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SCIENCE DIRECT
Soil & Tillage Research 84 (2005) 67–75
Soil & Tillage Research
www.elsevier.com/locate/still

Tillage impacts on soil aggregation and carbon and nitrogen sequestration under wheat cropping sequences

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Received 3 September 2003; received in revised form 10 August 2004; accepted 3 September 2004

Abstract

No tillage (NT) and increased cropping intensity have potential for enhanced C and N sequestration in agricultural soils. The objectives of this study were to investigate the impacts of conventional tillage (CT), NT, and multiple cropping sequences on soil organic C (SOC) and N (SON) sequestration and on distribution within aggregate-size fractions in a southcentral Texas soil at the end of 20 years of treatment imposition. Soil organic C and SON sequestration were significantly greater under NT than CT for a grain sorghum [*Sorghum bicolor* (L.) Moench]/wheat (*Triticum aestivum* L.)/soybean [*Glycine max* (L.) Merr.] rotation (SWS), a wheat/soybean doublecrop (WS), and a continuous wheat monoculture (CW) at 0–5 cm and for the SWS rotation at 5–15 cm. At 0–5 cm, NT increased SOC storage compared to CT by 62, 41, and 47% and SON storage by 77, 57, and 56%, respectively, for SWS, WS, and CW cropping sequences. Increased cropping intensity failed to enhance SOC or SON sequestration at either soil depth compared to the CW monoculture. No-tillage increased the proportion of macroaggregates (>2 mm) at 0–5 cm but not at 5–15 cm. The majority of SOC and SON storage under both CT and NT was observed in the largest aggregate-size fractions (>2 mm, 250 μm to 2 mm). The use of NT significantly improved soil aggregation and SOC and SON sequestration in surface but not subsurface soils.

Keywords: Carbon sequestration; Conventional tillage; Cropping sequences; Nitrogen sequestration; No-tillage

1. Introduction

Increasing importance has been placed on the use of agricultural soils for the mitigation of atmospheric CO_2 through sequestration of soil C. Enhancement of C sequestration may be achieved by adoption of best management practices such as NT and residue management. Impacts of tillage on soil organic matter (SOM) have been well documented, but results vary due to many factors, such as soil type, cropping systems, residue management, and climate (Reicosky et al., 1995). Cultivation reduces SOM and alters the distribution and stability of aggregates (Six et al., 1998). No tillage can increase soil aggregation and C and N storage, and improve soil physical, chemical, and biological properties (Paustian et al., 1997; Hendrix et al., 1998). Most impacts of NT on C sequestration

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0167-1987/$ – see front matter
doi:10.1016/j.still.2004.09.017

have been observed in surface soils, near the rooting zone and crop residues (Dick, 1983; Franzluebbers et al., 1994a, 1995b; Potter et al., 1998; Bossuyt et al., 2002). The greatest increases in SOM are often observed in highly intensive cropping systems, where multiple crops are grown annually (Wood et al., 1991; Franzluebbers et al., 1994a, 1995b; Ortega et al., 2002).

Types of crop residues play important roles in C sequestration and soil aggregation, possibly due to C/N ratio or other qualities of residues (Lynch and Bragg, 1985; Franzluebbers et al., 1995a; Potter et al., 1998). The initial rate of degradation of crop residues is often governed by C/N ratio (Oades, 1988; Ghidey and Alberts, 1993; Chesire and Chapman, 1996), but as residues undergo decomposition, they become more recalcitrant and degradation becomes controlled by the lignin content or lignin/N ratio (Melillo et al., 1982; Tian et al., 1992). Thus, the ability of soils to sequester C is also closely linked to N cycling.

