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Soil Aggregation, Aggregate Carbon and Nitrogen, and Moisture Retention Induced by Conservation Tillage

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We investigated the effects of 13 yr of plow tillage (CT), no-tillage (NT), and ridge tillage (RT) on soil aggregation and moisture holding capacity under two cropping systems, corn (*Zea mays* L.) alone and cotton (*Gossypium hirsutum* L.) followed by corn at two depths. The experiment was conducted on an Hidalgo sandy clay loam (fine-loamy, mixed, active, hyperthermic Typic Calciustoll). Few cropping system differences were found. Aggregation was significantly greater at the 0- to 5-cm depth with NT and RT, especially in the >4750- and 500- to 212-μm size classes, where aggregate C and N contents were as much as 60% and >100%, respectively, higher than in CT. At 10 to 15 cm, CT produced greater aggregation in all but the >4750-μm size class but showed little enhancement of C and N retention compared with NT and RT. Mass-weighted data revealed a more biphasic retention of C and N at the 0- to 5-cm depth; more C and N were retained in the >4750- and 500- to 212-μm size classes at 0 to 5 cm. Most C and N was detected in the >4750-μm size fraction at the 10- to 15-cm depth. Water holding capacity was significantly greater with NT and RT by >12% over CT management. The beneficial effects of conservation tillage are directly related to soil content and accumulation of C and N. In this hot climate, in which crop residues are rapidly oxidized, soil C and N accretion rates with conservation tillage are slow but demonstrable.

Abbreviations: CT, conventional plow tillage; MWD, mean weight diameter; NT, no-tillage; RT, ridge tillage.

Intensive soil tillage initiates a cascade of events that has been shown to both benefit and impair agricultural productivity. Net losses in soil fertility and soil integrity have led to the development of alternative management strategies that control problems associated with intensive tillage while affording acceptable conditions of seedbed preparation, fertility, and weed control.

One of these strategies entails reducing tillage, which often leads to the accumulation of soil organic matter (SOM) in surface soil horizons. Soil organic matter accumulation improves soil quality and fertility and contributes to sequestration of C (Six et al., 2000; Mikha and Rice, 2004; Wright and Hons, 2005a). The impact of tillage modification depends on soil type, residue management practices, and climate (Paustian et al., 1997).

Soil aggregate formation and stabilization are linked to SOM dynamics. Aggregation is controlled by microbiota, soil organic C, clay, and carbonate content of the soil (Bronick and Lal, 2005). The distribution of organic C in different aggregate size classes may affect erosion (Eynard et al., 2005). Decomposition of crop residues promotes soil aggregate formation (Tisdall and Oades, 1982), which has been shown to protect entrapped organic matter (Hassink et al., 1993; Wander and Bidart, 2000; Wright and Hons, 2005a) thereby contributing to C retention in soils. Most of the influence of NT on soil C sequestration was found to occur in surface soils, especially in the rooting zone (Franzluebbers et al., 1994).

The complex processes involved with aggregate formation and stabilization start with organic matter inputs. Rates of formation might be expected to vary with prevailing precipitation and temperature conditions in a geographic region. Natural levels of SOM are often linked to climatic conditions (Wright and Hons, 2005a), being greater in cooler soils with greater moisture. Gains in soil C and N can be lost if soils managed with conservation tillage are plowed again (Koch and Stockfish, 2006), so the condition is a fragile balance between inputs and outputs of C and N.

Management of soil C in the tropics is of particular importance since so many of the soils are more susceptible to SOM loss (Feller and Beare, 1997). Similarly, accreting soil C in semiarid, subtropical environments is also a challenge. Potter et al. (1998) found soil C retention to be inversely related to mean annual temperature across a large transect in Texas. This suggests that characteristically hot climates will undergo slower rates of improvement than cooler climates with the adoption of reduced tillage and conservative residue management practices.

Most studies on C retention come from experiments performed in cooler climates (Wright and Hons, 2005a), which are mostly wetter climates as well. The lack of pertinent information in the tropics constrains development of appropriate tillage and

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residue management practices (Fernandes et al., 1997); information needs for subtropical agriculture are equally insufficient. Additional information is needed to expand the understanding of the potentials of reducing tillage for improving the soil environment of agricultural systems in hot climates by determining the long-term distribution of C and N in aggregate size classes. The objectives of this experiment were to determine long-term (13-yr) effects of reduced tillage on soil aggregate stability, moisture holding properties, and the distribution of C and N among aggregate size fractions in a semiarid, subtropical agricultural system.

MATERIALS AND METHODS

Soil Properties and Plot History

The study site and tillage methods were previously described (Zibilske et al., 2002). Briefly, tillage treatments (moldboard plow, no-till, and ridge-till) were established in 1992 as a randomized block design with four replications on irrigated plots at Weslaco, TX (26°9′N, 97°57′W) on a pH 7.8 Hidalgo sandy clay loam. Locally recorded weather station data (not shown) indicate lower (<400 mm yr^{-1}) than normal (∼500 mm) precipitation in the past 5 yr. Common soil and air temperatures have been reported previously (Zibilske and Materon, 2005) and annually range from 15 to 34°C for soil at the 10-cm depth, and from 8 to 38°C for air measured at 2 m above ground level. Complete particle size analysis (University of Missouri Soil Characterization Lab., Columbia) yielded 58% sand, 18% silt, and 24% clay in the surface 25 cm of soil. Two cropping systems were used: continuous corn, planted in August of each year, or a more intensive system in which cotton was planted in March and corn in August of each year using only N fertilizer (90 and 168 kg N ha^{-1} for cotton and corn, respectively), according to soil test recommendations. Phosphorus fertilization is not often used in this region because soil tests commonly report high levels of P in the soils.

Soil Moisture Holding Capacity

Undisturbed soil cores were collected by manually pressing brass rings (5-cm diam., 2.5-cm height) vertically into the soil surface. Rings were gently lifted after cutting around the perimeter of the ring. The bottom surface was flush cut smoothly across the core face using the bottom edge of the ring as a guide. In the laboratory, three samples from each replication were placed on presaturated ceramic plate extractors and allowed to wet to saturation. Excess liquid was aspirated from the pressure plate chambers (Soil Moisture Equipment Co., Santa Barbara, CA), which were then closed and pressure applied via air compressor to generate −10, −33, or −100 kPa of pressure (Klute, 1986). Soil samples were allowed to equilibrate for 3 d in the chambers. The chambers were opened and soil samples removed for weighing, oven drying, and reweighing. Soil moisture retained at each potential was expressed as percentage moisture on a dry-soil basis.

Soil Aggregate Size Distribution: Sample Collection

Additional soil samples were collected by excavating a 40-cm-wide by 50-cm-deep trench. A 20-cm-long cutting blade was pushed vertically into the soil to produce a 30-cm square at the edge of the trench. A long knife was then pushed horizontally into the trench face at a depth of 5 cm and the slit extended to 30 cm. This produced a 30 by 30 by 5 cm soil slab, which was gently transferred to a soil bag. Samples were also collected from the 10- to 15-cm depth, just below where the surface samples were taken. These samples were taken as described above but after the soil between 5 and 10 cm was carefully removed. Three such collections, two depths each, were made from randomly located sites within each plot. These samples were not pooled, but analyzed independently.

