

Soil Carbon Sequestration in Kansas: Long-Term Effect of Tillage, N Fertilization, and Crop Rotation

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ABSTRACT

Soil C sequestration in agricultural ecosystems is a near-term option to mitigate the increase in the atmospheric CO₂ concentration. Some of the management practices to reduce C loss or induce C gains from agriculture soils include reduced tillage intensity and bare fallow periods, enhanced rotations, and the use of winter cover crops. The objective of our study was to determine the influence of long-term management practices such as tillage, N fertilization, and crop rotations on soil C content, and to estimate C sequestration rates under Kansas conditions. Four long-term experiments covering a range of climate conditions and management systems were sampled for soil organic carbon (SOC). All the sites evaluated (Tribune, Manhattan, Parsons, Hays) included tillage systems as a variable: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). Nitrogen (N) fertilization was evaluated in studies at Parsons (0 and 140 kg N ha⁻¹) and at Hays (0, 22.45, and 67 kg N ha⁻¹). Crop rotation effects were studied at Manhattan, including continuous winter wheat (*Triticum aestivum* L.) (W-W), continuous sorghum (*Sorghum bicolor* L. Moench) (S-S), continuous soybean (*Glycine max* L. Merrill) (B-B), wheat-soybean (W-B), and sorghum-soybean (S-B). Soil samples were taken at depths of 0-5, 5-15 and 15-30 cm. Total C contents were determined by dry combustion. Soil organic C contents were significantly greater under NT, compared with CT, at 0-5 cm; differences were less pronounced at deeper depths. At 0-30 cm, SOC tended to be greater under NT than under CT. The presence of a fallow period in the rotations negatively affected C sequestration rates even under NT systems. Nitrogen fertilization increased C sequestration rates. Rotations that had wheat or sorghum had the greatest C rates, and continuous soybean had the lowest rates. The combination of conservation tillage and rotations that contributes with a greater amount of residue showed greater C sequestration rates.

Keys words: carbon sequestration, tillage, fertilization, crop rotation

Abbreviations: C, carbon; NT, no tillage; CT, conventional tillage; RT, reduced tillage; SOC, soil organic carbon, N, nitrogen.

INTRODUCTION

Over the past 150 years, an increase in atmospheric CO₂ has been attributed to an increase in fossil fuel combustion, deforestation, and land use change (Lal, 2004). Several strategies have been presented to reduce CO₂ emissions over both near- and long-term. Caldeira et al. (2004) summarized a range of management options to reduce C emissions: those that attempt to reduce C sources to the atmosphere, and those that tend to increase C sinks from the atmosphere. Some of the options available in the near-term include changes in agricultural management practices, and improved efficiency of appliances, lighting, motors, buildings, industrial processes, and vehicles (Calderia et al., 2004). Long-term options include C storage in geologic reservoirs or oceans, large-scale development of solar and wind resources, cessation of deforestation, development of energy-efficient transportation systems, development of highly efficient coal technologies, and generation of electricity from biomass (Caldeira et al., 2004).

Soil C sequestration is a viable near-term option to mitigate increased atmospheric CO₂ because it is relatively low cost and can be rapidly deployed across large areas (Post et al., 2004; Caldeira et al., 2004). Soils can be managed to maintain, restore, and/or enhance SOC content (Johnson, 1995). Enhanced soil C also can improve soil quality, productivity, water infiltration, and fertility, and reduce soil erosion (Halvorson et al., 2000).

Accumulation of soil organic C (SOC) is influenced by several factors, including climate, soil properties, vegetation, time, and management (Johnson, 1995). Soil C is a balance between inputs and outputs. Management practices that reduce C loss from

agricultural soils include reduced tillage intensity, a reduction in bare fallow period, and those that enhance inputs of crop residues, such as rotations, winter cover crops, and water management (Lal et al., 1998; Paustian et al., 2000; West and Post, 2002; Lal, 2004; Post et al., 2004).

In the U.S. Great Plains, several years of cultivation under crop-fallow rotation have led to a significant loss of soil C (Peterson et al., 1998). The intent of fallow was to accumulate water, but fallowing results in no crop residue additions, whereas microbial activity and organic matter decomposition continue (Halvorson et al., 2002; Campbell et al., 2005). The introduction of conservation tillage systems such as reduced and no-tillage systems allow better retention of water, and can allow an intensification of the cropping system and reducing the fallow period. As a result, soil C content may increase, as noted by Peterson et al. (1998). Sherrod et al. (2003) also found greater SOC under continuous cropping than in a wheat-fallow system in the central Great Plains. In annual cropping systems in the northern Great Plains, Halvorson et al. (2002) found that soil C increased by $0.23 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ and $0.025 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ for no-till and minimum tillage, respectively, but decreased by $0.141 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ under CT. Conversely, Sainju et al. (2006) reported that tillage and crop rotation did not influence SOC in a 6-yr experiment conducted in the northern Great Plains, which may be due to the time needed to detect changes in SOC.

Adequate N fertilization is needed to ensure optimum productivity and crop residue returns to the soil. Some studies have reported a positive effect of N application on SOC content (Rasmussen and Rohde, 1988; Campbell et al., 1997; Bowman and

Halvorson, 1998; Halvorson et al., 1999), but others have reported little or no effect of N fertilizer on SOC stocks (Halvorson et al., 2002; Russell et al., 2005).

A reduction in tillage can reduce C losses and even increase soil C content. West and Post (2002) analyzed data from numerous long-term studies across the world and reported an average C gain of $0.57 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ when changing from CT to NT systems and $0.20 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ by increasing the crop rotation intensity. West and Marland (2002), analyzing 76 long-term experiments in the USA, reported a potential rate of C sequestration of $0.337 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ for the conversion of CT to NT in agricultural soils.