Impacts of tillage on distribution of SOM among aggregate-size fractions are not widely reported, especially in the southern USA. No tillage may promote soil aggregation through enhanced binding of soil particles as a result of increased SOM content (Paustian et al., 2000; Six et al., 2000). Macroaggregates often form around particles of undecomposed SOM, thus, providing protection from mineralization (Gupta and Germida, 1988; Gregorich et al., 1989; Six et al., 2000). Macroaggregates also form from microaggregates because of effects of binding agents, such as polysaccharides and fungal hyphae (Tisdall and Oades, 1982; Beare et al., 1997). Microaggregates are more stable than macroaggregates, and tillage subsequently disrupts large aggregates more than smaller aggregates, making SOM more susceptible to mineralization (Cambardella and Elliott, 1993; Six et al., 1998). Since CT often increases the proportion of microaggregates to macroaggregates (Six et al., 2000), there may be less crop-derived SOM in CT than NT soils (Six et al., 1999). Thus, SOC and SON sequestration may be enhanced by increasing the proportion of macroaggregates in soil through the utilization of reduced tillage. Specific objectives of this study were to determine the impacts of tillage and wheat cropping sequences on SOC and SON sequestration and distribution within aggregate-size fractions 20 years after adoption of NT and residue management in a southcentral Texas soil.

2. Materials and methods

2.1. Site description

A long-term field experiment was initiated in 1982 on the Brazos River floodplain in southcentral Texas (30°32′N, 96°26′W). Long-term average annual rainfall is approximately 980 mm, and average annual temperature is 20 °C. The soil used was a Weswood silty clay loam (fine-silty, mixed, superactive, thermic Udifluventic Haplustepts) with pH 8, having 115 g sand kg^{-1}, 452 g silt kg^{-1}, 310 g clay kg^{-1}, and 94 g $CaCO_3$ kg^{-1}. Three cropping sequences were established under both CT and NT. Cropping sequences included a grain sorghum [*Sorghum bicolor* (L.) Moench]/wheat (*Triticum aestivum* L.)/soybean [*Glycine max* (L.) Merr.] rotation (SWS), a wheat/soybean doublecrop (WS), and a continuous wheat monoculture (CW). For CT under wheat, soil was disked three to four times after harvest. Conventional tillage in sorghum and soybean consisted of disking to a depth of 10–15 cm after harvest, followed by chiseling to 25 cm, a second disking, and ridging prior to winter. Conventional tillage sorghum and soybean also received one to three in-season cultivations annually. Sorghum stalks were shredded for both CT and NT treatments. Under NT, no soil disturbance occurred except for banded fertilizer application and planting.

For CW and WS, wheat was planted in 0.18 m wide rows in November and harvested in May, followed by the soybean crop for WS. Soybean was planted in 1 m wide rows in early June and harvested in October. For the SWS rotation, sorghum was planted in 1 m wide rows in March and harvested in August, followed by wheat in winter, then soybean the following summer. The rotation resulted in three crops every 2 years. Wheat received 68 kg N ha^{-1} as NH_4NO_3, with half surface broadcast applied shortly after emergence, and half in late February. Nitrogen was subsurface applied preplant at 90 kg N ha^{-1} for sorghum. Soybean received 34 kg P_2O_5 ha^{-1} banded preplant with no added N. Field plots measured 4 m wide by 12.2 m long and treatments were replicated four times.

2.2. Soil sampling

Soil samples were taken in May 2002 after wheat harvest from SWS, WS, and CW sequences. Soil cores were taken to a depth of 20 cm with a 2.5 cm diameter probe, with 25 cores being taken per plot. The top 15 cm were sectioned into 0–5 and 5–15 cm depth intervals. Samples from respective depths in each plot were then combined, dried at 50 °C for 7 d, and passed through a 4.75 mm sieve. Additional triplicate samples were taken using an 8 cm sampler for measurement of bulk density (Blake and Hartge, 1986).