Aggregate Size Distribution: Analysis

Unsieved soil samples (100 g) were transferred to plastic rings (7.6-cm diam. by 6.4 cm) fitted with filter paper secured across the bottom of the ring. Soil was gently moved to ensure no voids were present. Bodies greater than approximately 9 to 10 mm were removed. These samples were placed on a sand bed attached to a water reservoir adjusted to maintain a head of 10 cm in the sand column. Samples were covered loosely with foil and allowed to wet by capillarity overnight. This results in minimal aggregate disruption (Márquez et al., 2004).

A wet-sieving method was used to separate water-stable aggregates. Nested 33-cm-diam. sieves (4750, 2000, 1000, 500, 212, 125, and 53 μm) were placed into a Yoder apparatus (Kemper and Rosenau, 1986) containing 4 L of deionized water. The wetted soil sample was transferred gently to the top (submerged) sieve of the stack. When the apparatus was activated, the motor moved the stack through a vertical distance of 2 cm, completing 33 cycles min^{-1}.

After 10 min, the motor was stopped and the sieve stack removed from the tank. Material retained on each sieve was gently washed into tared aluminum dishes and dried at 60°C for approximately 3 d. Dry weights were recorded and samples preserved for further processing.

Slaked fines and particles (<53-μm diam.) remaining in the Yoder tank were quantified by the pipette method (Gee and Bauder, 1986). At appropriate time intervals, suspended material was aspirated, dried, and weighed to quantify the 20- to 5-, 5- to 2-, and <2-μm fractions.

Soil Aggregate Total Carbon and Nitrogen

Dried aggregates were ground with mortar and pestle after removal of any coarse (≥∼2 mm) organic particles. Ground samples were mixed thoroughly, subjected to acid decomposition of carbonates (Zibilske et al., 2002) and analyzed for total organic C and N by dry combustion (VarioMax CNS analyzer, Elementar Americas, Mt. Laurel, NJ). The analytical reference soil standard used was a calcareous soil of similar texture with known organic C and N contents (Cascade Science, Gainesville, FL, Reference Soil no.1, catalog no. E11035: total C, 3.500%; total inorganic C, 2.613%; total organic C, 0.887%; total N, 0.216%). The mass of material passing the 53-μm sieve, collected by the Lowy pipette, was insufficient for determining C and N content.

Calculations and Statistical Analyses

The amount of sand-free soil contained in each fraction was determined by dispersing the dried contents of several replicates with 5% (w/v) sodium hexametaphosphate, shaking vigorously for 10 min, and passing the suspension through a 53-μm sieve. Sand remaining on the sieve was dried and weighed. The corresponding correction factor determined for each sieve size was applied to the dry weights of aggregates collected in that size range. Thus, aggregate dry weights are expressed as sand-free weights.

Mean weight diameters (MWD; Martens, 2000) were calculated for each tillage × depth combination. All data are reported on a dry-soil basis.

Carbon and N contents of aggregates were mass-weighted for comparison by multiplying C concentration in the aggregate size fractions by the mass of soil in each aggregate fraction, giving the total C (per 100 g original soil sample) contained in a particular aggregate size class.

Data from the randomized complete block design (four replications) were analyzed with the PROC MIXED module of SAS (Version 9.1, SAS Institute, Cary, NC). Tillage treatments (three) and soil depths (two) were designated as fixed variables and replication (four) was designated a random variable in the model. Least squares means were further evaluated with the DIFF option with Bonferroni adjustment for multiple comparisons. Orthogonal contrasts were performed on selected combinations of treatments where appropriate.

RESULTS AND DISCUSSION

Distribution of Water-Stable Aggregate Sizes

Tillage treatments at the 0- to 5-cm depth significantly (highest $P = 0.02$) affected the distribution of soil among aggregate sizes in all size fractions except for the 125- to 53-μm fraction ($P = 0.27$). Cropping system (corn or cotton–corn), did not have an effect at either depth, nor were there any significant cropping system × tillage interactions. At the 0- to 5-cm soil depth, the largest size fraction, >4750 μm (Fig. 1a), constituted a significantly ($P < 0.01$) greater mass of the soil in the NT treatment than RT, and NT and RT together were significantly ($P < 0.01$) greater than the CT treatment. Considering smaller aggregate sizes, from 4750 to 500 μm, the proportion of soil accounted for in those size fractions declined more in NT and RT than in CT, compared with the >4750-μm class. In the 2000- to 500-μm range, the CT treatment contained the largest amount of soil in the 2000- to 1000-μm fraction, which was significantly ($P < 0.05$) greater than RT. A similar trend was noted in the 1000- to 500-μm fraction, in which aggregation in the CT treatment was significantly ($P < 0.01$) greater than in either the NT or RT treatments, which were not different from each other ($P = 0.41$). Smaller aggregate size fractions, from 500 μ to <53 μm, constituted the largest portion of aggregated soil at the 0- to 5-cm depth (Fig. 1a). Moving from 500 μm down to 125 μm, the proportion of soil aggregated among the treatments was larger than that seen in the larger sized aggregate fractions. Where NT dominated over RT in the larger fractions (>4750–1000 μm), the opposite was true in the smaller fractions (500 to <53 μm). Conventional tillage also maintained greater amounts of soil in that aggregate range than did NT. Dry weights in the two smallest fractions, 125 to 53 μm, and <53 μm were dominated by the CT treatment. This may reflect a tillage effect. Where soil is not tilled at all, large aggregates tend to dominate. Conversely, where even minimal (RT) or intensive tillage (CT) is used, those treatments appear to dominate the smaller aggregate fractions. Since the <53-μm fraction included slaked clays, the dominance of the CT treatment could be expected since plowing should contribute greatly to aggregate disruption. This pattern of a greater proportion of small aggregates and lower proportion of large aggregates due to CT is similar to the results of Mikha and Rice (2004). Plow tillage has often been implicated in the destruction of aggregates (Blevins and Frye, 1993; Tisdall and Oades, 1982). Six et al. (2000) proposed that, compared with CT, NT develops a reduced rate of macroaggregate turnover (formation and destruction), resulting in greater stabilization of the C in microaggregates. Protection of C in small aggregates inhibits mineralization, thus increasing C retention in soil, since microaggregates are more stable than macroaggregates (Cambardella and Elliott, 1993). Indeed, small aggregates themselves are found inside macroaggregates >250 μm (Six et al., 2000; Denef et al., 2004). This entrapment may also contribute to the longevity of small aggregates and the C and N contained therein (Besnard et al., 1996; Gregorich et al., 1996). The binding agents that form microaggregates into macroaggregates are the main sources of C lost when tillage occurs (Holeplass et al., 2004).