Evaluation of the changes in SOC due to land use, agricultural practices, and climate will be necessary, and the use of models will play a key role in determining regional estimates of C sequestration under these practices. These estimates are important to policy makers who will use these management practices as strategies to reduce greenhouse gases (GHG) emissions (Falloon et al., 1998). Models have been used to determine the impact of management practices on soil C storage; however, SOC measurements from long-term experiments are needed for model validation. Campbell et al. (2005) compared the rates of change in SOC using the Century model and Campbell et al. (2000) model. Both models effectively simulated the effect of cropping frequency, but the values were lower than those reported from the experiment. The degree of soil C change will vary according to the crop, crop rotation, soil type, and climate (Donigian et al., 1997). Donigian et al. (1997) reported that SOC could increase 10 to 15% for reduced tillage and up to 50% for NT compared with CT, but further model testing and validation are needed.

Long-term studies are needed to validate model estimations of the effects of management practices on C sequestration (Izaurralde et al., 2001). It is necessary to collect information on the amount of C sequestered for a specific soil and duration (Post et al., 2004). Understanding the effect of management practices on biological and edaphic processes will help identify the best management options to offset increased atmospheric CO₂.

The objectives of our study was to determine the influence of different long-term management practices of tillage, N fertilization, and crop rotations on soil C storage, and to estimate the C sequestration rates under these management practices in different locations in Kansas.

MATERIALS AND METHODS

Site description

Four long-term experiments were selected covering a range of climate conditions, soils and management systems in Kansas (Table 1).

The Tribune experiment, initiated in 1988, was located in western Kansas (38° 30'N, 101° 41'W). The 30-yr average annual precipitation is 422 mm, with an annual mean temperature of 11.3 °C. The soil was classified as Richfield silt loam (fine-smectitic, mesic Aridic Argiustolls). The crop rotation was wheat-grain sorghum-fallow, with three tillage systems: CT, RT, and NT. Conventional tillage consisted of three or four operations per year with a sweep plow between crop harvest and planting the next crop. The RT system used a combination of tillage (primarily sweep plow) and herbicides for weed control during fallow. The number of tillage operations with RT was

approximately 50% of CT. No-tillage consisted of planting directly into the residue. Nitrogen fertilizer as urea ammonium nitrate (UAN) was broadcast applied at 67 kg N ha⁻¹ yr⁻¹ to 112 kg N ha⁻¹ yr⁻¹, depending on the year or crop. Native sod was included as part of the experimental design, which represented the natural vegetation types of C₃ and C₄ grass, with the dominant species being buffalograss (*Buchloe dactyloides*). The treatments were arranged in a randomized complete block design with four replications.

The Hays experiment is located in central Kansas (38° 51'N, 99° 20'W). This experiment was initiated in 1965 on a Harney silt loam soil (fine, smectitic, mesic Typic Argiustoll). The 30-yr average annual precipitation was 533 mm with an annual mean temperature of 11.9 °C. The crop rotation was wheat-grain sorghum-fallow, with three tillage systems: conventional tillage (CT), reduced tillage (RT), and no-tillage (NT). Conventional tillage consisted of using tools such as disk, one-way plow, and mulch treader. Reduced tillage included V-blade, sweeps or rod weeder. No-tillage consisted of planting directly into the residue. From the beginning of the experiment to 1975, N rates were 0 and 45 kg N ha⁻¹. Since 1975 four N rates were evaluated, 0 (0-N), 22 (22-N), 45 (45-N), and 67 (67-N) kg N ha⁻¹ yr⁻¹. Nitrogen fertilizer was applied as ammonium nitrate in the previous fall for June sorghum planting and in August prior to September wheat planting. The experimental design was split-plot with four replications, with tillage as the main plot and N as sub-plot.

The Manhattan experiment, initiated in 1974, was located on the Kansas State University Agronomy Farm, Manhattan (Riley County; 39° 07'N, 96° 37'W). Soils were Muir silt loam (fine-silty, mixed, mesic Cumulic Haplustoll) and Reading silt loam (fine, mixed, mesic Typic Argiudoll). The 30-yr average annual precipitation was 813 mm,

which was mainly concentrated in the spring-summer period, with an annual mean temperature of 11.3 °C. Crop rotation and tillage systems were evaluated in this experiment. The experimental design was split-plot with four replications, with rotation as the main plot and tillage as sub-plot. The three crops, soybean (B) (*Glycine max* (L.) Merrill), grain sorghum (S) (*Sorghum bicolor* (L.) Moench), and winter wheat (W) (*Triticum aestivum* L.), were combined in five rotations: continuous sorghum (S-S), sorghum-soybean (S-B), continuous soybean (B-B), wheat-soybean (W-B), and continuous soybean (B-B). The three tillage treatments were CT, RT, and NT systems. Conventional tillage included chisel, disk, and field cultivator. Reduced tillage included disk and field cultivator. No-tillage consisted of planting directly into the residue and chemical weed control. A blend of urea and diammonium phosphate fertilizer providing 112 kg N ha⁻¹ and 11.3 kg P ha⁻¹ was broadcast applied prior to the last tillage operation before planting of each crop and year.

The Parsons experiment is located in southeastern Kansas (37° 21.02'N, 95° 17.13'W). The 30-yr average annual precipitation is 1016 mm, with an annual mean temperature of 13.7°C. This experiment was initiated in 1983 on a Parsons silt loam soil (fine, mixed, active, thermic Mollic Albaqualfs). The crop rotation was grain sorghum-soybean, with three tillage systems (conventional tillage, reduced tillage, and no-tillage), and two N rates, 0 (0-N) and 140 kg N ha⁻¹ yr⁻¹ (140-N). Nitrogen fertilizer was urea-ammonium nitrate (UAN) solution. Conventional tillage included chisel, disk, and field cultivator. Reduced tillage included disk and field cultivator. No-tillage consisted of planting directly into the residue and using chemical weed control. The experimental

design was split-plot with four replications, with tillage as the main plot and N as sub-plot.

