporate either the unburned wheat straw or the wheat straw ashes to 150 mm depth, followed by mouldboard ploughing to a depth of 250 mm in February when the soil is sufficiently moist and easy to work. The stubble mulch treatments was not disked, but cut at 100–150 mm using a v-blade and then ripped with a 50 mm width chisel plough at 300 mm spacing, to the same depth and at the same time as the ploughed treatments. The no-tilled treatments are not ploughed.

Weeding is done once in the relevant treatments when needed the first time, generally in March. This was done either by a mechanical cultivator (rodweeder or v-blade depending on the soil water level until 2002, after which a tine tiller was used) or by spraying non-selective herbicides (initially only Roundup with 360 g a.i. l^{-1} was used, later on it was alternated with Paraquat with 200 g a.i. l^{-1} to reduce chances of herbicide resistance developing) at recommended rates.

All the treatment plots were slightly disturbed with a combined seeder-fertilizer drill used for sowing the wheat seed together with the premixed fertilizer. Since 2003 a DBS no-tillage planter was used which made it unnecessary to premix the fertilizer by hand. Application rates of this planter are computer-controlled, and separate N and phosphorus (P) sources are mixed automatically.

Until 2002 a 3:2:0(25) NPK + 0.75 % Zn fertilizer blend was applied at a rate that results in N, P and Zn applications of 20, 13 and 1 kg ha^{-1}, respectively. Limestone ammonium nitrate (28 % N) was thoroughly mixed with this fertilizer blend and applied to supplement the N levels to 30 and 40 kg ha^{-1} in the relevant treatments. From 2003 limestone ammonium nitrate and single superphosphate (10.5 % P) were used as fertilizer sources with the DBS no-tillage planter. The planter was set to accurately apply 20, 40 and 60 kg N ha^{-1} and a constant application of 12.5 kg P ha^{-1}. Note must be taken that from 2003 about 13 kg S ha^{-1} was applied with single superphosphate which was not necessarily the case before, since the concentration of S in the fertilizer blend is unknown.

From the start of the experiment until 2004 the cultivar Betta was planted. As Betta has become obsolete a newer cultivar, Elands, was therefore introduced in 2005.

For comparison purposes, the same sampling procedure was adhered to as with the previous sampling events during the lifespan of this trial. However, there was only a difference in the sampling depth and month. Thus in 1989/1990 soil sampling was done in May at 0–50, 50–250, 250–450 and 450–650 mm intervals, while in 1999 and 2010 soil samples were taken in June at 0–50, 50–100, 100–150, 150–250, 250–350 and 350–450 mm intervals. To serve as reference, composite soil samples were collected at the headlands covered with perennial grass (see mean SOM index values in Table 1) outside the trial with a 70 mm diameter auger. Subsamples were collected at two sites 50 m apart, 100 m from the highest, and at two sites 50 m apart, 100 m from the lowest corner of the trial and mixed thoroughly. Three auger cores (70 mm diameter) were taken from the centre-line of each treatment plot and mixed thoroughly. To allow for maximum soil settling after the last cultivation, sampling was done after the rainy season just before planting in June 2010, similarly to the previous sampling events. The samples were dried at room temperature and sieved

Table 1 Mean values of SOM indices in the headlands covered with perennial grass outside the trial

Depth (mm)	Organic C (%)	Total N (%)	Total S (%)
0–50	1.54	0.13	0.02
50–100	1.23	0.11	0.02
100–150	0.81	0.07	0.02
150–250	0.72	0.06	0.02
250–350	0.69	0.06	0.03
350–450	0.68	0.06	0.04

through a 2 mm sieve and then stored for analysis. Chemical analyses were done in triplicate according to standard methods (The Non-Affiliated Soil Analysis Work Committee 1990). The analyses that were carried out to determine selected SOM indices were SOC (Walkley–Black method), STN (Kjeldahl method) and STS (Leco combustion).

Only concentration values of SOM indices will be dealt with since bulk density was measured neither in the previous studies nor the current study; therefore, calculations of the actual contents were impossible. In addition, we believe that the latter would show similar trends as with the concentrations since at the time of sampling bulk density should almost be similar. For these South African soils (also sampled in June/July), a difference in bulk density of less than 4 % between ploughed and native land was reported in two different studies (Lobe et al. 2001; Preger et al. 2010).

Grain yield data of wheat representing the entire trial period of 32 years (1979–2010) were supplied by the ARC-Small Grain Institute for use as a supplement to the soil data. These data are actually only for 26 years because in some seasons no grain yields were recorded due to oat being planted (1990, 1991 and 2010) or severe drought (1980, 1981 and 2004). The yield data were divided into three periods (1979–1990 with 9 years data, 1991–2000 with 9 years data, and 2001–2010 with 8 years data) to correspond with the intervals at which SOM indices were measured.

Analyses of variance were computed for every soil layer using measurement means of the stated soil indices. The yield data for the three periods corresponding with the sampling events and the entire period (1979–2010) were also subjected to analyses of variance. All analyses of variance were computed at a 95 % confidence level using NCSS software package of Hintze (1997). This software was also used to compare treatment means with Tukey's honestly significant difference post hoc test (HSD_T) at a 95 % confidence level.