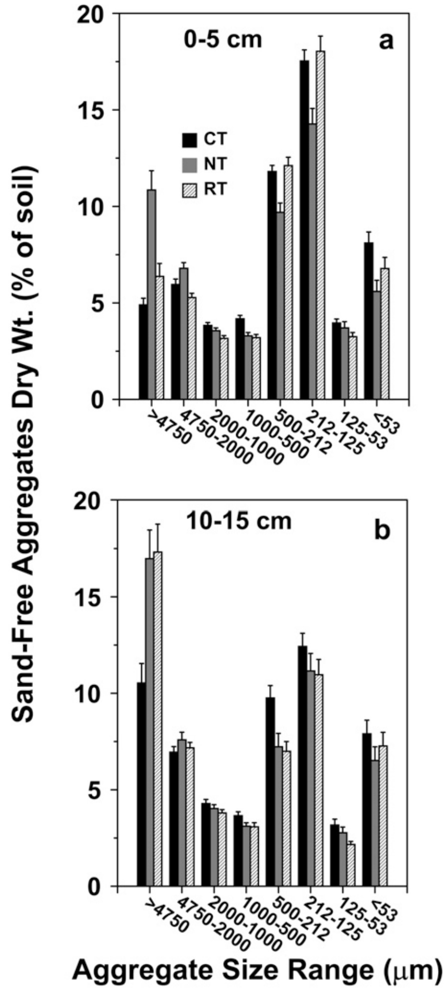

Fig. 1. Mass distribution of soil from two depths among aggregate size fractions after 13 yr of conventional tillage (CT), no-tillage (NT), or ridge tillage (RT). Original soil sample size was 100 g. Bars are ±1 SEM, *n* = 4.

At the 10- to 15-cm depth, the distribution of soil mass among the aggregate size fractions (Fig. 1b) revealed a different pattern than the surface soil (0–5 cm) results. As with the surface soil, there were no significant effects on soil distribution among the aggregate classes due to cropping system or to a cropping system × tillage interaction. There were, however, several significant effects due to tillage treatment. The >4750-μm fraction contained the largest amount of soil in the NT and RT treatments, which were similar ($P = 0.99$), but significantly ($P < 0.01$) greater than the CT. All fractions smaller than 4750 μm, however, were not dominated by the conservation tillage treatments; soil mass in the CT treatment dominated the fractions <1000 μm (Fig. 1b). A significant ($P < 0.01$) tillage effect was detected in the 500- to 212-μm fraction where

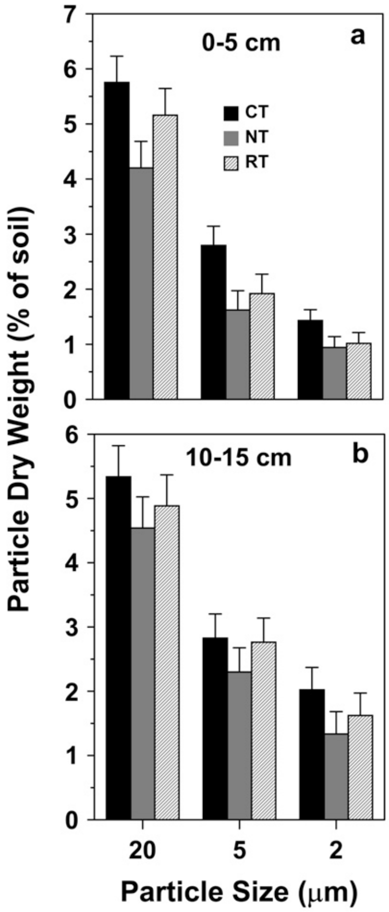

Fig. 2. Distribution of particle sizes in the <53-μm classification after 13 yr of conventional tillage (CT), no-tillage (NT), or ridge tillage (RT). Original soil sample size was 100 g. Bars are ±1 SEM, *n* = 4.

CT supported a greater mass of water-stable aggregates than the conservation tillage treatments (Fig. 1b). Similarly, but with a much smaller mass, the 125- to 53-μm fraction reflected a tillage effect ($P < 0.05$), where CT resulted in greater aggregation than the two conservation tillage treatments. There were no other significant effects of tillage at the 10- to 15-cm soil depth. These results differ somewhat from those of Wright and Hons (2005a) in that their study showed CT and NT elicited similar aggregation effects but reflected significant cropping

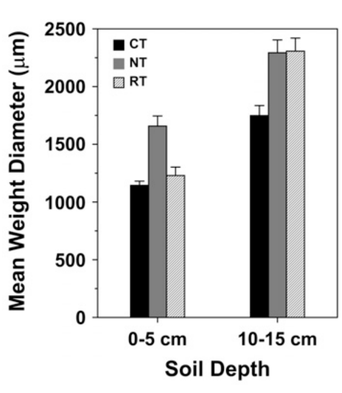

Fig. 3. Mean weight diameters of soil from two depths among aggregate size fractions after 13 yr of conventional tillage (CT), no-tillage (NT), or ridge tillage (RT). Bars are ±1 SEM, *n* = 4.

system influences. This probably is explained by the differences in soil type (a silty clay loam vs. a sandy clay loam in the present study) and differences in the cropping systems used, either in cropping intensity or in the crops used.

Silt and Clay Fractions

The smallest size fraction evaluated, <53 μm, contained dispersed clays, silt, and any smaller aggregates not retained on coarser sieves. This material, which passed through all sieves, was further segregated into size fractions by the pipette method to yield the 20-, 5-, and 2-μm fractions. Analysis of these data (<53 μm, Fig. 1a and 1b) revealed significant differences among tillage treatments at both soil depths, but no significant cropping effect. There was a significant ($P < 0.01$) tillage × crop interaction for summed silt and clay only in the 0- to 5-cm depth (Fig. 1a). For the corn cropping system, NT reduced ($P = 0.01$) the total silt and clay fraction. There was no difference ($P = 0.14$) between the CT and RT treatments. In the intensively cropped system, however, RT was more effective in reducing ($P < 0.01$) the total silt and clay fraction. There was no difference ($P > 0.05$) between the NT and RT treatment when evaluated for the more intensively cropped system (cotton followed by corn in the same year).

Evaluating the different size fractions within the <53-μm class reveals that the most silt and clay at the 0- to 5-cm depth (Fig. 2a) was present in the CT treatment, the least in NT, while RT had an intermediate effect in all three size fractions. The effects of conservation tillage treatments (NT and RT) compared with CT was the weakest ($P = 0.06$) of the orthogonal comparisons. Comparing NT and RT with CT for the 5- and 2-μm fractions however, revealed significant ($P < 0.01$ and 0.02, respectively) reductions in these fractions due to the conservation tillage treatments. There were no significant crop or tillage × crop interactions.

Weight fractions determined for the 10- to 15-cm depth (Fig. 2b) showed similar trends for treatment effects as observed with the 0- to 5-cm depth, but none of the main effects or interactions differed significantly ($P > 0.05$) from each other. Apparently, no tillage effects extended to this depth, even after 13 yr of treatment. Data in Fig. 1 and 2 do suggest, however, that conservation tillage is reducing the amounts of silt and clay fractions in this soil compared with conventional tillage. In an 8-yr study on a silt loam soil, Rhoton (2000) also found water-dispersible clays to be less with NT management than with CT. The hot climate in which the present study was conducted probably slows net gains of soil C due mainly to higher oxidation rates.

Mean Weight Diameter

Treatment effects on soil aggregation may be summarized in the mean weight diameter (MWD) calculation. Tillage was found to significantly ($P < 0.01$) affect MWD at both 0- to 5- and 10- to 15-cm depths (Fig. 3). The NT effect was significantly ($P < 0.01$) greater than RT, which was significantly ($P < 0.01$) greater than CT at the 0- to 5-cm depth. There were no significant (lowest $P = 0.49$) interactions between cropping system and tillage treatment at either depth, nor were there significant (lowest $P = 0.30$) cropping system main effects on MWD values.