2.3. Soil analyses

Fractionation of soil aggregates was achieved using a wet-sieving procedure (Elliott and Cambardella, 1991; Cambardella and Elliott, 1994). Approximately, 90 g soil samples were capillary-wetted to field capacity to prevent slaking following immersion. Wetted soil was immersed in water on a nest of sieves (2 mm, 250 μm, 53 μm) and shaken vertically 3 cm for 50 times during a 2 min period. Soil aggregates retained on sieves were then backwashed into pre-weighed containers, oven dried at 50 °C for 2–3 d, and weighed. Material that passed through the 53-μm sieve was not collected, but contents of this fraction were determined by calculation of the difference between whole soil and the sum of the three aggregate-size fractions (>2 mm, 250 μm to 2 mm, 53–250 μm). Aggregate-size fractions included macroaggregates (>2 mm), small macroaggregates (250 μm to 2 mm), microaggregates (53–250 μm), and silt + clay associated particles (<53 μm). Subsamples from aggregate-size fractions were ground past a 0.5-mm sieve and analyzed for SOC and SON. Whole soil samples that did not undergo aggregate-size fractionation were also analyzed for SOC and SON.

Soil organic carbon was determined using a modified Mebius method (Nelson and Sommers, 1982). Briefly, 0.5 g soil was digested with 5 ml of 1.0 N $K_2Cr_2O_7$ and 10 ml of H_2SO_4 at 150 °C for 30 min, followed by titration of digests with standardized $FeSO_4$. Soil organic N was quantified using a Kjeldahl digestion procedure (Gallaher et al., 1976), with NH_4–N analyzed colorimetrically (Technicon Industrial Systems, 1977).

2.4. Statistical analyses

The experimental design was a split-split plot within a randomized complete block. Tillage treatment served as the main plot, cropping sequence was the split plot, and N application rate was the split-split plot, although only one N rate was tested in this study. Data were analyzed using JMP Software (SAS Institute Inc., 1995). Analysis of variance (ANOVA) was performed for individual treatment comparisons at $P < 0.05$ with separation of means by the least significant difference (LSD). The determination of differences between aggregate-size fractions was performed using a three-way ANOVA with factors being cropping sequence, tillage regime, and aggregate-size fractions.

3. Results

3.1. Bulk density

Bulk density was not impacted by tillage regime at either 0–5 or 5–15 cm. Bulk density increased with depth, averaging 1.42 g cm^{-3} at 0–5 cm and 1.67 g cm^{-3} at 5–15 cm. Bulk density was significantly affected by cropping sequences at both soil depths. At 0–5 cm, the bulk density of CW (1.46 g cm^{-3}) was significantly higher than SWS (1.27 g cm^{-3}) under NT. Under CT, the bulk density of

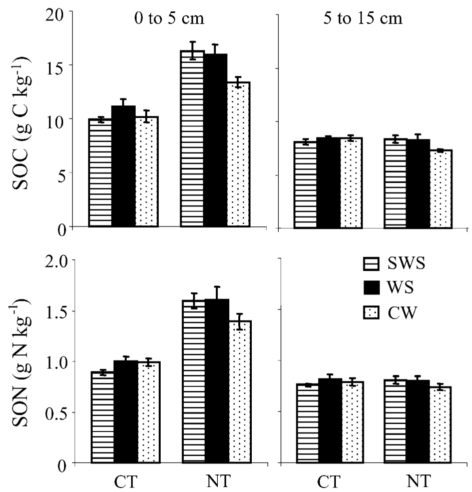

Fig. 1. Soil organic C (SOC) and organic N (SON) concentrations at 0–5 and 5–15 cm soil depths. CT and NT refer to conventional and no tillage. SWS, WS, and CW denote sorghum/wheat/soybean, wheat/soybean, and continuous wheat sequences, respectively. Error bars represent the standard error of the mean.

CW (1.64 g cm^{-3}) was higher than both SWS and WS (1.26 and 1.42 g cm^{-3}, respectively). At 5–15 cm under CT, bulk density was significantly higher for CW (1.77 g cm^{-3}) than for SWS (1.59 g cm^{-3}) and WS (1.65 g cm^{-3}).

3.2. SOC and SON concentrations of whole soil

No tillage significantly increased SOC and SON concentrations for all cropping sequences at 0–5 cm, but no impacts of tillage or cropping sequences were observed at 5–15 cm (Fig. 1). At 0–5 cm, no differences among cropping sequences were observed under CT, but CW had the lowest SOC and SON concentrations under NT. Both SOC and SON concentrations were significantly higher at 0–5 cm than 5–15 cm for all cropping sequences.