Soil Sampling

Soil samples were taken from each plot at 0- to 5, 5- to 15 and 15- to 30-cm depth increments. Sterile polypropylene bags (3.78 L) were filled with soil collected randomly from each plot using a 2-cm diam. Oakfield soil-probe (Forestry Suppliers, Inc., Jackson, MS). Samples were collected in March 2003 (before planting) on the sorghum rotation phase of the Hays experiment. For Parsons, samples were taken in December 2003 after sorghum harvesting. Tribune samples were collected in April 2004 in each phase of rotation (planted wheat, harvested sorghum, and fallow) and native sod. Soil samples from Manhattan were taken in May 2004, after soybean and sorghum planting and before wheat harvesting. Soil samples were passed through a 4-mm sieve, roots were removed, and samples were stored at 4°C until use.

Bulk density was determined using a 2-cm diam. Oakfield soil-probe (Forestry Suppliers, Inc., Jackson, MS). Two intact soil samples were taken at 0-5, 5-15, and 15-30 cm and dried at 105°C.

Total C

Soil samples were dried and ground to a fine powder with a mortar and pestle. Total C contents were determined by dry combustion using a C/N Elemental Analyzer

(Flash EA1112, Carlo Erba Instruments, Milano, Italy). Total C expressed in mass was calculated using bulk density data at each depth.

C sequestration rates: Calculations

Carbon sequestration rates were calculated using two approaches:

- 1) Baseline data: Rates were determined as the difference between the C values in 2003-2004 and the original values (calculated or measured) at the beginning of each experiment (37, 16, 20, and 29 yr for Hays, Tribune, Parsons, and Manhattan, respectively).

$$\text{C rate (Mg C ha}^{-1} \text{ yr}^{-1}) = (\text{SOC}_x - \text{SOC}_0) / \text{years}$$

where

SOC_x= soil organic C content at time x
SOC₀= soil organic C content at initial point
years= number of years under the experiment

- 2) As a difference between NT or RT with respect to CT treatments in 2003-2004.

$$\text{C rate (Mg C ha}^{-1} \text{ yr}^{-1}) = (\text{SOC}_{\text{RT or NT}} - \text{SOC}_{\text{CT}}) / \text{years}$$

where

SOC_{RT}= soil organic C content under reduced tillage
SOC_{NT}= soil organic C content under no-tillage.
SOC_{CT}= soil organic C content under conventional tillage.
years= number of years under the experiment

Carbon values at the beginning of the experiment (1965) in Hays were obtained from the sorghum phase. Bulk density values of 1.30 and 1.40 Mg m⁻³ for 0-5 and 5-15

cm were assumed to express the baseline data in mass of C. These values were close to the average bulk density data obtained in 2004.

For Tribune, it was assumed that the native prairie C values obtained in 2004 were the initial values because the experiment was established under native prairie soil in 1988. Bulk density was measured in 2004 to calculate C mass.

For Parsons, C concentrations were obtained in 1983 at the beginning of the experiment. Bulk density was assumed to be 1.35 Mg m^{-3} for 0-15 and 0-30 cm; these values were the average bulk density data obtained in 1983 at 0-5 cm.

For Manhattan, the initial values of 1975 were estimated by considering the C values from 1981 (Peterson, 1983). Soil C was measured 6 yr after implementation of the treatments. We assumed that there was a linear increase in C from 1975 to 1981. The rate of change between 2004 and 1981 (23 yr) for continuous wheat under CT was used to extrapolate estimated C values in 1975. Carbon values used as a reference were from plots under CT in the continuous wheat rotation, which were representative of the traditional management of the area before the experiment was started. Bulk density values used were those reported by Havlin and Kissel (1997), 1.36 Mg m^{-3} for 0-15 cm, and by Budde (2004) 1.46 Mg m^{-3} for 15-30 cm.

Statistical Analysis

Analysis of variance was performed by using SAS PROC MIXED (SAS Institute, 2002) to assess treatment differences on soil C and C sequestration rates. Results were considered statistically significant at $P < 0.05$, except where noted. Means were compared using LSD values.

RESULTS

Soil Organic Carbon

Tillage Effects

Soil organic C at Hays was significantly affected by tillage in the 0-5 and 15-30 cm depths (Table 2). No-tillage had greater amounts of SOC than RT and CT at the soil surface, but SOC was greater under CT than under RT or NT at 15-30 cm. No differences between tillage systems were observed when SOC was calculated for 0-15 and 0-30 cm.

At Tribune, SOC was similar between NT and RT, which were significantly greater than CT at 0-5 cm. There were no significant differences between tillage systems at the other depths, although NT had 2.1 Mg C ha⁻¹ more C than CT for 0-30 cm (Table 2).

At Parsons, tillage significantly affected SOC values at 0-5 cm with no-tillage averaging 3 Mg C ha⁻¹ more SOC than RT or CT (Table 2). No differences were observed at 5-15, 15-30 and 0-30 cm soil depths. Although, for 0-15 cm, NT had significantly greater amounts of SOC than RT and CT at $P=0.08$.

At Manhattan, a significant effect of rotation and tillage on SOC was observed at all depths. There was no significant interaction between tillage and rotation. At 0-5 cm, NT resulted in the highest SOC values; however, RT resulted in greater SOC at 5-15 and 15-30 cm, compared with NT and CT (Table 2). Soil organic carbon was similar between the NT and RT treatments, which were significantly greater than CT at 0-15 cm and 0-30 cm.