At the 10- to 15-cm depth (Fig. 3), MWDs resulting from the NT and RT treatments were significantly ($P < 0.01$) greater than those from CT. In contrast to our findings, Franzluebbers (2002) found little difference in MWD values through soil depths to 12 cm in a comparison of long-term NT and CT treatments. The soil used in that study was a Cecil sandy loam, which may have less potential for aggregation and stabilization than the Hidalgo sandy clay loam soil used in our experiments. Figure 3 also shows a large shift (increase) in MWDs when comparing the 0- to 5- and 10- to 15-cm depths. Bulk soil C in roughly corresponding soil depths for each of the tillage treatments was observed in 2002 (Zibilske et al., 2002) to be 16, 14.2, and 9.5 g C kg^{-1} soil for NT, RT, and CT, respectively, at the 0- to 4-cm soil depth. At 8 to 16 cm, the values were 11.5, 10.5, and 11 g C kg^{-1} soil, respectively. This increase in MWD in the conservation tillage treatments, especially in the 0- to 5-cm depth, is probably related to increased soil C in those treatments. Shukla and Lal (2005) detected increasing MWDs in soils managed with NT with increasing years. They found MWDs were lower in soils where NT had been used for fewer years. This indicates that MWD increases are more likely to be observed later, rather than sooner. This may be especially true of hot climates, in which organic matter oxidation rates can be much greater than those of cooler climates. Our results are also supported by the findings of Blair et al. (2006), who found farmyard manure increased MWDs. The even larger increases in MWDs at the 10- to 15-cm depth (Fig. 3), however, cannot be explained by increased C in the bulk soil. The mass-weighted C content of the aggregates, however, shows a shift in C content to larger aggregates at the 10- to 15-cm depth (Fig. 4b), and also suggests that mass-weighted data also explains lower MWDs at the 0- to 5-cm depth (Fig. 4a). Therefore, aggregate C might be expected to better explain changes in MWDs than bulk soil C.

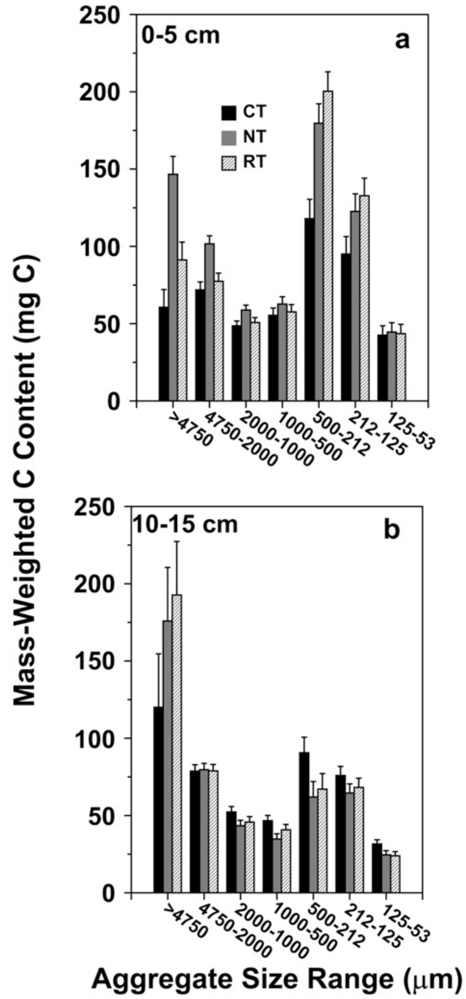

Fig. 4. Mass-adjusted organic C content in aggregate size fractions of soil from two depths after 13 yr of conventional tillage (CT), no-tillage (NT), or ridge tillage (RT). Original soil sample size was 100 g. Bars are ±1 SEM, *n* = 4.

Soil Moisture Holding Capacity

Moisture holding capacity (MHC) can be an important determinant in crop productivity, especially in hot climates. High crop water demand promotes rapid soil drying by evapotranspiration, which can lead to plant moisture stress. Improvements in soil moisture holding capacity through aggregation and enhanced organic matter content are commonly observed in reduced tillage systems. After 13 yr, tillage was found to have a significant ($P < 0.01$) effect on MHC at the three moisture tensions tested (Fig. 5). There was not an effect due to cropping system (continuous corn vs. the more intensive corn following cotton in the same year, lowest $P = 0.28$), nor was there a crop × tillage interaction (lowest $P = 0.56$). Conventional tillage produced lower MHCs at all tensions, while RT and NT were similar ($P = 0.18$), but significantly ($P < 0.01$) greater than CT at −10 kPa. At −33 kPa, MHC in the NT treatment was significantly ($P < 0.01$) greater than RT, and both were significantly greater ($P < 0.01$) than the CT treatment. The highest moisture tension, −100 kPa, maintained the significant difference between RT and NT ($P < 0.05$), and also had significantly ($P < 0.01$) greater MHCs than the CT treatment. With increasing tension from −10 to −100 kPa, CT retained an average 67.49% of the −10 kPa MHC, while NT retained 70.72%, and RT 65.73%. In a similar semiarid climate and heavy soil, Bescansa et al. (2006) found greater water holding capacity when reduced tillage was compared with conventional plow tillage. They found, for soil at −33 kPa, moisture retention was 11% lower in the conventionally tilled treatment than no-tilled soil. In our experiment, the CT treatment was 15.7% lower than NT and 8.8% lower

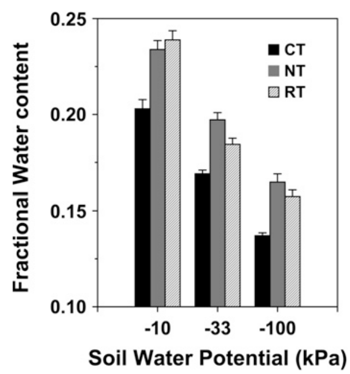

Fig. 5. Water holding capacity at three water potentials in the top 2.5 cm of soil after 13 yr of conventional tillage (CT), no-tillage (NT), or ridge tillage (RT). Bars are ±1 SEM, *n* = 4.

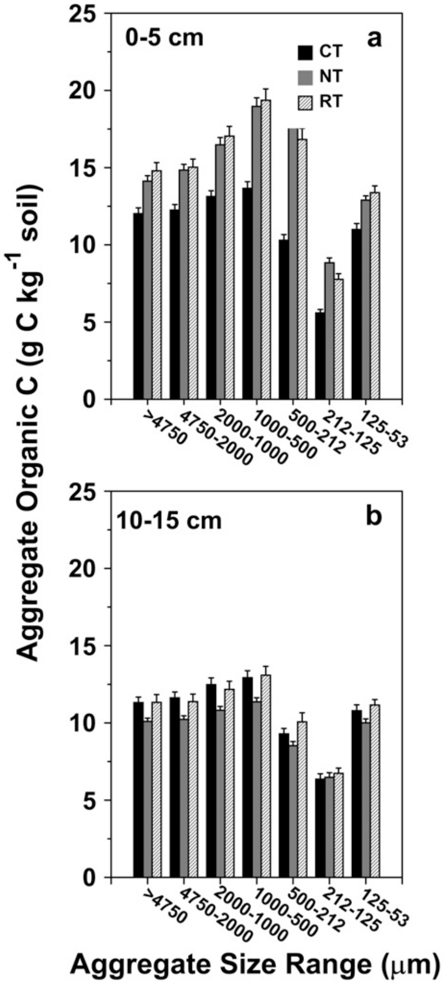

Fig. 6. Organic C concentration in soil aggregate size fractions of soil from two depths after 13 yr of conventional tillage (CT), no-tillage (NT), or ridge tillage (RT). Original soil sample size was 100 g. Bars are ±1 SEM, *n* = 4.

than RT at −33 kPa. Our results indicate significant improvement in MHC with both conservation tillage treatments. Moisture holding capacity is often cited as one of the benefits of reducing tillage, but the effect may not be apparent in the short term (Bescansa et al., 2006). In a dryland wheat (*Triticum aestivum* L.) system, NT was found to increase soil moisture as well, but the improvement was attributed to other effects of NT, namely increased infiltration rates and lower rates of evaporation and runoff (Norwood, 1994). These additional effects of NT undoubtedly contributed to the overall effects on soil moisture in our experiments, but they were not quantified. Results suggest that the increase in organic C with conservation tillage produces a system that holds significantly more water in the plant-available water range and beyond. In an arid climate, conservation tillage would make an economic difference in terms of scheduling irrigation and retaining off-season precipitation, both of which improve water use efficiency.