Results and discussion

Soil organic C

Main effects

Soil organic C as an index of organic matter was influenced by tillage more than either straw management or weed control methods. Although there were no significant differences in any of the soil layers, plots where residues were burned had slightly higher SOC than plots where residues were not burned (Fig. 1a). These findings are similar to those established after 20 years on this trial (Kotzé and Du Preez 2007). Bhupinderpal-Singh and Rengel (2007) highlighted that straw burning reduces microbial activity, and thus residue decomposition. The same authors after reviewing a number of research works also stated that partially burned straw, leaves recalcitrant pools of C behind that are less preferred by microorganisms as their source of energy; therefore, such recalcitrant pools may accumulate over time and still be detected during soil analysis. Yadvinder-Singh et al. (2005) on the other hand indicated that sometimes variations between studies occur due to differences in fire intensity, sampling depth as well as climatic conditions. According to the same authors, the direction (accumulation or depletion) of SOC change during burning is determined by the quantity of crop residues burned.

As displayed in Fig. 1b, different tillage systems had a strong influence on SOC throughout the sampled profile; however, significant effects were only observed in the 0–50, 150–250 and 350–450 mm layers. In the 0–50 mm soil layer, the no-tilled plots had 0.75 % SOC, and the mulched and ploughed plots had 0.67 % SOC. Higher SOC levels in the upper soil layer under no-tillage treatments compared to ploughing were also reported by Duiker and Beegle (2006), Kotzé and Du Preez (2007), Thomas et al. (2007) and Van Den Bossche et al. (2009) who attributed this response to surface placement of crop residues, lack of soil mixing and slow residue

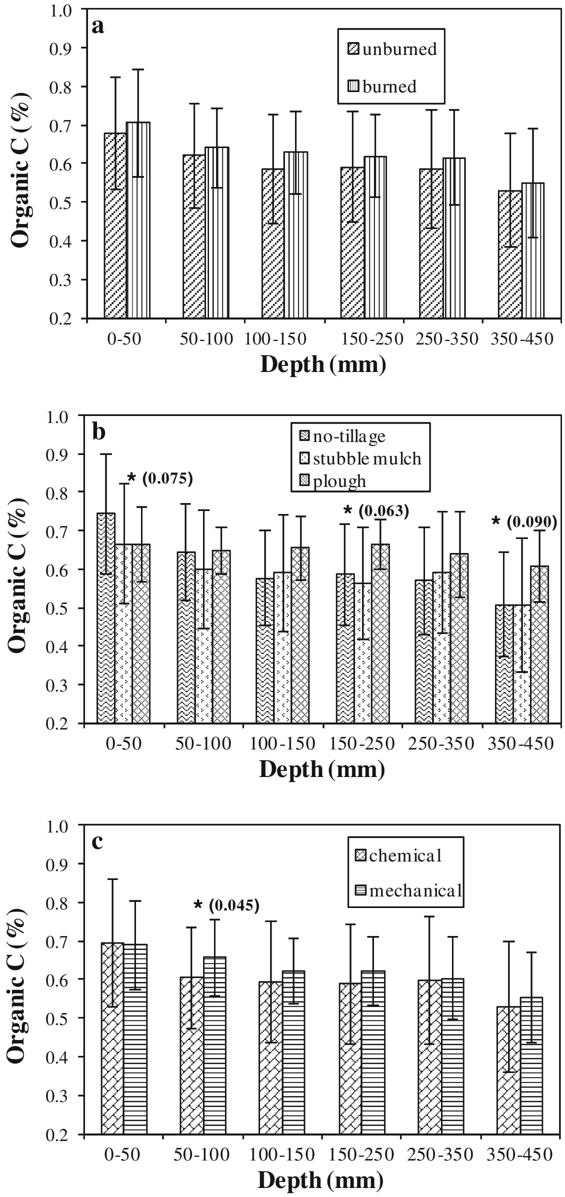

Fig. 1 Effect of straw management **a**, tillage **b**, and weed control **c** methods on organic C. HSD_T-values are shown where applicable. *Vertical bars* indicate standard deviation

decomposition rates in no-tillage. However, below 100 mm depth, higher SOC levels were recorded in the ploughed plots compared to either no-tilled or stubble mulched plots. SOC under the ploughed plots was almost similar throughout the six soil layers, suggesting a homogeneous distribution of SOC by tillage implements. This finding can be explained by tillage implements which are able to turn over C-rich topsoil layers and mix them with subsoil layers. This is not the case in no-tillage treatments.

Weed control methods did not influence SOC except in the 50–100 mm soil layer, wherein the concentration of SOC differed significantly between chemical and mechanical weeding (Fig. 1c). Soil organic C in this soil layer was 0.61 % in the chemically weeded and 0.66 % in mechanically weeded plots. Even below 100 mm soil depth, plots that were mechanically weeded had slightly higher SOC levels than plots that were treated with herbicides. The chemically weeded plots showed a minor increase in SOC only in the upper soil layer (0–50 mm). These findings are not in agreement with the results recorded in 1999 (Kotzé and Du Preez 2007), and are unusual because any mechanical disturbance of the soil aerates the soil, resulting in rapid oxidation and degradation of organic matter.