3.3. Aggregate-size distribution

Aggregate-size distribution was generally not impacted by tillage regime at either soil depth. Only in the >2 mm fraction at 0–5 cm and in the 250 μm to 2 mm fraction at 5–15 cm was the proportion of whole soil greater under NT than CT (Fig. 2). The two largest aggregate-size fractions represented the greatest proportions of whole soil at both 0–5 and 5–15 cm. Few differences between cropping sequences were observed at 0–5 cm. At 5–15 cm, SWS had a greater proportion of soil in the

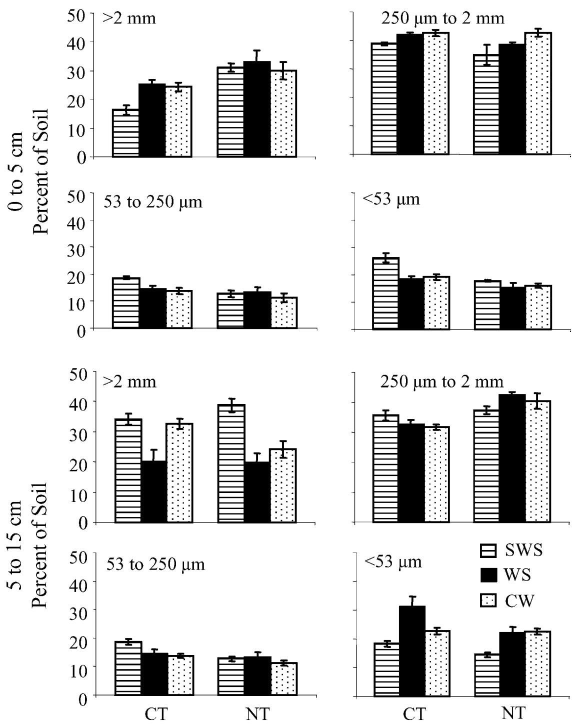

Fig. 2. Percent of soil as water-stable aggregates as influenced by tillage and cropping sequences at 0–5 and 5–15 cm soil depths. CT and NT refer to conventional and no tillage. SWS, WS, and CW denote sorghum/wheat/soybean, wheat/soybean, and continuous wheat sequences, respectively. Error bars represent the standard error of the mean.

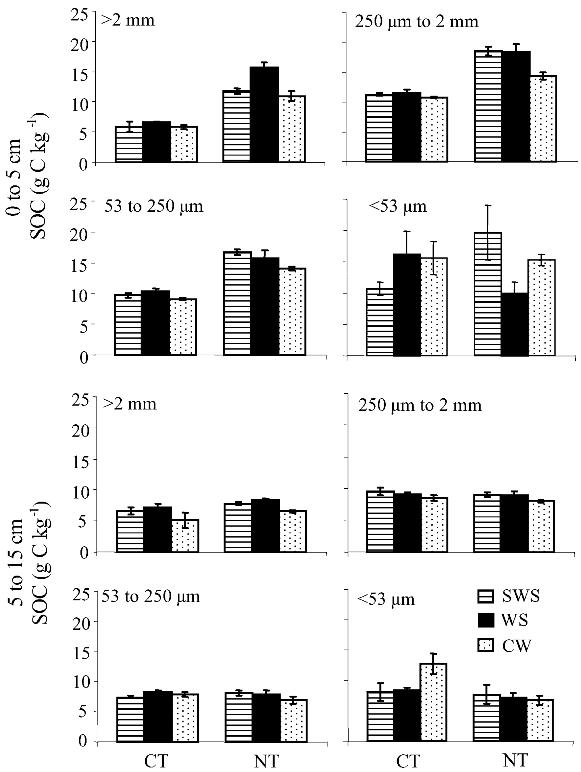

Fig. 3. Soil organic C (SOC) concentrations of four aggregate-size fractions at 0–5 and 5–15 cm soil depths. CT and NT refer to conventional and no tillage. SWS, WS, and CW denote sorghum/wheat/soybean, wheat/soybean, and continuous wheat sequences, respectively. Error bars represent the standard error of the mean.