Aggregate Carbon

Conservation tillage is often a beneficial method for reducing C losses in agricultural soils. In general, trapping C in aggregates can slow mineralization and result in a net gain in soil C (Mikha and Rice 2004). In a previous study (Zibilske and Bradford, 2003), significantly greater C mineralization, alkaline phosphatase activity, and O_2 uptake were found in the surface 25 cm of these tillage treatments, indicating enhanced microbiological activity.

At the 0- to 5-cm soil depth (Fig. 6a), a significant ($P = 0.03$) interaction of tillage and cropping system was detected. This effect was confined to the 125- to 53-μm size class, in which the RT treatment coupled within the cotton–corn cropping system resulted in a greater C concentration (14.13 g C kg soil^{-1}) than with the corn-alone cropping system (11.88 g C kg soil^{-1}). A significant ($P < 0.05$) cropping system effect was also seen for this size class in which the cotton–corn system had a greater mean C concentration (12.70 g C kg soil^{-1}) than the corn-alone system (11.87 g C kg soil^{-1}). All aggregate size classes in soil managed with NT and RT concentrated significantly ($P < 0.01$) more C than the CT treatment (Fig. 6a). The largest differences between the conservation tillage treatments and CT occurred in the size ranges from 2000 to 125 μm, peaking in the 1000- to 500-μm class. Similarly, Wright and Hons (2005a) found that NT increased organic C storage at the 0- to 5-cm soil depth in the 2000- to 250-μm aggregate size class. The lowest concentrations of aggregate C were found in the 212- to 53-μm range (Fig. 6a). Carbon concentration in the >4750- and 4750- to 2000-μm classes for CT were similar, but reflected the upward trend in C concentration going toward smaller aggregate sizes in both conservation tillage treatments (Fig. 6a). The C concentration of the material passing all sieves (the <53-μm fraction) was not determined because it was not possible to segregate the components into microaggregates and dispersed silt and clay.

Organic C in the aggregate fractions collected at the 10- to 15-cm depth (Fig. 6b) reveals generally lower concentrations than in the corresponding fractions from the 0- to 5-cm depth. There were no significant cropping system effects, nor were there any significant cropping system × tillage interactions. It appeared that the effects of tillage were not as large as in the 0- to 5-cm depth, but several important differences were noted. In general, CT had a more dominant effect that NT, but was similar to the effect of RT among the larger aggregate fractions (>4750–500 μm). This suggests that, while the effects of NT and RT were strongly dominant in the surface few centimeters of soil, their effects on C storage in aggregates >500 μm at the lower depth were not as influential. This is supported by the fact that there were no significant tillage effects observed for aggregate size classes <500 μm. This contrasts with the determination that C storage in every size class was significantly affected by tillage at the 0- to 5-cm soil depth. At the 10- to 15-cm depth, C in the larger aggregate (>4750–500-μm) classes was most affected by the CT and NT treatments, which were not significantly different from each other (adjusted $P = 0.99$). Both CT and RT were, however, in all cases, significantly (highest $P < 0.05$) more effective in C storage than the NT treatment at that depth. In the smaller aggregate classes (<2000 μm) from the 10- to 15-cm depth, the RT treatment again became dominant, with the exception of the 212- to 125-μm class, in which no significant (smallest $P = 0.41$) effect of tillage on C storage was observed. Once again, a comparison with the corresponding small aggregate classes (500–53 μm) in the 0- to 5-cm depth (Fig. 6a), reveals contrasting effects of tillage between surface and deeper soil depths. The conservation tillage treatments were more effective in storing C at 0 to 5 cm than in the 10- to 15-cm depth. Results indicate that, even in a dry, hot climate, increases in soil C occur with the use of conservation tillage. This accreted C should help stabilize the soil, leading to improved sustainability of the system.

A different view of these data is achieved by mass weighting C and N data for each aggregate size fraction (Fig. 4). Analysis of these data for the 0- to 5-cm depth (Fig. 4a) indicated a significant ($P < 0.05$) cropping system × tillage interaction, which occurred only for the 1000- to 500-μm aggregate class. There were no other significant interactions and no significant effect of cropping system alone for any aggregate size class. Significant tillage effects were found for several aggregate size classes. A significantly ($P < 0.01$) greater C content in NT than in RT was seen for the >4750-μm class. This is due mainly to the greater mass of soil found in that size class (Fig. 1a), since C concentrations were similar for NT and RT (Fig. 6a). For the 4750- to 2000-μm class, NT contained significantly ($P < 0.01$) more C than the RT treatment.

Data from the 10- to 15-cm samples (Fig. 4b) show a generally diminished effect of conservation tillage treatments. In the >4750-μm class, however, conservation tillage treatments accounted for much greater C content than seen in the CT treatment. Our results differ somewhat from published data in that regard. We found relatively low amounts of C in the 2000- to 500-μm size class (Fig. 4b), while Wright and Hons (2005a) found significant C enrichment in those ranges. Hevia et al. (2003) also found C enrichment in the 2000-to 100-μm size class, although they used samples taken from the 0- to 20-cm depth in an Argentinean loess. Again, soil type may be a factor in these differences.

Aggregate Nitrogen

The influence of tillage treatments on aggregate N concentration is shown in Fig. 7. After 13 yr, N concentration was greater in both conservation tillage treatments for all aggregate size fractions at the 0- to 5-cm soil depth (Fig. 7a). One significant ($P < 0.05$) tillage × cropping system interaction was detected in the 500- to 212-μm aggregate size class. This effect was due to the RT treatment, and resulted in more N concentration in the cotton–corn cropping system (1.10 g N kg soil^{-1}) than in the corn-alone system (0.99 g N kg soil^{-1}). This contrasts with the findings of Wright and Hons (2005b). In their study, cropping system significantly affected both C and N retention. The most effective crop in their study was wheat, and mostly in the NT treatment. In our study, the highest intensity cropping system was cotton–corn, which could have produced a larger amount of organic inputs to the system compared with corn alone, but not as much, perhaps, as in a wheat system.