Interactions

The combination of straw management with weeding had a significant effect on SOC across all depth intervals ($HSD_T = 0.10$ % in the 0–50 mm, 0.08 % in the 50–100 mm, 0.12 % in the 100–150 mm, 0.08 % in the 150–250 mm, 0.13 % in the 250–350 mm and 0.12 % in the 350–450 mm soil layer). Chemical weeding in the plots where residues were not burned resulted in a lower SOC when compared to mechanical weeding viz. 0.61 versus 0.75 %, 0.54 versus 0.71 %, 0.51 versus 0.66 %, 0.52 versus 0.67 %, 0.52 versus 0.66 % and 0.45 versus 0.61 %, respectively; however, the difference was not significant in the 250–350 mm soil layer. In contrast, in the plots where residues were burned, chemical weeding increased SOC more than mechanical weeding, though the differences were significant only in the 0–50 mm and 150–250 mm soil layers viz. 0.79 versus 0.63 % and 0.66 versus 0.58 %, respectively. Similarly, in the chemically weeded plots, straw burning increased SOC relative to no-burning (0.79 versus 0.61 %, 0.68 versus 0.54 %, 0.68 versus 0.51 %, 0.66 versus 0.52 %, 0.68 versus 0.52 % and 0.61 versus 0.45 %, respectively), whereas in mechanically weeded plots, no-burning resulted in a significantly higher SOC in the 0–50 mm, 50–100 mm and 150–250 mm soil layers viz. 0.75 versus 0.63 %, 0.71 versus 0.61 % and 0.67 versus 0.58 %, respectively when compared to straw burning.

There was an interaction between tillage and weeding methods on SOC throughout the soil profile (HSD_T = 0.13 % in the 0–50 mm, 0.12 % in the 50–100 mm, 0.16 % in the 100–150 mm, 0.11 % in the 150–250 mm, 0.18 % in the 250–350 mm and 0.16 % in the 350–450 mm layers). In the plots that were treated with herbicides, stubble mulch reduced SOC (0.55, 0.49, 0.51, 0.46, 0.51 and 0.39 %, respectively) significantly when compared to either no-tillage (0.82, 0.67, 0.59, 0.59, 0.58 and 0.54 %, respectively) or mouldboard ploughing (0.72, 0.66, 0.69, 0.72, 0.71 and 0.67 %, respectively). In contrast to that, the differences in SOC were not significant between no-tillage and stubble mulch in the 100–150 mm, 250–350 mm and 350–450 mm soil layers. The trend reversed in mechanically weeded plots where stubble mulch increased SOC (0.78 %) significantly in the upper layer (0–50 mm) compared to ploughing (0.62 %) but not with no-tillage (0.67 %). The applied tillage systems in mechanically weeded plots did not influence SOC in the rest of the depth intervals. Conversely, in the stubble mulched treatments, mechanical weeding increased SOC levels compared to chemical weeding viz. 0.78 versus 0.55 %, 0.72 versus 0.49 %, 0.68 versus 0.51 %, 0.67 versus 0.46 %, 0.68 versus 0.51 % and 0.63 versus 0.39 %, respectively. Chemical weeding in no-tilled plots enhanced SOC relative to mechanical weeding; however, a significant increase was found only in the upper layer (0.82 vs. 0.67 %). In the ploughed treatments, weed control methods did not show any significant effect on SOC in any of the sampled layers.

Soil total N

Main effects

Methods of straw management affected STN more than either tillage or weeding methods. The concentration of STN in the plots where residues were not burned was significantly higher than in the plots where residues had been burned, particularly in the upper three soil layers (Fig. 2a). The mean values for STN ranged from 0.058 to 0.065 % in the 0–50 mm, 0.055–0.060 % in the 50–100 mm and 0.055–0.057 % in the 100–150 mm soil layers. In the deeper soil layers, there were no significant differences in STN due to straw management; however, there was a trend to higher STN levels in the treatments where straw was not burned. Similar observations were reported earlier by Kotzé and Du Preez (2007) who found that no-burning increased STN in all the sampled soil layers compared to straw burning, although differences were significant only in the 250–350 mm soil layer. This could be due to the low volatilization