Nitrogen effects

Nitrogen application at Hays significantly affected SOC values for 0-5 cm and 0-15 cm. The higher N rates, 45-N and 67-N, resulted in greater SOC (8 and 8.4 Mg C ha⁻¹, respectively) than the 0-N and 22-N rates (7.3 and 7.4 Mg C ha⁻¹, respectively). For 0-15 cm, N application significantly affected SOC ($P=0.058$) where the 67-N rate (22.9 Mg C ha⁻¹) resulted in similar SOC to that for 47-N (22.2 Mg C ha⁻¹), but was greater than the SOC at the lower N rates (21.4 Mg C ha⁻¹).

At Parsons, there was a significant effect of N application at 0-30 cm where the 140-N rate (39.2 Mg C ha⁻¹) had 1.9 Mg C ha⁻¹ more C than the 0-N rate (37.3 Mg C ha⁻¹). Also, differences in SOC between N rates were observed at 0-5 cm ($P=0.0953$) and 0-15 cm ($P=0.0695$), 0.5 Mg C ha⁻¹ and 1.3 Mg C ha⁻¹, respectively.

Rotation effects

At Manhattan, continuous wheat resulted in the greatest amount of SOC at 0-5 cm, and continuous soybean resulted in the least SOC (Table 3). Continuous sorghum and S-B had similar SOC content, but less than W-W. At 5-15, 0-15 and 0-30 cm, SOC was greater under continuous wheat than under wheat in rotation (W-B). Also, SOC was greater where sorghum was in the rotation (S-S and S-B). Continuous soybean resulted in the lowest SOC (Table 2.3). At 15-30 cm, rotations with wheat had significantly greater SOC than those rotations that had sorghum or continuous soybean.

Carbon Sequestration Rates

Carbon sequestration rates for 0-15 cm at Hays were positive and significantly greater with NT systems, compared with CT and RT systems, which loss C (Table 4).

Nitrogen application increased C sequestration rates ($p < 0.10$). Across tillage, there was a reduction in the loss of C with the increase in the rate of N application, with no gain or loss in the 67-N treatment (Table 4). It should be noted that N application is considered sub-optimal over the course of the experiment as yield potential of the varieties changed. The N response would be expected to be greater under NT.

At Tribune, soil C sequestration rates were negative for all tillage systems at 0-15 and 0-30 cm, indicating a net loss of C from the system. This was not surprising given that this experiment was initiated in native prairie; however, NT lost the least amount of C (Table 5).

At Parsons, C sequestration rates were not significantly different among treatments, except at 0-30 cm where the 140-N rate resulted in a greater C sequestration rate ($0.32 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) than the 0-N rate ($0.21 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) (Table 6). There was an increasing trend for greater C sequestration rate as tillage intensity decreased.

At Manhattan, a significant rotation and tillage effect on C sequestration rates at the 0-15 and 0-30 cm depths. NT had similar rates of C sequestration as RT, but they were significantly greater than those under CT systems (Table 7). For 0-15 and 0-30 cm, the rates of C sequestration had the following order: W-W > W-B > S-B ~ S-S > B-B. Soybean monoculture had the lowest and negative C rate, which indicates a significant reduction in the SOC stocks after 29 yr of cultivation (Table 3).

Relative differences with respect to CT (Avoided C loss)

At Hays, the differences between NT or RT and CT were not significantly affected by tillage or N application. At 0-15 cm, the negative rates indicate a net C loss in both tillage systems, but this decrease tended to be greater under RT than under NT (Table 4). After 37 yr, NT lost 0.78 Mg C ha⁻¹ and RT lost 2.04 Mg C ha⁻¹ compared with CT.

At Tribune, there were no significant differences among tillage systems, but NT tended to have a greater C sequestration rate compared with RT at both depths (Table 5). After 16 yr, NT retained 1.59 Mg C ha⁻¹ and RT 0.83 Mg C ha⁻¹ compared with CT at 0-15 cm. At 0-30 cm, NT had 2.16 Mg C ha⁻¹ and RT had 0.38 Mg C ha⁻¹ compared with CT after 16 yr.

Similar to Tribune, there were no significant differences with respect to CT at the Parsons site (Table 6). On average, after 20 yr, NT had a positive increase in TOC of 1.76 Mg C ha⁻¹, compared with CT, at 0-15 cm and an increase of 2.37 Mg C ha⁻¹ at 0-30 cm. The RT systems resulted in positive values only at 0-30 cm (Table 6).

At the Manhattan site, tillage was not significant, but C sequestration rates tended to be greater under NT systems than under RT at both depths (Table 7). At 0-30 cm, relative C sequestration rates tended to be greater under S-S, S-B, and B-B rotation (Table 7). These results reflect that a change to conservation tillage had a greater impact on C sequestration rates in continuous soybean or sorghum rotations.

DISCUSSION

Our results present differences in response to management practices, according to site location and previous and current management. The impact of tillage was reflected at the soil surface (0-5 cm) where SOC was greater under NT than under CT at all sites evaluated (Table 2, Fig. 1a). The differences between NT and CT were less at deeper depths (5-15 and 15-30 cm) (Fig 1b, c). Several authors have found that the tillage impact is confined to the soil surface (Six et al., 1999; West and Post, 2002; Deen and Kataki, 2003; Fabrizzi et al., 2003; Mikha and Rice, 2004; Wright and Hons, 2004, 2005a,b). Results from our research showed the positive impact that reduced tillage and no-tillage systems have on SOC accumulation. The limited soil disturbance and better aggregation (McVay et al., 2006) under these systems could explain the greater C storage with respect to CT systems.