In all cases, the conservation tillage treatments resulted in highly significant ($P < 0.01$) concentrations of organic N among the aggregate size classes, compared with the CT treatment (Fig. 7a). The highest concentrations were found in the 1000- to 212-μm classes. In all aggregate classes, N concentration in the CT treatment was significantly (highest $P < 0.03$) lower than NT. Nitrogen concentration in the CT treatment were very similar among the larger aggregate fractions, from >4750 to 500 μm, but were lower in the 500- to 125-μm

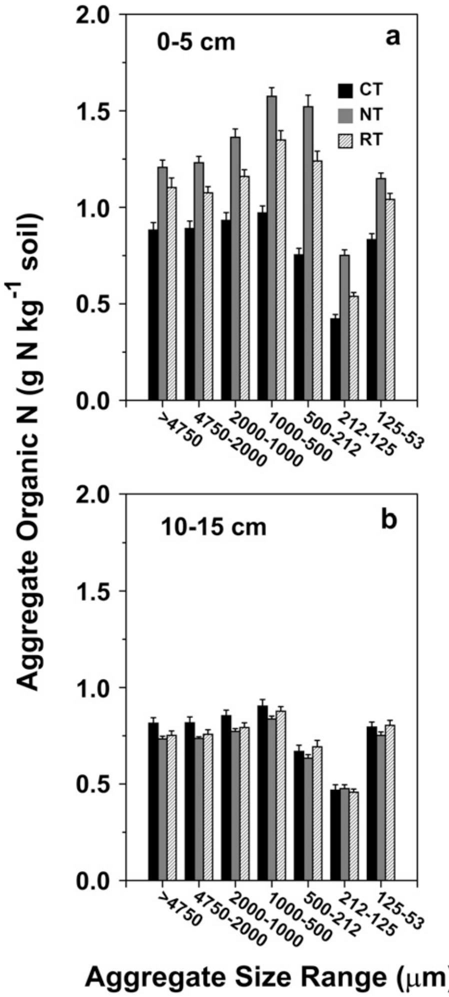

Fig. 7. Organic N concentration in aggregate size fractions of soil from two depths after 13 yr of conventional tillage (CT), no-tillage (NT), or ridge tillage (RT). Original soil sample size was 100 g. Bars are ±1 SEM, *n* = 4.

classes, and was greater again in the smallest size class. The low values for N concentration in the 212- to 125-μm class correspond to similarly low C values for that aggregate class (Fig. 6a). Beare et al. (1994) also found, in a sandy clay loam soil, a similar trend toward more N in NT aggregates than in those from the CT treatment.

At the lower soil depth, 10 to 15 cm (Fig. 7b), generally lower N concentrations were detected among the aggregate fractions than at the 0- to 5-cm depth. The only differences among the size class N concentrations occurred in the range between 1000 and 4750 μm. While there was no significant (lowest $P = 0.55$) difference between the conservation tillage treatments, there was a significant difference between the conservation tillage and CT treatments regarding aggregate N concentration in size classes >1000 μm ($P < 0.01$ for the 2000–1000-, 4750–2000-, and >4750-μm classes). This effect probably also extended to the 1000- to 500-μm class ($P = 0.05$). The lower amounts of N in most size classes >53 μm (compared with larger classes) and the smaller effect of tillage treatments on N are similar to the findings of Beare et al. (1994), who found few tillage effects at the 5- to 15-cm soil depth. There were no significant interactions between tillage treatment and cropping system, nor were there

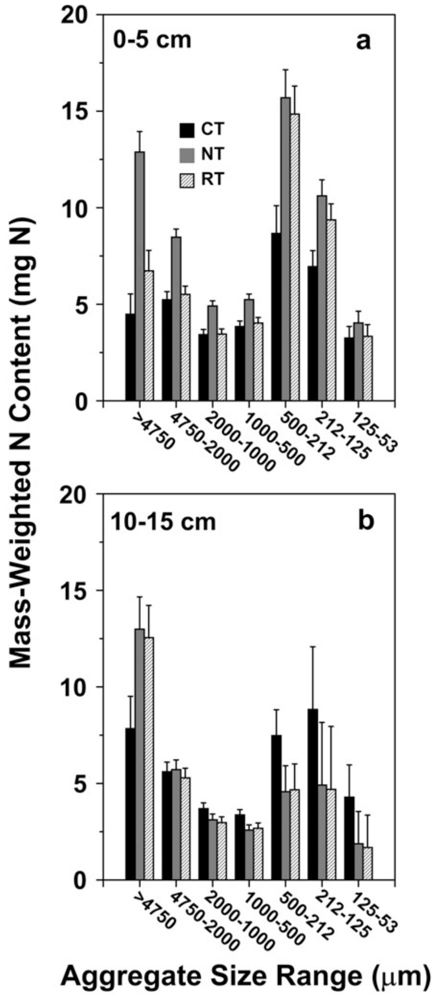

Fig. 8. Mass-adjusted organic N content in aggregate size fractions of soil from two depths after 13 yr of conventional tillage (CT), no-tillage (NT), or ridge tillage (RT). Original soil sample size was 100 g. Bars are ±1 SEM, *n* = 4.

significant differences in aggregate N concentration due to cropping system at the 10- to 15-cm depth.

By mass weighting the aggregate N data, a value is produced that reflects the total N contained in that class. These values also show a clear dominance of NT management on N contained in aggregates from the 0- to 5-cm soil depth (Fig. 8a). A significant ($P < 0.01$) tillage × cropping system interaction was detected in the 500- to 212-μm class. This was the same interaction that showed a significant effect on N concentration (Fig. 7a). This was probably due mainly to the tillage effect on N concentration, since there were no significant cropping systems × tillage interactions. Significant ($P < 0.01$) tillage effects were detected in all size fractions, although the effect for the125- to 53-μm fraction was not as strong ($P = 0.05$). Pronounced positive effects on N content among the aggregate classes was observed for the conservation tillage treatments (Fig. 8a), especially in the >4750-, 500- to 212-, and 212- to 125-μm classes. Midsized aggregate classes (2000–500 μm) did not contain as much N as larger and smaller classes, even though their N concentrations (Fig. 7a) indicated fairly large concentrations in those classes. At the 0- to 5-cm depth (Fig. 8a), approximately 40% of the total N contained in the 500- to 212-μm class was accounted for by the NT treatment. About 53% of the N in the >4750-μm class was accounted for by the NT treatment, as was 39% in the 212- to 125-μm size class.

Samples taken at the 10- to 15-cm depth displayed a different pattern of tillage effects than seen in the 0- to 5-cm depth (Fig. 8b). At this depth, there were no significant interactions between tillage and cropping system (lowest $P = 0.22$), nor were there significant cropping systems effects (lowest $P = 0.14$). There were, however, several significant tillage effects.