>2 mm fraction than WS, and the SWS sequence exhibited the lowest proportion of whole soil in the <53 μm fraction.

3.4. SOC and SON concentrations of aggregate-size fractions

Soil organic C concentrations for all cropping sequences and for all aggregate-size fractions, except the <53 μm fraction, were significantly higher under NT than CT at 0–5 cm (Fig. 3). At 0–5 cm, averaged across cropping sequences, the highest SOC concentrations under CT were observed in the <53 μm fraction and the lowest concentrations in the >2 mm fraction. Under NT, the highest SOC concentrations were observed in the 250 μm to 2 mm fraction. At 5–15 cm, few differences in SOC concentrations were observed between cropping sequences or tillage treatments. Likewise, SOC concentrations were similar among aggregate-size fractions at this lower depth.

At 0–5 cm, NT significantly increased SON concentrations for all cropping sequences and for all aggregate-size fractions, except for WS in the >2 mm fraction and CW in the 250 μm to 2 mm fraction (Fig. 4). Few significant differences between cropping sequences were observed at 0–5 cm. At 0–5 cm, the highest SON concentrations were observed in the <53 μm fraction under NT, and at 5–15 cm, the highest concentrations were observed in the <53 μm fraction under both CT and NT. At 5–15 cm, few impacts of tillage on SON concentrations were observed, but SWS had the highest SON in the <53 μm fraction.

The C/N ratio of whole soil (C/N = 10.5) was not impacted by tillage or cropping sequences, and did not vary with depth. However, at 0–5 cm, the C/N ratio of the >2 mm fraction (C/N = 8.2) was significantly lower than the average ratios of the other three aggregate-size fractions (C/N = 11.3).

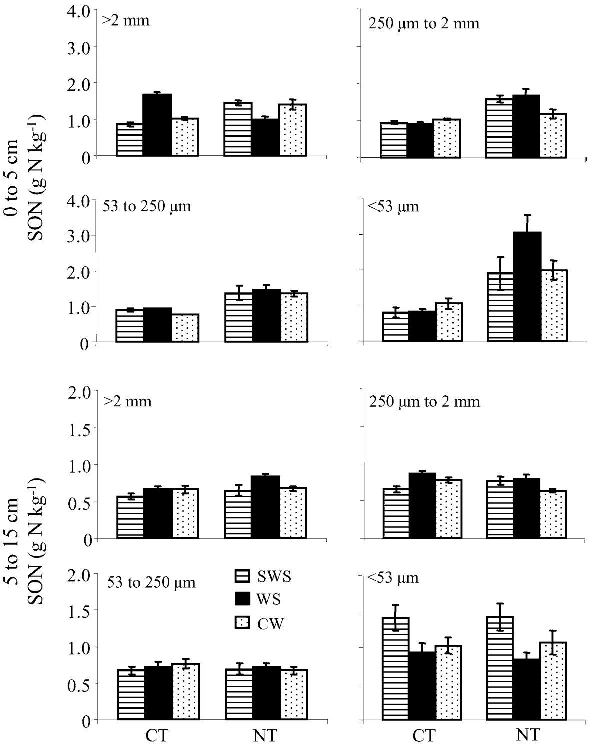

Fig. 4. Soil organic N (SON) concentrations of four aggregate-size fractions at 0–5 and 5–15 cm soil depths. CT and NT refer to conventional and no tillage. SWS, WS, and CW denote sorghum/wheat/soybean, wheat/soybean, and continuous wheat sequences, respectively. Error bars represent the standard error of the mean.

3.5. SOC and SON storage

No-tillage significantly increased SOC and SON storage for all cropping sequences at 0–5 cm (Fig. 5).