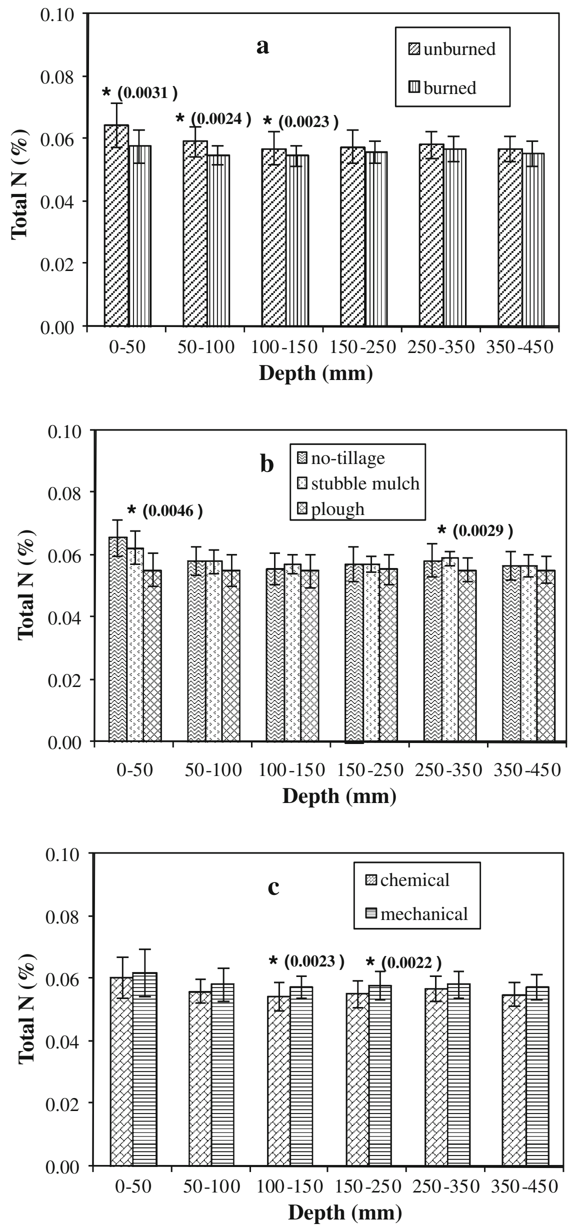

Fig. 2 Effect of straw management **a**, tillage **b** and weed control **c** methods on total N. HSD_T-values are shown where applicable. *Vertical bars* indicate standard deviation

temperature (200 °C) of N (Bhupinderpal-Singh and Rengel 2007). Thus, even N that is already bound in SOM can be lost if burning of the residues exceeds this temperature.

Further inspection of Fig. 2b shows that different tillage systems had a significant influence on STN only in the 0–50 and 250–350 mm intervals. At 0–50 mm soil depth, the concentration of STN was highest under no-tillage followed by stubble mulch and then ploughing, viz. 0.066, 0.063 and 0.055 %, respectively. In the 250–350 mm soil layer, the mulched plots had slightly higher STN than no-tilled plots, while both (mulched and no-tilled plots) had significantly higher STN than the ploughed plots. It is interesting, however, to note that although the effect of tillage methods on STN was significant only in these two layers, STN was higher in both no-tillage and stubble mulch treatments than in ploughed treatments throughout the soil profile. Kotzé and Du Preez (2007) also found higher concentrations of STN under conservation tillage systems as opposed to mouldboard ploughing.

As with SOC, the STN of mechanically weeded plots was higher than that of chemically weeded plots throughout the soil profile (Fig. 2c). In the 100–150 and 150–250 mm intervals, the STN concentration differed significantly between the weeding methods. Thus, in both layers (100–150 and 150–250 mm) mechanically weeded plots had on average 0.058 % STN, while chemically weeded plots had on average 0.055 % STN. These observations are not consistent with the results reported in 1999 (Kotzé and Du Preez 2007). In their study STN was greater in the plots treated with herbicides compared to those that were subjected to mechanical weeding.

Interactions

A significant interaction on STN was found between tillage and weed control methods only in the 150–250 mm soil layer ($HSD_T = 0.006$ %). In contrast to stubble mulched and ploughed treatments, mechanical weeding in no-tillage treatments increased STN more than chemical weeding viz. 0.066 versus 0.054 %. The applied tillage systems did not affect STN in either the chemically or mechanically weeded plots. There were no significant interaction effects of tillage and weeding methods on STN in the other soil layers. There were no interactions between methods of straw management with either tillage systems or weeding methods on STN throughout the soil profile.

Soil total S

Main effects

Despite the fact that crop demand for S is often similar or sometimes higher than that of P (Scherer 2001; Eriksen 2009), S has been neglected since the commencement of this trial. Soil total S was affected significantly by weed control method, and the effects were greater than those of either tillage or straw management. Soil total S was significantly higher in plots where residues were not burned than in plots where residues had been burned at the 50–100 and 100–150 mm soil depths (Fig. 3a). The concentration of STS ranged from 0.017 to 0.021 % in the 50–100 mm and 0.018 to 0.024 % in the 100–150 mm soil layers. Like N, S is also sensitive to high temperatures, therefore burning of crop residues can result in great oxidative losses of this nutrient (Adetunji 1997). There were no significant differences observed in the other soil layers; however, residue burning slightly increased STS only in the upper soil layer (0–50 mm) compared to no-burning.

Different tillage methods affected STS significantly up to a 150 mm soil depth (Fig. 3b). At 0–50 mm depth, the ploughed plots had the highest concentration of STS (0.027 %), followed by mulched plots (0.018 %) and then no-tilled plots (0.015 %). In the 50–100 mm soil depth, the mulched and ploughed plots contained almost the same level of STS, viz 0.022 and 0.019 %, respectively, but significantly higher than that of no-tilled plots (0.015 %). A similar trend was observed at 100–150 mm depth, although in this particular case STS was slightly higher in the ploughed treatments than in the stubble mulch treatments, while it was consistently lower in the untilled treatments. Frequent and intensive soil cultivation is known to cause rapid oxidation of SOM and therefore offset reserves of SOM indices (Itanna 2005; Yadvinder-Singh et al. 2005; Du Preez et al. 2011b; Houx et al. 2011); however, in the case of STS the opposite turned out to be true.