When all the soil layers were combined (0-15 or 0-30 cm), there were no significant differences in SOC contents between tillage systems, except at the Manhattan site, although in most cases NT tended to result in greater SOC content (Fig. 2 and 3). At the Manhattan site, NT and RT had similar SOC contents, but values were significantly greater than those of CT at both depths. Previous researchers have reported similar positive gains with no-tillage management (Cambardella and Elliot, 1994; Six et al., 1999; Fabrizzi et al., 2003). However other studies found no increase in SOC contents under NT systems (Angers et al., 1997; Franzluebbbers et al., 1999; Needelman et al., 1999; Puget and Lal, 2005; Sainju et al., 2006). Explanations for the lack of NT response for SOC are high initial content of SOC, high clay content, fine-textured and poorly drained soils, less crop residue returns to the soil, and reduced decomposition in cold-wet soils. Time is another factor for SOC (Needelman et al.,

1999), however our studies were conducted at long-term sites that had been managed for 16 yr or more.

Crop yields under NT were similar or lower than under CT or RT except at the Tribune and Manhattan site (Table 8). The lower yields might explain the lower response in SOC for NT at the Hays and Parsons sites. The increase in SOC seems to be related to less decomposition and greater physical protection of the C under NT systems (Mikha and Rice, 2004) since C inputs were generally the same or less with no-tillage systems.

One concern comparing different tillage systems is redistribution of SOC to shallower depths in NT with greater SOC in CT systems at deeper depths. Our results indicated that there was no redistribution of C among tillage systems. At 0-30 cm NT had a greater, but not significant C mass than CT, which is mainly due to the increase of 2 to 6% C under NT with respect to CT at 0-5 cm. There were no differences in SOC mass at 15-30 cm except at Hays. Our results are in accord with those reported by Frye and Blevins (1997), who found greater SOC under NT systems at 0-30 cm after 20 yr, with most of this C increase observed at 0-5 cm, however they observed greater SOC in NT at 5-15 and 15-30 cm. The authors mentioned that the increase in SOC at depth under NT could be related to inputs from crop roots. Olson et al. (2005) reported greater SOC under NT than under CT at down to 75 cm; all depths evaluated showed an increase of SOC compared with CT.

The C rates under CT and RT at Hays indicate a loss of C from the system, whereas the rate under NT was positive ($0.020 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$). Thompson and Whitney (2000) for the same experiment reported no significant change in SOM after 30 yr,

suggesting that the buildup or depletion was very slow because of the rotation and low annual precipitation for this area. The lower rates of C sequestration observed under NT might be explained by the presence of bare fallow in the rotation and the sub-optimal N fertilization (67 kg N ha^{-1}), which probably reduced the potential crop yield, and therefore the amount of residue returned to the soil.

Land use history is important when evaluating the effect of management on soil C (Paustian et al., 1997). At the Tribune site, all tillage systems had a negative C sequestration rate, but the C loss rate was lower under NT (4%) than under either RT (7%) or CT (9%). This experiment was initiated in native prairie sod, thus having a better initial soil C condition than the other experiments, which had been under cultivation before the establishment of the tillage systems. Similar results were reported for a long-term experiment in Kentucky initiated in a native sod, in which the loss of C in the early years was less under no-tillage management (9%) than under conventional tillage (15%) for a continuous corn (*Zea mays*)-winter cover crop rotation (Frye and Blevins, 1997). In the experiment at Kentucky, SOC content after 20 yr was similar for CT, and greater under NT compared with SOC of the native sod. Our results showed that, even with the introduction of NT, after 16 yr it was not possible to reach the same C values present in the native prairie. Other authors also found similar results (Olson et al., 2005; Lyon et al., 1996).

Inclusion of bare fallow in the rotation had a negative effect on the buildup of SOC. The intent of the fallow is to accumulate soil water for plant growth, but during this period, increased soil water supports, microbial activity and decomposition of soil organic matter while no plant material is added to the soil (Halvorson et al., 2002). This

scenario results in a net loss of soil C. West and Post (2002) reported no significant increase in SOC for a change from CT to NT under wheat-fallow rotations. In the northern Great Plains, a change from crop-fallow to more intensive systems can have a positive impact on C sequestration and farm profitability (Peterson et al., 1998; Halvorson et al., 2002; Sherrod et al., 2003). Several studies have mentioned that an intensification of the rotation by including more crops is needed to increase and maintain SOC stocks (Russell et al., 2005; Varvel, 2006; Sherrod et al., 2003; Halvorson et al., 2002; Campbell et al., 2005; Machado et al., 2006).

Nitrogen fertilization significantly affected C sequestration rates where the highest rate of N application had the greatest C sequestration rates, which can be attributed to greater amount of residues produced with increased N. These results are in accord with those reported by Nyborg et al. (1995) and Halvorson et al. (1999), however Halvorson et al. (2002) reported that N fertilization had little effect on C sequestration, even when the amount of residue returned increased with N fertilization.

Crop rotations that included wheat or sorghum had the greatest C sequestration rates. Soybean monoculture had a net loss of C from the system. The rotation effect could be related to residue quality. Wheat residues have a higher C/N ratio and lower turnover rates compared with sorghum and soybean residues (Wright and Hons, 2005a). Continuous soybean generally results in less SOC (Studdert and Echeverría, 2000; Wright and Hons, 2004). Carbon sequestration rates under W-B and W-W were similar or greater than those reported by Lal et al. (1998, 1999), which averaged $0.20 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ for an improvement in crop rotation management, and by West and Post

(2002), who also reported an average mean C rate of $0.20 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$, excluding changes from continuous corn to a corn-soybean rotation.

The Intergovernmental Panel of Climate Change (IPCC) has developed guidelines to determine the National Greenhouse Gas Inventory through the estimation of emissions and sinks of GHG. They have recommended coefficients to estimate soil C stocks by different agricultural land-use and management practices. The IPCC suggests a tillage factor of 1.10 for NT and 1.05 for RT compared to CT, at 0-30 cm, to estimate the potential to sequester C. Our factor was 1.14 for NT, and 1.08 for RT at 0-30 cm (Fig. 2.3). Adopting reduced tillage, results in an increase in SOC about half of that obtained under NT systems. West and Post (2002) found values similar to our results (1.16 for CT to NT).