In the >4750-μm class, the conservation tillage treatments contained significantly ($P < 0.01$) greater amounts of N compared with CT. The NT and RT treatments contained 39 and 38%, respectively, of the total N in the size class, and were, together, significantly ($P < 0.01$) greater than the CT treatment, which contained about 24% of the N in that size class. There were no differences in aggregate N content due to tillage treatment in the 4750- to 2000-μm size class. The midsize aggregate classes, though low in N content, were significantly affected by tillage. There was no difference between NT and RT N content in the 2000- to 1000-μm class (Fig. 8b), but the two conservation tillage treatments were significantly ($P < 0.01$) lower in N than the CT treatment. In the next smaller class, the 1000- to 500-μm fraction, NT and RT were similar ($P = 0.76$), but CT was significantly ($P < 0.05$) greater than the conservation tillage treatments. The 500- to 212-μm size class contained much more N than the two larger size classes. Again, there was no significant ($P = 0.93$) difference in N content among the conservation tillage treatments. But the CT treatment was significantly ($P < 0.01$) greater in N than the conservation tillage treatments. Similarly, the 212- to 125-μm class contained about the same amount of N as the 500- to 212-μm fraction, and CT accounted for a greater amount of N than the previous, larger class. Variation was high in this group, however, and none of the differences were significant (lowest $P = 0.27$). The smallest fraction displayed a similar dominance of the CT tillage treatment, but variation was too great to detect significant (lowest $P = 0.18$) differences. At the 0- to 5-cm depth, conservation tillage treatments dominated the N content of the aggregates (Fig. 8a), but the CT treatment did so at the 10- to 15-cm depth (Fig. 8b). These data show a marked effect of tillage on N content in aggregates at the 10- to 15-cm depth. Expressing them in this manner gives a different view of the effects to that seen in Fig. 7, which shows few tillage effects on N percentage in the aggregates. The data in Fig. 7 are more consistent with those of Wright and Hons (2005c), which show few effects of tillage on N concentrations at the 10- to 15-cm soil depth, indicating that the effects of the conservation tillage treatments, after 13 yr of application in a hot climate, had not affected the N content of the midsized aggregates, and except for the >4750-μm fraction's reduced N content.

Aggregate Carbon/Nitrogen Ratio

Carbon/N ratios can provide some information concerning availability of the elements, as well as some information on the relative lability of the organic material contained in the aggregates. Carbon/N ratios were calculated on C and N concentration values for each aggregate size fraction (Fig. 9). Analysis showed that there were no significant (lowest $P = 0.46$) interactions between cropping systems and tillage. There were also no significant (lowest $P = 0.29$) cropping system main effects as well. Significant tillage main effects were found only at the 0- to 5-cm depth (Fig. 9a).

The lowest C/N ratios were produced by the NT treatment in all aggregate size fractions (Fig. 9a). The ratios for NT were significantly (highest $P < 0.001$) lower in all aggregate classes. In addition, the conservation tillage treatments together were significantly (highest $P < 0.04$) lower than the C/N ratio of the CT treatment. The CT, NT, and RT treatments at the 0- to 5-cm depth averaged C/N ratios of 14.6, 11.9, and 14.1, respectively. The C/N values were remarkably similar across aggregate size classes at the 0- to 5-cm depth, while mass-weighted values for C (Fig. 4a) and N (Fig. 8a) content of different aggregate size fractions were strongly affected by tillage treatments.

The results for samples taken at the 10- to 15-cm depth were generally similar to those from 0 to 5 cm. There were no significant interactions between tillage and cropping systems (lowest $P = 0.46$) and no significant tillage (lowest $P = 0.09$) or cropping system (lowest $P = 0.51$) main effects. Orthogonal contrasts, however, detected a significant ($P = 0.03$) difference between NT and RT effects on C/N in the >4750-μm aggregate size class, and in the 500- to 212-μm class ($P < 0.05$; Fig. 9b).

These results again point to greater effects of tillage at the 0- to 5-cm depth than the 10- to 15-cm depth. Apparently, C and N enrichment that often results from the use of conservation tillage is very slow to impact soils, even to a modest depth, in this climate. This agrees with the findings of Zibilske et al. (2002), who found distinct tillage effects on the vertical distribution of total C and N in bulk soil managed with conservation tillage. Kushwaha et al. (2001), however, found wider C/N ratios in macroaggregate fractions (>300 μm) in a tropical rice (*Oryza sativa* L.)–barley (*Hordeum vulgare* L.) system.

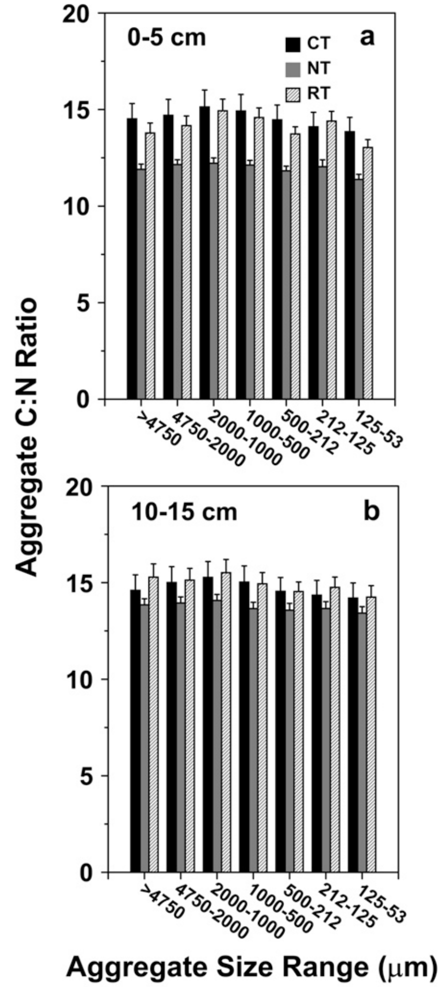

Fig. 9. Soil C/N ratio in aggregate size fractions of soil from two depths after 13 yr of conventional tillage (CT), no-tillage (NT), or ridge tillage (RT). Original soil sample size was 100 g. Bars are ±1 SEM, $n = 4$.

CONCLUSIONS

These results show the cumulative effects of 13 yr of conservation tillage on a sandy silt loam soil in the semiarid subtropics. At 0 to 5 cm, soil mass contained in larger aggregate size fractions (>4750–2000 μm) was generally greater for NT, but was more affected by CT and RT in aggregate size classes <2000 μm. At the 10- to 15-cm depth, more soil was found in the largest aggregates (>4750–2000 μm) from the NT and RT treatments compared with that from the CT treatment; however, CT was responsible for more soil contained in aggregates <2000 μm. At both depths, most of the dispersed clay and particles sized <53 μm was attributable to CT. Water holding capacities were greater for conservation tillage treatments at all tested moisture tensions, reemphasizing the positive effects of reduced tillage on soil aggregation. A greater percentage of C was found in all aggregate size classes with the conservation tillage treatments than CT at the 0- to 5-cm depth. At the 10–15-cm depth, however, the highest C percentages were found in aggregates from the CT and RT treatments, again reflecting a probable lower deposition of C due to the NT treatment at the lower depth. Organic N percentages in the aggregates were uniformly greater in all aggregate size classes with the conservation tillage treatments at the 0- to 5-cm depth. This contrasts somewhat with C percentages for this depth in that many of the highest C percentages were due more to the NT than to the RT treatment, whereas N percentages were more positively affected by NT. At 10 to 15 cm, however, CT led to slightly greater percentages of N across the aggregate size classes, but treatment effects were much more uniform. Most of the N was contained in aggregates of the >4750- and 500- to 212-μm classes. For aggregates <2000 μm, however, the N content of the aggregates at the lower depth appears to have been dominated more by the CT treatment. These results demonstrate positive, albeit slow, effects of both conservation tillage practices on C and N retention in soil. These results also show that, in this hot climate, conservation tillage effects on soil C and N were greater in the 0- to 5-cm depth, suggesting that very different conditions exist for organic matter decomposition between the surface layers and those below. Improvements in C and N content and in soil water relationships have been achieved over the long term in this semiarid, subtropical agroecosystem. This may be changed, however, by increasing cropping intensity with cover crops. Little effect of cropping system on aggregate C and N distribution and accumulation was detected, which suggests that, in hot climates, cotton or corn residue management may not be as important as reducing tillage to improve soil organic matter content. Adding diversity and intensity to the cropping system may accelerate soil organic matter increase and further change the distribution of C an N in soil aggregates.