Weed control methods showed a consistent effect on STS across all the soil layers (Fig. 3c). Mechanically weeded plots had significantly higher STS

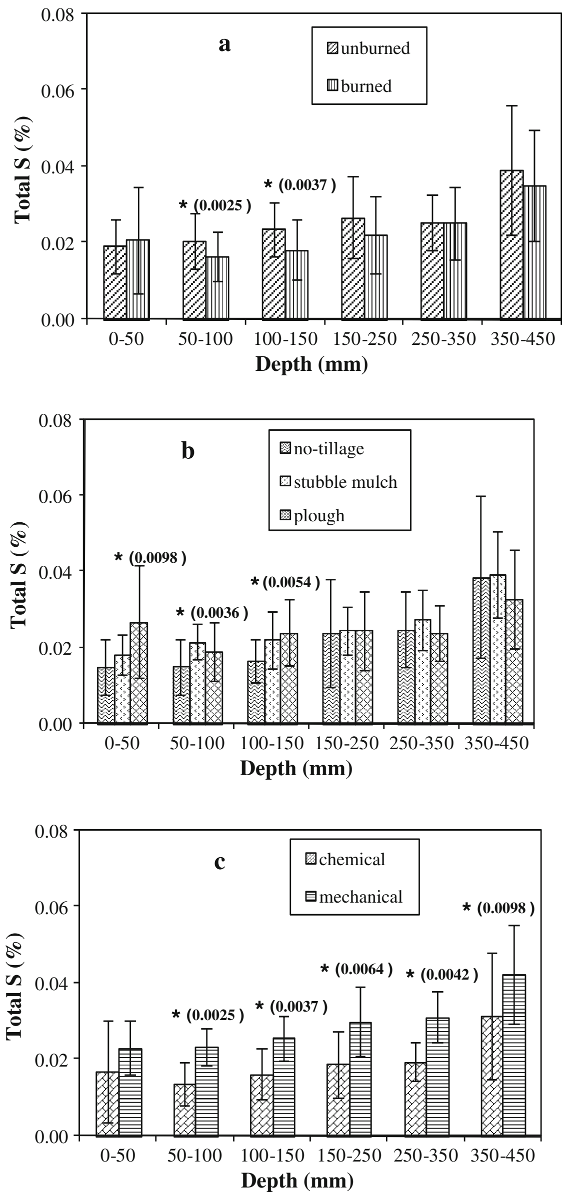

Fig. 3 Effect of straw management **a**, tillage **b** and weed control **c** methods on total S. HSD_T-values are shown where applicable. *Vertical bars* indicate standard deviation

compared to the chemically weeded plots, although this was not significant in the upper soil layer (0–50 mm). In contrast to both SOC and STN, STS increased with soil depth under all the applied treatments. A similar trend was also noticed in soil samples collected outside the trial (Table 1). This behaviour is indicative of high S mineralization followed by downward movement of the latter.

Interactions

The only significant interaction on STS was found between methods of straw management and tillage in the 50–100 mm (HSD_T = 0.006 %) soil depth. Unburned straw in the ploughed plots resulted in a higher STS when compared to the burned straw (0.024 vs. 0.014 %). The effects on STS in no-tilled or mulched treatments did not differ significantly due to straw management. However, in the plots where straw was not burned, no-tillage reduced STS (0.016 %) significantly when compared to either stubble mulch (0.023 %) or mouldboard ploughing (0.024 %). No significant differences could be found in the plots where residues had been burned due to tillage systems. The combination of weed control methods with either straw management or tillage did not influence STS in any of the studied soil layers.

Summary and conclusion

Levels of SOC, STN and STS indicate that the different treatments that have been applied for 32 years influenced organic matter concentration and distribution in this Plinthosol. The effects of the treatments however, varied between SOC, STN and STS. Although all are indices of SOM, they responded differently to straw management and tillage methods. Application of N and S fertilizers may be responsible for these contrasting results. Nevertheless, since SOC is generally considered as an index of SOM, and the concentrations of STN and STS may not exactly mimic SOC responses, the contrasting results with regard to these indices are ignored. Therefore it can be indicated that the burned straw resulted in a slightly higher SOM when compared to unburned straw. No-tillage treatments had a higher SOM only in the upper layer (0–50 mm). Mechanical weed control also increased SOM more than chemical weeding although not always significantly. This observation is contrasting to the findings of Kotzé and Du Preez (2007). However, nothing changed in the last 10 years to explain this reverse effect of weed control treatments on SOM. No reason could be found in literature to explain the higher SOM under mechanical weeding relative to chemical weeding.