To determine temporal changes in SOC stocks, Izaurralde et al. (2001) described two alternatives for selecting the control; one considers SOC at time-zero, followed by sampling of SOC at another time, and the second is to measure SOC at the same time between the new practices with respect to the conventional management. Our data reflect the variability in response to management on the calculation of the C sequestration rates (Izaurralde and Rice, 2006); thus, both the baseline and the change in practices should be reported. McGill et al. (1996) concluded that both ways to calculate C were important to monitor soil C sequestration for determining soil C sinks.

In summary, combining management practices can increase C sequestration in soils. Practices that have reduced disturbance, such as no-tillage, combined with rotations that contribute with greater amount of residue, showed greater rates of C sequestration. There was a gradient on C rates according to the precipitation rates; an increase in C

rates was observed from west to east. The presence of fallow in the rotation affected the rates even under no-tillage management, for which a small rate or no change was observed. The IPCC default value is a conservative estimator of the effect of NT. It seems from our results that the effect of RT systems on SOC is about 50% of the effect of NT systems. These results can be further used to validate models that will extrapolate C rates in the state of Kansas for different management practices

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1 **FIGURES**

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3 Figure 1. Soil organic carbon (SOC) at 0-5, 5-15, and 15-30 cm as a result of changing
4 from conventional tillage (CT) to reduced tillage (RT) or no-tillage. Dashed line
5 indicates 1:1 relationship.

6 Figure 2. Soil organic carbon (SOC) at 0-15 cm as a result of changing from
7 conventional tillage (CT) to reduced tillage (RT) or no-tillage. Dashed line
8 indicates 1:1 relationship.

9 Figure 3. Soil organic carbon (SOC) at 0-30 cm as a result of changing from
10 conventional tillage (CT) to reduced tillage (RT) or no-tillage. Dashed line
11 indicates 1:1 relationship.

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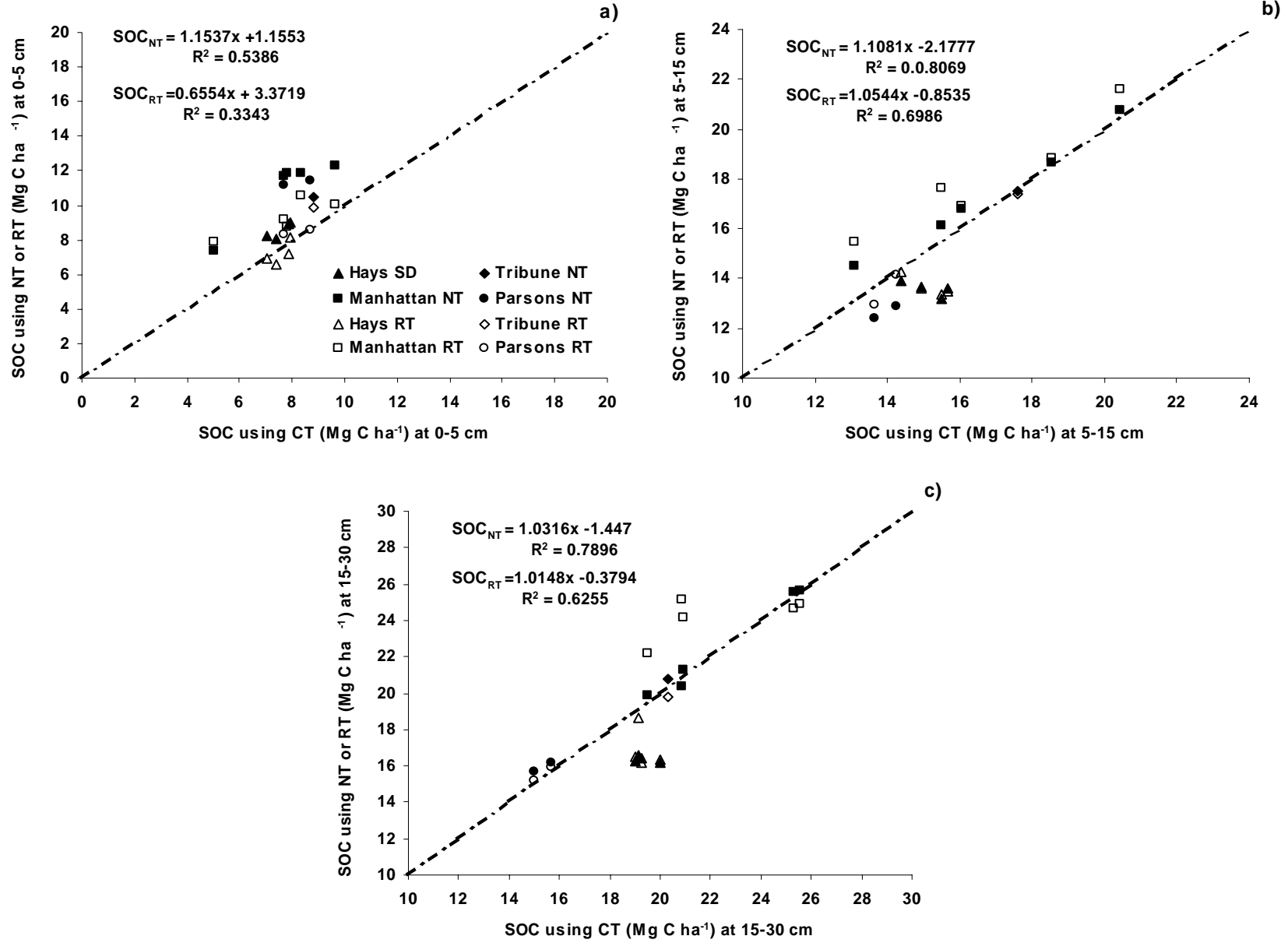