REFERENCES

Beare, M.H., P.F. Hendrix, and D.C. Coleman. 1994. Water-stable aggregates and organic matter fractions in conventional- and no-tillage soils. Soil Sci. Soc. Am. J. 58:777–786.

Bescansa, P., M.J. Imaz, I. Virto, A. Enrique, and W.B. Hoogmoed. 2006. Soil water retention as affected by tillage and residue management in semiarid Spain. Soil Tillage Res. 87:19–27.

Besnard, E., C. Chenu, J. Balesdent, P. Puget, and D. Arrouays. 1996. Fate of particulate organic matter in soil aggregates during cultivation. Eur. J. Soil Sci. 47:495–503.

Blair, N., R.D. Faulkner, A.R. Till, M. Korschens, and E. Schulz. 2006. Long-term management impacts on soil C, N, and physical fertility. Part II. Bad Lauchstadt static and extreme FYM experiments. Soil Tillage Res. 91:39–47.

Blevins, R.L., and W.W. Frye. 1993. Conservation tillage: An ecological approach to soil management. Adv. Agron. 51:33–58.

Bronick, C.J., and R. Lal. 2005. Soil structure and management: A review. Geoderma 124:3–22.

Cambardella, C.A., and E.T. Elliott. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57:1071–1076.

Denef, K., J. Six, R. Merckx, and K. Paustian. 2004. Carbon sequestration in microaggregates of no-tillage soils with different clay mineralogy. Soil Sci. Soc. Am. J. 68:1935–1944.

Eynard, A., T.E. Schumacher, M.J. Lindstrom, and D.D. Malo. 2005. Effects of agricultural management systems on soil organic carbon in aggregates of Ustolls and Usterts. Soil Tillage Res. 81:253–263.

Feller, C., and M.H. Beare. 1997. Physical control of soil organic matter in the tropics. Geoderma 79:69–116.

Fernandes, E.C.M., P.P. Motavalli, C. Castilla, and L. Mukurumbira. 1997. Management control of soil organic matter dynamics in tropical land-use systems. Geoderma 79:49–67.

Franzluebbers, A.J. 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Tillage Res. 66:197–205.

Franzluebbers, A.J., F.M. Hons, and D.A. Zuberer. 1994. Long-term changes in soil carbon and nitrogen pools in wheat management systems. Soil Sci. Soc. Am. J. 58:1639–1645.

Gee, G.W., and J.W. Bauder. 1986. Particle-size analysis. p. 383–411. *In* A. Klute (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. SSSA Book Ser. 5. SSSA, Madison, WI.

Gregorich, E.G., B.H. Ellert, C.F. Drury, and B.C. Liang. 1996. Fertilization effects on soil organic matter turnover and corn residue C storage. Soil Sci. Soc. Am. J. 60:472–476.

Hassink, J., L.A. Bouwman, K.B. Zwart, J. Bloem, and L. Brussaard. 1993. Relationships between soil texture, physical protection of organic matter, soil biota, and C and N mineralization in grassland soils. Geoderma 57:105–128.

Hevia, G.G., D.E. Buschiazzo, E.N. Hepper, A.M. Urioste, and E.L. Antón. 2003. Organic matter in size fractions of soils of the semiarid Argentina. Effects of climate, soil texture and management. Geoderma 116:265–277.

Holeplass, H., B.R. Singh, and R. Lal. 2004. Carbon sequestration in soil aggregates under different crop rotations and nitrogen fertilization in an Inceptisol in southeastern Norway. Nutr. Cycling Agroecosyst. 70:167–177.

Kemper, W.D., and R.C. Rosenau. 1986. Aggregate stability and size distribution. p. 425–442. *In* A. Klute (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. SSSA Book Ser. 5. SSSA, Madison, WI.

Klute, A. 1986. Water retention: Laboratory methods. p. 635–662. *In* A. Klute (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. SSSA Book Ser. 5. SSSA, Madison, WI.

Koch, H.-J., and N. Stockfish. 2006. Loss of soil organic matter upon ploughing under a loess soil after several years of conservation tillage. Soil Tillage Res. 86:73–83.

Kushwaha, C.P., S.K. Tripathi, and K.P. Singh. 2001. Soil organic matter and water-stable aggregates under different tillage and residue conditions in a tropical dryland agroecosystem. Appl. Soil Ecol. 16:229–241.

Márquez, C.O., V.J. Garcia, C.A. Cambardella, R.C. Schultz, and T.M. Isenhart. 2004. Aggregate-size stability distribution and soil stability. Soil Sci. Soc. Am. J. 68:725–735.

Martens, D.A. 2000. Plant residue biochemistry regulates soil carbon cycling and carbon sequestration. Soil Biol. Biochem. 32:361–369.

Mikha, M.M., and C.W. Rice. 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. Soil Sci. Soc. Am. J. 68:809–816.

Norwood, C. 1994. Profile water distribution and grain yield as affected by cropping system and tillage. Agron. J. 86:558:563.

Paustian, K., H.P. Collins, and E.A. Paul. 1997. Management controls in soil carbon. p. 15–49. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate ecosystems: Long-term experiments in North America. CRC Press, Boca Raton, FL.

Potter, K.N., H.A. Torbert, O.R. Jones, J.E. Matocha, J.E. Morrison, Jr., and P.W. Unger. 1998. Distribution and amount of soil organic C in long-term management systems in Texas. Soil Tillage Res. 47:309–321.

Rhoton, F.E. 2000. Influence of time on soil response to no-till practices. Soil Sci. Soc. Am. J. 64:700–709.

Shukla, M.K., and R. Lal. 2005. Erosional effects on soil physical properties in an on-farm study on Alfisols in west central Ohio. Soil Sci. 170:445–456.

Six, J., E.T. Elliott, and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32:2099–2103.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33:141–163.

Wander, M.M., and M.G. Bidart. 2000. Tillage practice influences on the physical protection, bioavailability and composition of particulate organic matter. Biol. Fertil. Soils 32:360–367.

Wright, A.L., and F.M. Hons. 2005a. Carbon and nitrogen sequestration and soil aggregation under sorghum cropping sequences. Biol. Fertil. Soils 41:95–100.

Wright, A.L., and F.M. Hons. 2005b. Soil carbon and nitrogen storage in aggregates from different tillage and crop regimes. Soil Sci. Soc. Am. J. 69:141–147.

Wright, A.L., and F.M. Hons. 2005c. Tillage impacts on soil aggregation and carbon and nitrogen sequestration under wheat cropping sequences. Soil Tillage Res. 84:67–75.

Zibilske, L.M., and J.M. Bradford. 2003. Tillage effects on phosphorus mineralization and microbial activity. Soil Sci. 168:677–685.

Zibilske, L.M., J.M. Bradford, and J.R. Smart. 2002. Conservation tillage induced changes in organic carbon, total nitrogen and available phosphorus in a semi-arid alkaline subtropical soil. Soil Tillage Res. 66:153–163.

Zibilske, L.M., and L.A. Materon. 2005. Biochemical properties of decomposing cotton and corn stem and root residues. Soil Sci. Soc. Am. J. 69:378–386.