We found higher SOM in the plots where residues were burned than in the plots where residues were not burned. Adetunji (1997) and Kumar and Goh (2002) showed that in contrast to burning, residue incorporation can have long-term beneficial effects on SOM and associated nutrients. On the other hand, incorporation of crop residues by tillage encourages rapid decomposition of crop residues and mineralization of SOC, and sometimes the deleterious effects of residue incorporation are found to be greater when compared to those of burning (Chan and Heenan 2005). In a series of long-term studies reviewed by Bhupinderpal-Singh and Rengel (2007) conservation practices were preferable to ploughing as they increase SOM in the upper soil layer as was found in the present study. Conservation tillage practices with proper straw management through their potential to improve SOM as well as soil, water and nutrient conservation can be positive for farmers practicing dryland agriculture in semi-arid zones (Martin-Rueda et al. 2007). This justifies the fact that conservation tillage can be considered as a viable technology for adaptation to climate change (Gattinger et al. 2011). In general, results of this study showed a rapid decline in SOC under no-tillage and stubble mulch as opposed to ploughing when the previous study (Kotzé and Du Preez 2007) served as a reference. For example, in the 0-50 mm soil layer, the ploughed, mulched and no-tilled plots had respectively 0.60, 0.72 and 0.84 % SOC after 20 years and 0.67, 0.67 and 0.75 % SOC after 32 years, indicative that SOC under conservation tillage systems decreased as opposed to conventional ploughing. This is not what was expected based on the results obtained by Van Den Bossche et al. (2009) who found that 3 years of ploughing, reduced or no-tillage did not affect SOC, but after 10–20 years significant changes occurred, and higher SOC levels were recorded under conservation practices relative to mouldboard ploughing. Therefore we presume that the amount of recycled wheat residues after 20 years of this trial was inadequate to sustain SOC accumulation in the conservation tillage as compared to conventional tillage.

The concentration of STN was lower in the upper two soil layers (0–50 and 50–100 mm) as well as in the most lower soil layer (350–450 mm) after 32 years when compared to the amounts obtained after 20 years. However, STN concentration was greater under conservation tillage systems than with mouldboard ploughing. Mineralization and uptake of N by wheat plants could be responsible for this phenomenon. However, in the lower soil layers (100–350 mm) the values of STN were higher than those presented by Kotzé and Du Preez (2007) after 20 years of this trial. Irrespective of the differences in the magnitude, SOC and STN in the current study tended to follow the trends obtained in the previous study (Kotzé and Du Preez 2007) except for the effects of weed control methods.

Results of this study also revealed that management of wheat residues resulted in a decline of SOM indices when compared to the perennial grassland outside the trial, except STS which remained the same under both grassland and inside the trial (Table 1). This suggests that a change in land use can contribute significantly to a decline or improvement of SOM (Du Preez et al. 2011b). The same authors highlighted that conversion of natural grassland to cropland represents a basis for SOM degradation. A decline in SOM usually leads to low soil productive capacity following soil physical, chemical and biological degradation (Barnard and Du Preez 2004; Van Den Bossche et al. 2009). Recycling of crop residues as well as reduced tillage intensity can at least maintain or compensate for the lost SOM in cropped soils (Schomberg et al. 1994). However, factors such as climate (rainfall and temperature), topography, parent material and time should be taken into consideration as they play an essential role in the build-up or loss of SOM (Du Preez et al. 2011b).

There were significant interactions between different treatment combinations on SOM indices. However results were inconsistent and therefore it is difficult to define the most effective treatment for SOM retention. It can be concluded that the combination of no-burning and chemical weeding, no-tillage and chemical weeding, stubble mulch and mechanical weeding as well as burning and mechanical weeding seemed to increase SOC. The increase of SOC with the first two treatment combinations and to a lesser extent with the third treatment combination could be expected due to the conservation nature of them. On account of the non-conservation nature of the last treatment combination the increase of SOC was surprising. No-tillage combined with mechanical weeding resulted in an accumulation of STN as could be expected. Contradictory to what was anticipated, no-burning combined with mouldboard ploughing enhanced STS.

Table 2 Effect of straw management, tillage and weeding methods on wheat grain yield (t ha^{-1}) over 32 years

Period	Straw			Tillage				Weeding		
	Unburned	Burned	HSD_T	No-tillage	Mulch	Plough	HSD_T	Chemical	Mechanical	HSD_T
1979–2010	2.28	2.12	0.04	2.11	2.19	2.28	0.07	2.20	2.19	ns
1979–1990	2.19	1.99	0.07	2.04	2.07	2.16	0.11	2.07	2.17	ns
1991–2000	1.94	1.90	ns	1.85	1.90	2.02	0.15	1.94	1.90	ns
2001–2010	2.47	2.25	0.08	2.33	2.29	2.46	0.11	2.38	2.35	ns

ns Non-significant

Table 3 Summary of seasonal rainfall data corresponding with period intervals (1979–2010 with 26 years data, 1979–1990 with 9 years data, 1991–2000 with 9 years data, and 2001–2010 with 8 years data) for wheat grain yield data (ARC-ISCW, 2011)

Season	Rainfall (mm)			
	1979–2010 SE	1979–1990 SE	1991–2000 SE	2001–2010 SE
Fallow: Jan–Jun	375 ± 29	337 ± 50	399 ± 50	391 ± 53
Growing: Jul–Dec	383 ± 24	384 ± 38	432 ± 36	327 ± 46
Annual: Jan–Dec	758 ± 35	721 ± 62	830 ± 51	717 ± 67