Figure 1

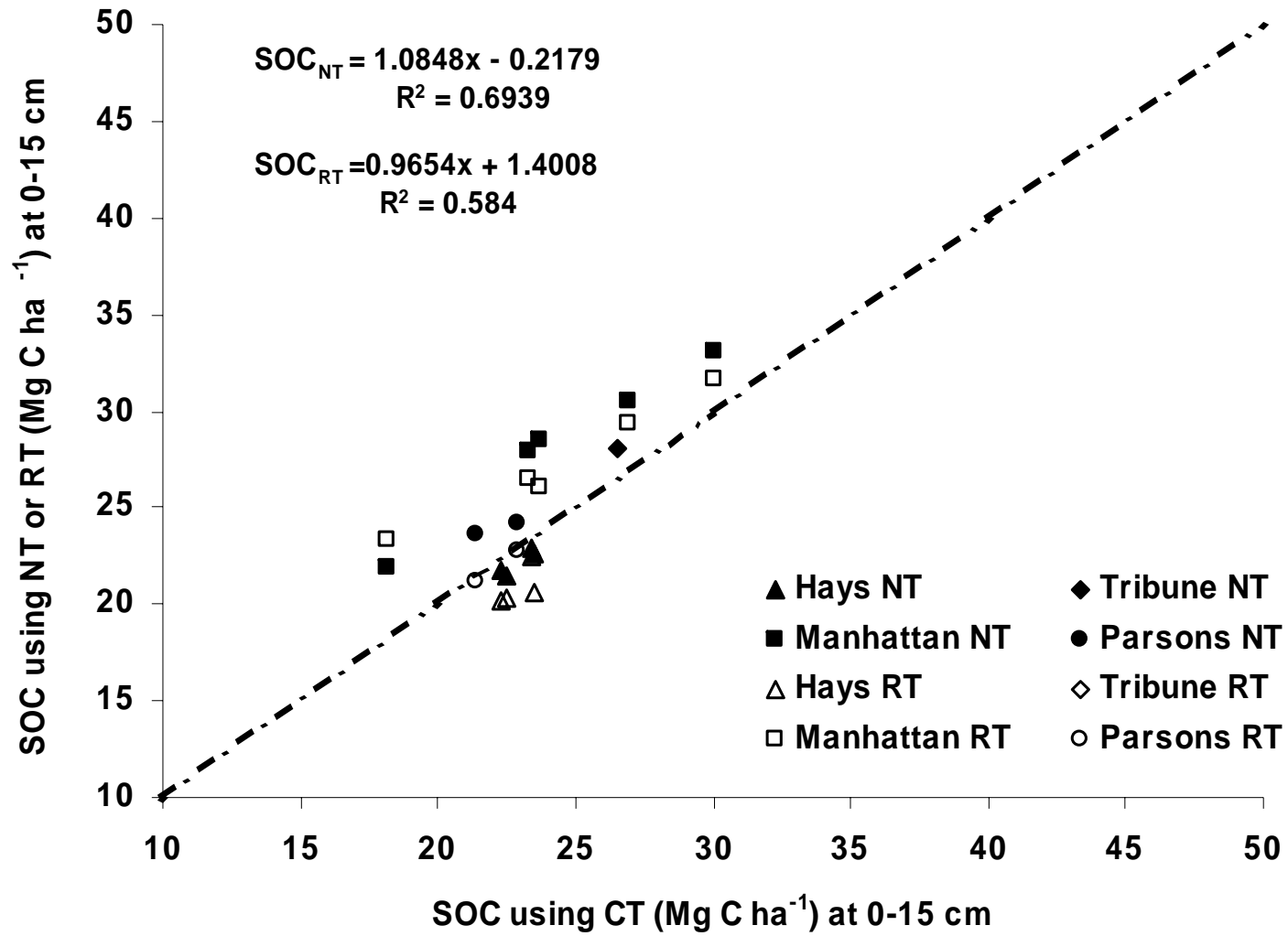
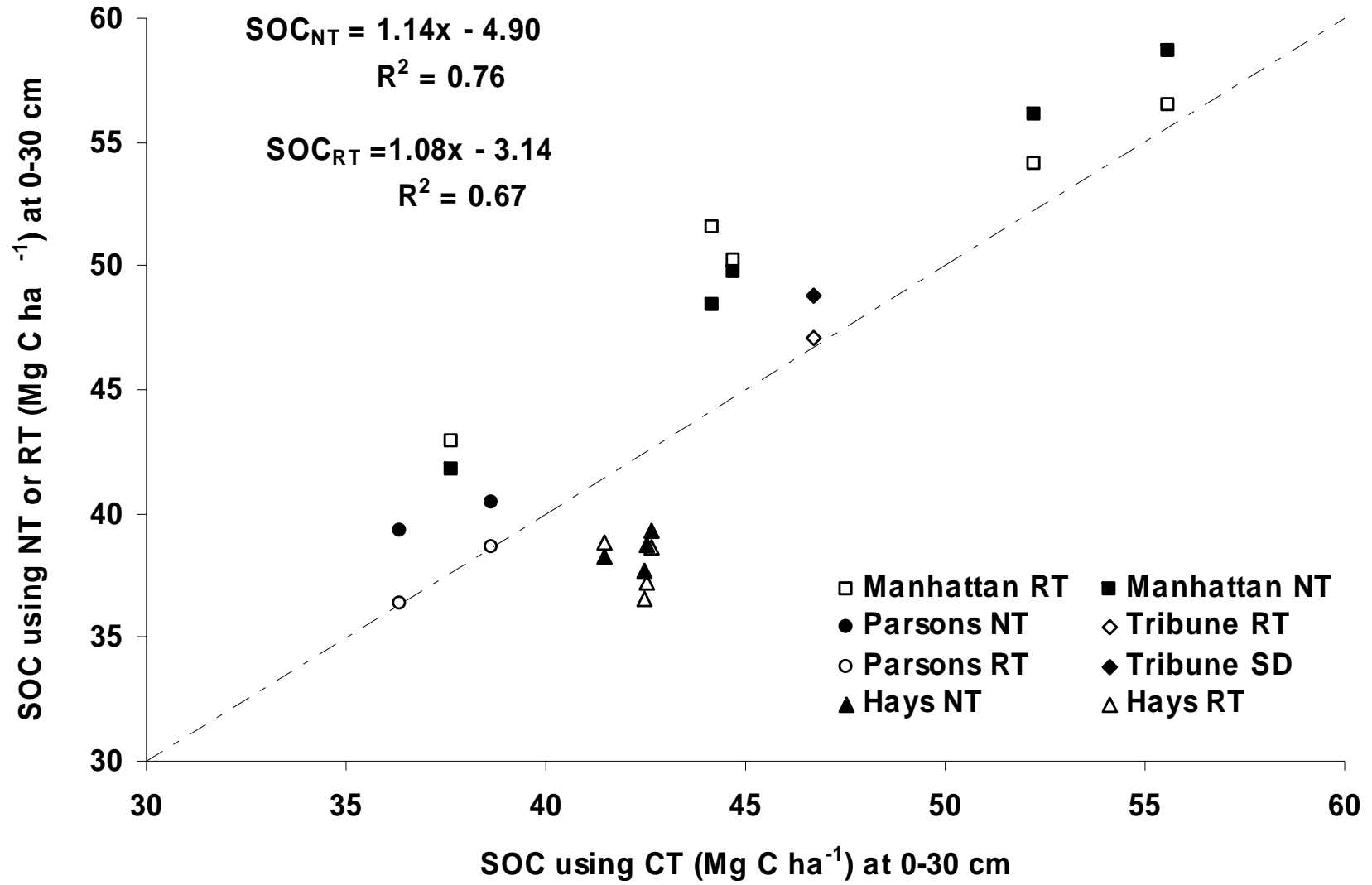