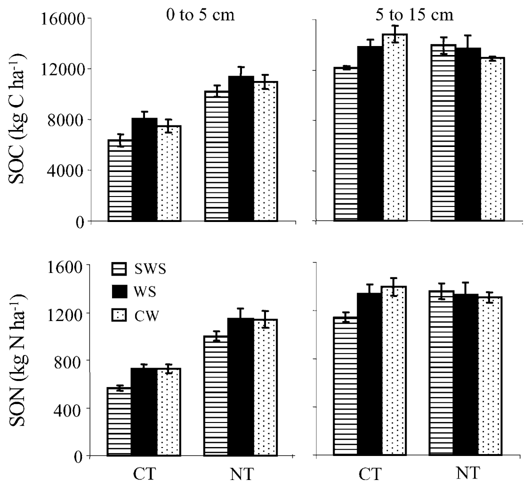

Fig. 5. Soil organic C (SOC) and organic N (SON) storage at 0–5 and 5–15 cm soil depths. CT and NT refer to conventional and no tillage. SWS, WS, and CW denote sorghum/wheat/soybean, wheat/soybean, and continuous wheat sequences, respectively. Error bars represent the standard error of the mean.

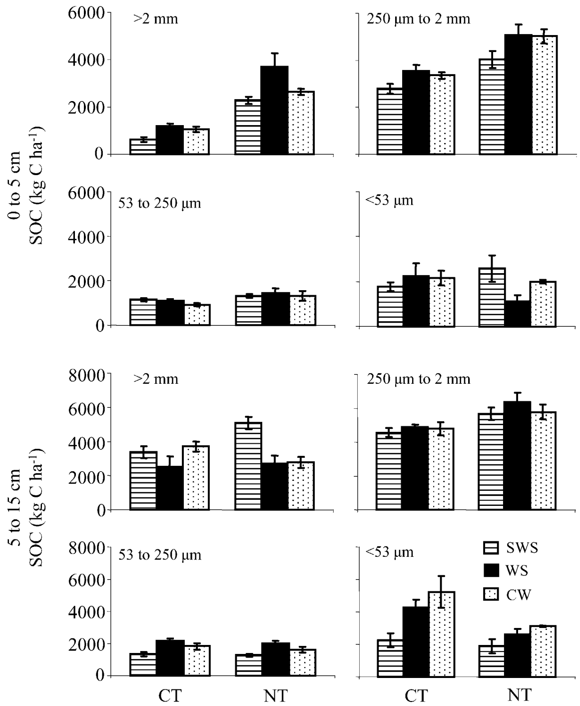

Fig. 6. Partitioning of soil organic C (SOC) storage among aggregate-size fractions at 0–5 and 5–15 cm soil depths. CT and NT refer to conventional and no tillage. SWS, WS, and CW denote sorghum/wheat/soybean, wheat/soybean, and continuous wheat sequences, respectively. Error bars represent the standard error of the mean.

At this depth, the lowest SOC and SON storage was observed for the SWS sequence under both CT and NT, while no differences were observed between WS and CW. At 0–5 cm, NT increased SOC storage by 62, 41, and 47% for SWS, WS, and CW, respectively. Likewise, NT increased SON storage by 77, 57, and 56%, respectively. At 5–15 cm, tillage had no influence on SOC and SON sequestration for WS and CW, but NT increased storage for the SWS sequence by an average of 15% for SOC and 19% for SON. Similar to 0–5 cm, the SWS sequence at 5–15 cm exhibited the least SOC and SON storage under CT, but under NT, no differences between cropping sequences were observed.

Soil organic C storage at 0–5 cm was significantly greater under NT than CT for all cropping sequences in the >2 mm and 250 μm to 2 mm fractions, but no impacts of tillage and few differences between cropping sequences were observed in the 53–250 μm and <53 μm fractions (Fig. 6). At 0–5 cm, NT increased SOC storage in the >2 mm fraction by 274, 208, and 152% for SWS, WS, and CW, respectively. To a lesser extent, NT increased SOC storage in the three smaller aggregate-size fractions by an average of 39%. For the two largest aggregate-size fractions at 0–5 cm, WS tended to have the highest SOC storage, while the SWS sequence had significantly lower SOC storage than other cropping sequences. The majority of SOC storage at 0–5 cm was observed in >2 mm and 250 μm to 2 mm fractions. At 5–15 cm, SOC storage was greater under NT than CT for all cropping sequences in the 250 μm to 2 mm fraction, and for SWS in the >2 mm fraction. In contrast to 0–5 cm, SOC storage at 5–15 cm was greater under CT than NT for WS and CW sequences in the <53 μm fraction and for CW in the >2 mm fraction. Similar to 0–5 cm, the two largest aggregate-size fractions at 5–15 cm exhibited the greatest SOC storage.