SE standard error

Table 2 shows wheat grain yield data for different period intervals. Wheat grain yields in all the periods were significantly influenced by straw management and tillage. Weed control methods did not show any significant effect in either of the period intervals. Unburned straw increased wheat grain yield more than the burned straw, though significant differences were recorded overall (1979–2010), as well as in the 1979–1990 and 2001–2010 period intervals. Although conservation tillage systems seemed to improve SOM indices, especially in the surface soil, wheat grain yields decreased significantly in these management systems when compared to mouldboard ploughing. It can only be speculated that better soil conditions and distribution of nutrients in the ploughed plots could be the reason for higher yields, while the lower yields in the no-tillage and stubble mulch treatments could be attributed to high nutrient accumulation in the top layer, which is likely to dry out quickly during dry seasons, resulting in low nutrient uptake by plants (Thomas et al. 2007). Despite the applied field treatments, wheat grain yield in the 2001–2010 period was slightly higher than that recorded in the 1979–1990 and 1991–2000 periods. Surprisingly, rainfall in the 2000–2010 period was slightly lower than that in other period intervals, especially during the growing season (Table 3). Perhaps sufficient moisture was conserved during the fallow period to sustain higher crop yields, or this could be attributed to the new cultivar that was introduced in 2005. Therefore it can be assumed that reluctance by farmers in some developing countries to adapt conservation practices is due to reduced yields, which occur mostly as a result of weeds and disease infestations, high nutrient immobilization rates and poor plant emergence (Chan and Heenan 2005).

It is challenging to explain why these results are contradictory to the findings of other researchers, for example in a long-term experiment in Central Mexico, it was reported that no-tillage with wheat-maize rotation and crop residue retention improved soil physical and chemical properties, resulting in higher and stable yields when compared to conventional tillage or no-tillage with residue removal (Govaerts et al. 2006). Gattinger et al. (2011) pointed out that duration of no-tillage is important in order to obtain higher and more stable yields; however, this was not the case in our study despite the long duration of the trial. The same authors however, indicated that good yields that were obtained in Brazil following the introduction of no-tillage could also be attributed to fertilizer and herbicide use as well as plant breeding. Therefore based on the results of this study and others, no-tillage can still produce comparable yields if problems associated with microbial nutrient immobilization and diseases can be addressed (Kumar and Goh 2002). Although fallow-crop systems are essential for soils to regenerate their productive capacity, they can result in SOM decline when compared to continuous cropping systems (Schomberg et al. 1994). Therefore rotation with summer crop (legume) is recommended in this trial.

References

Adetunji MT (1997) Organic residue management, soil nutrient changes and maize yield in a humid Ultisol. Nutr Cycl Agroecosyst 47:189–195

ARC-ISCW (2011) Agrometeorological data base. ARC-Institute for Soil Climate and Water, Pretoria

Bakht J, Shafi M, Jan MT, Shah Z (2009) Influence of crop residue management, cropping system and N fertilizer on soil N and C dynamics and sustainable wheat (*Triticum aestivum* L.) production. Soil Till Res 104:233–240

Barnard RO, Du Preez CC (2004) Soil fertility in South Africa: the last twenty five years. S Afr J Plant Soil 21:301–315

Chan KY, Heenan DP (2005) The effects of stubble burning and tillage on soil carbon sequestration and crop productivity in South Eastern Australia. Soil Use Manage 21:427–431

Chen H, Hou R, Gong Y, Li H, Fan M, Kuzyakov Y (2009) Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. Soil Till Res 106:85–94

Dalal RC, Allen DE, Wang WJ, Reeves S, Gibson I (2011) Organic carbon and total nitrogen stocks in a Vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation. Soil Till Res 112:133–139

Derpsch R, Friedrich T (2009) Development and current status of no-till adoption in the world; Proceedings on CD, 18th triennial conference of the International Soil Tillage Research Organization (ISTRO), June 15–19, 2009. Izmir, Turkey

Du Preez CC, Van Huyssteen CW, Mnkeni PNS (2011a) Land use and soil organic matter in South Africa 1: a review on spatial variability and the influence of rangeland stock production. S Afr J Sci 107:27–34

Du Preez CC, Van Huyssteen CW, Mnkeni PNS (2011b) Land use and soil organic matter in South Africa 2: a review on the influence of arable crop production. S Afr J Sci 107:35–42

Duiker SW, Beegle DB (2006) Soil fertility distributions in long-term no-till, chisel/disk and mouldboard plow/disk systems. Soil Till Res 88:30–41

Eriksen J (2009) Soil sulfur cycling in temperate agricultural systems. Adv Agron 102:55–89

FAO (1978) World reference base for soil resources. World resources Report No. 84 FAO, Rome

Gattinger A, Jawtusch J, Muller A, Màder P (2011) No-till agriculture—a climate smart solution? Report No. 2. Misereor IHR Hilfswerk, Germany

Govaerts B, Mezzalama M, Sayre KD, Crossa J, Nicol JM, Deckers J (2006) Long-term consequences of tillage, residue management and crop rotation on maize/wheat root rot and nematode populations in subtropical highlands. Appl Soil Ecol 32:305–315

Govaerts B, Verhulst N, Castellanos-Navarrete A, Sayre KD, Dixon J, Dendooven L (2009) Conservation agriculture and soil carbon sequestration: between myth and farmer reality. CRC Crit Rev Plant Sci 28:97–122

Heard J, Cavers C, Adrian G (2006) Up in smoke-nutrient loss with straw burning. Better Crops 90:10–11

Hintze JL (1997) NCSS 2000 user's guide. Number cruncher statistical systems, Kaysville, Utah

Houx JH III, Wiebold WJ, Fritschi FB (2011) Long-term tillage and crop rotation determines the mineral nutrient distributions of some elements in a Vertic Epiaqualf. Soil Till Res 112:27–35

Itanna F (2005) Sulfur distribution in five Ethiopian Rift Valley soils under humid and semi-arid climate. J Arid Environ 62:597–612

Kotzé E, Du Preez CC (2007) Influence of long-term wheat residue management on organic matter in an Avalon soil. S Afr J Plant Soil 25:14–21

Kumar K, Goh KM (2002) Management practices of antecedent leguminous and non-leguminous crop residues in relation to winter wheat yields, nitrogen uptake, soil nitrogen mineralization and simple nitrogen balance. Eur J Agron 16:295–308

Lal R (2005) World crop residues production and implications of its use as a bio fuel. Environ Int 30:855–892

Land Type Survey Staff (2001) Land types of South Africa. ARC-Institute for Soil Climate and Water, Pretoria

Lemke RL, Vandenbygaart AJ, Campbell CA, Lafond CP, Crant B (2010) Crop residue removal and fertilizer N: effects on soil organic carbon in a long-term crop rotation experiment on an Udic Boroll. Agric Ecosys Environ 135:42–51

Lobe I, Amelung W, Du Preez CC (2001) Losses of carbon and nitrogen with prolonged arable cropping from sandy soils of the South African highveld. Eur J Soil Sci 52:93–101

Mandal KG, Misra AK, Hati KM, Bandyopadhyay KK, Ghosh PK, Mohanty M (2004) Rice residue management options and effects on soil properties and crop productivity. Food Agric Environ 2:224–231

Martin-Rueda I, Muñoz-Guerra LM, Yunta F, Esteban E, Tenorio JL, Lucena JJ (2007) Tillage and crop rotation effects on barley yield and soil nutrients on a Calciortidic Haploxeralf. Soil Till Res 92:1–9

Menzies NW, Gillman GP (2003) Plant growth limitation and nutrient loss following piled burning in slash and burn agriculture. Nutr Cycl Agroecosyst 65:23–33

Mills AF, Fey MV (2003) Declining soil quality in South Africa: effects of land use on soil organic matter and surface crusting. S Afr J Plant Soil 99:429–436

Preger AC, Kösters R, Du Preez CC, Brodowski S, Amelung W (2010) Carbon sequestration in secondary pasture soils: a chronosequence study in the South African Highveld. Eur J Soil Sci 61:551–562

Ross SM (1993) Organic matter in tropical soils: current conditions, concerns and prospects for conservation. Progr Phys Geogr 17:265–305

Scherer HW (2001) Sulphur in crop production-invited paper. Eur J Agron 14:81–111

Schomberg HH, Ford PB, Hargrove WL (1994) Influence of crop residues on nutrient cycling and soil chemical properties. In: Unger PW (ed) Managing agricultural residues. Lewis Publishers, Boca Raton, pp 99–121

Sharma PK, Mishra B (2001) Effect of burning rice and wheat residues: loss of N, P, K and S from soil and changes in the nutrient availability. J Ind Soc Soil Sci 49:425–429

Singh B, Rengel Z (2007) The role of crop residues in improving soil fertility. In: Marschner P, Rengel Z (eds) Soil biology: nutrient cycling in terrestrial ecosystems. Springer, Berlin, pp 183–214

Soil Survey Staff (1987) Keys to soil taxonomy. SMSS techical monograph No. 6, Ithaca, New York

The Non-Affiliated Soil Analysis Work Committee (1990) Handbook of standard soil testing methods for advisory purposes. Soil Science Society of South Africa, Pretoria

Thomas GA, Dalal RC, Standley J (2007) No-till effects on organic matter, pH, cation exchange capacity, and nutrient distribution in a Luvisol in the semiarid subtropics. Soil Till Res 94:295–304

Van Den Bossche A, De Bolle S, De Neve S, Hofman G (2009) Effect of tillage intensity on N mineralization of different crop residues in a temperate climate. Soil Till Res 103:316–324

Wiltshire GH, Du Preez CC (1993) Long-term effects of conservation practices on the nitrogen fertility of a soil cropped annually to wheat. S Afr J Plant Soil 10:70–76

Yadvinder-Singh Bijay-Singh, Timsina J (2005) Crop residue management for nutrient cycling and improving soil productivity in rice based cropping systems in the tropics. Adv Agron 85:269–407