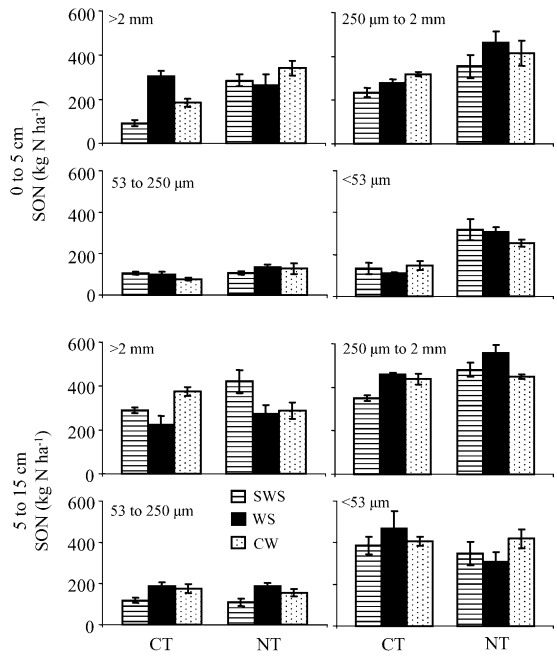

Fig. 7. Partitioning of soil organic N (SON) storage among aggregate-size fractions at 0–5 and 5–15 cm soil depths. CT and NT refer to conventional and no tillage. SWS, WS, and CW denote sorghum/wheat/soybean, wheat/soybean, and continuous wheat sequences, respectively. Error bars represent the standard error of the mean.

No tillage significantly increased SON storage at 0–5 cm for all cropping sequences in the 250 μm to 2 mm and <53 μm fractions, and for SWS and CW in the >2 mm fraction (Fig. 7). No tillage increased SON storage in the >2 mm aggregate-size fraction by 212, 0, and 85% for SWS, WS, and CW, respectively. No tillage increased SON storage in the three smaller aggregate-size fractions by an average of 71%. The greatest amount of SON storage was observed in the 250 μm to 2 mm fraction. Similar to SOC, SON storage tended to be lowest for the SWS sequence in the two largest aggregate-size fractions. However, for the two smallest aggregate-size fractions at 0–5 cm, no differences in SON storage were observed among cropping sequences. Few impacts of tillage on SOC and SON storage were observed at 5–15 cm. At 5–15 cm, NT increased SON storage only for SWS in the >2 mm fraction, and for SWS and WS in the 250 μm to 2 mm fraction.

4. Discussion

Higher cropping intensity often results in greater SOC and SON sequestration (Franzluebbers et al., 1994a, 1995b; Wright and Hons, 2004). At the end of 9 years, SOC was only 6–10% greater for SWS and WS than for CW under NT, and there were no observed differences in SOC among cropping sequences for CT (Franzluebbers et al., 1994a). At the end of 20 years, SOC storage for SWS and WS were only 1 and 5% greater than CW under NT, while SWS had lower SOC than other cropping sequences under CT. Both SOC and SON storage were lowest in continuous soybean monoculture, and highest in SWS or WS sequences (Wright and Hons, 2004), corresponding to lower residue inputs for monocultures and higher residue inputs for multiple cropping sequences (Franzluebbers et al., 1995a). For other Texas soils, SOC contents were greater for continuous wheat than sorghum cropping systems, even though sorghum produced up to 200% greater aboveground biomass (Potter et al., 1998). This result was attributed to the lower N content of wheat than sorghum residues (Potter et al., 1998).

In this study, the CW monoculture exhibited SOC and SON storages under both CT and NT and at both soil depths similar to the WS doublecrop, and occasionally exhibited greater storages than the SWS sequence, even though estimated crop residue inputs were approximately, 741, 907, and 555 g m^{-2} for SWS, WS, and CW, respectively (Franzluebbers et al., 1995a). These results may be attributed to higher C/N ratios of wheat residues and lower turnover rates compared to lower C/N ratios of residues from cropping sequences containing sorghum or soybean (Franzluebbers et al., 1995a; Potter et al., 1998). Wheat residues returned to soil having lower N contents (Franzluebbers et al., 1995a), may promote N immobilization, and may subsequently depress SOM degradation, leading to SOC and SON storages comparable to high-intensity cropping sequences; even though these sequences have significantly higher total residue inputs. Organic matter turnover, mineralizable C, and soil microbial biomass were reportedly greater for high-intensity sequences than for monoculture crops (Franzluebbers et al., 1994a,b; Salinas-Garcia et al., 1997). This suggests that greater residue inputs from high-intensity sequences were to some degree offset by enhanced organic matter degradation. Thus, both residue quantity and quality played important roles in SOC and SON sequestration in these soils.

Soil C/N ratio has been shown to be a good predictor of aggregate stability (Bird et al., 2002). Lower C/N ratios for macroaggregate fractions than for smaller aggregate-size fractions were indicative of accumulation of recently deposited plant material in macroaggregates. Soil aggregation and the stability of macroaggregates were likely affected by the C/N ratio or the quality of crop residues returned to soil, and residue quality played important roles in regulating long-term SOM storage in other studies (Lynch and Bragg, 1985; Ghidey and Alberts, 1993).

At 5–15 cm, NT generally failed to increase SOC and SON storage beyond levels of CT soils. This result was likely due to the return of crop residues to this lower soil depth by tillage; thus, comparable SOC and SON levels at 5–15 cm were observed regardless of tillage treatment. The physical breakdown of plant residues returned to subsurface soils by tillage promotes the turnover of organic materials. Thus, at 5–15 cm, SOC and SON under CT, although storages were generally equivalent to storages under NT, were likely more labile since CT subsurface soils contained recently deposited plant residues. This may have important implications for SOC and SON sequestration when soil conditions become more favorable for

SOM degradation, such as would occur during future tillage operations or changes in residue management. Thus, long-term stability of SOC and SON storage at 5–15 cm under CT may be dependent on the continued return of plant residues by tillage.

Short-term increases in SOC under NT are seldom observed in subsurface soils. At the end of 4 years of NT, SOC increased in the surface 0–5 cm, but not in subsurface soil (Wood et al., 1991). Even with 8 years of NT, increases in SOC storage were only observed at 0–5 cm (Ortega et al., 2002). Thus, many years of NT may be required for increases in SOC and SON storage at lower soil depths to be observed. In a related study at the end of 9 years of NT, SOC in the top 20 cm of soil was 25% higher under NT than CT (Franzluebbers et al., 1998). Thus, long-term NT and high-intensity cropping systems have potential for significant increases in SOC and SON storage.

5. Conclusions

No-tillage significantly influenced SOC and SON sequestration. Soil organic C and SON storage were increased by NT in surface soils but seldom in subsurface soils, presumably due to the return of crop residues to subsurface soils by tillage. No tillage increased the proportion of macroaggregates in soil, and the greatest storage of SOC and SON was observed in the largest aggregate-size fractions under both CT and NT. Thus, the long-term stability of SOM in soils may be dependent on maintenance of large aggregate-size fractions. Since macroaggregates are less stable than microaggregates, the long-term stability of SOC and SON is likely dependent on the continuation of reduced tillage and residue management. Increased cropping intensity failed to increase SOC and SON sequestration compared to the wheat monoculture sequence, suggesting that residue quality, in addition to the quantity of residues returned to soil, has important implications for SOC and SON sequestration potential.

Acknowledgment

This research was partially funded by the Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGS).

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