Figure 2

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Figure 3

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Table 1. Description of the experimental sites.

Site	Location	Soil Type	Yr. after initiation	Precipitation	Clay	Silt	Sand
			years	mm%.....		
Tribune	Southwest	Aridic Argiustolls	16	421	24	60	16
Hays	North Central	Typic Argiustolls	37	578	27	63	10
Manhattan	Northeast	Cumulic Haplustolls	29	813	20	71	9
Parsons	Southeast	Mollic Albaqualfs	20	1014	13	68	19

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Table 2. Soil organic carbon (SOC) under conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) for each experiment.

Site	Depthcm.....	SOCMg C ha ⁻¹			
		CT	RT	NT	Native Prairie
Tribune	0-5	8.8 b	9.9 a	10.5 a	11.46
	5-15	17.6	17.4	17.5	17.11
	15-30	20.3	19.8	20.8	22.48
	0-15	26.5	27.2	28.0	28.57
	0-30	46.7	47.1	48.8	51.05
	Hays	0-5	7.6 b	7.2 b	8.6 a
5-15		15.4	13.7	13.5	
15-30		19.4 a	16.9 b	16.3 b	
0-15		22.9	20.9	22.2	
0-30		42.3	37.8	38.5	
Parsons		0-5	8.2 b	8.4 b	11.3 a
	5-15	14.0	13.6	12.7	
	15-30	15.3	15.5	15.9	
	0-15	22.2	22.0	23.9	
	0-30	37.5	37.5	39.9	
	Manhattan	0-5	7.7 c	9.3 b	11 a
5-15		16.7 b	18.1 a	17.4 b	
15-30		22.4 b	24.2 a	22.5 b	
0-15		24.4 b	27.4 a	28.4 a	
0-30		46.8 b	51.6 a	50.9 a	

Different letters represent significant differences between tillage systems at each depth ($P < 0.05$).

1 Table 3. Effect of crop rotation on soil organic carbon (SOC) in Manhattan experiment.

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Site	Depthcm.....	SOCMg C ha ⁻¹				
		B-B	S-S	S-B	W-B	W-W
Manhattan	0-5	6.7 d	9.5 b	9.5 b	10.3 ab	10.6 a
	5-15	14.4 d	16.4 c	16.6 c	18.7 b	20.9 a
	15-30	20.5 b	22.1 b	22.1 b	25.2 a	25.3 a
	0-15	21.1 d	25.9 c	26.1 c	29.0 b	31.5 a
	0-30	41.6 d	48.0 c	48.2 c	54.2 b	56.8 a

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Different letters represent significant differences between crop rotations at each depth (P<0.05).

1 Table 4. Carbon sequestration rate (C rate) and C rate as difference with CT, under conventional tillage (CT),
 2 reduced tillage (RT), and no-tillage (NT); with 0, 22, 45, or 67 kg N ha⁻¹ at 0-15 cm soil depth in Hays experiment.
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Treatments	C rate	NT/RT - CT
Mg C ha ⁻¹ yr ⁻¹	
CT	-0.055 b	
RT	-0.036 b	-0.055
NT	0.020 a	-0.021
0-N	-0.039 b	-0.038
22-N	-0.039 b	-0.045
45-N	-0.017 ab	-0.051
67-N	0.001 a	-0.019
Source <i>P</i> values.....	
Tillage (T)	0.0175	0.3496
Nitrogen (N)	0.0596	0.7475
T x N	0.9108	0.9362

1 Table 5. Carbon sequestration rate (C rate) and C rate as difference with CT, under conventional tillage (CT), reduced
 2 tillage (RT), and no-tillage (NT) at 0-15 and 0-30 cm soil depth in Tribune experiment.
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Treatments	C rate		RT/NT -CT	
Mg C ha ⁻¹ yr ⁻¹Mg C ha ⁻¹ yr ⁻¹	
 0-15 cm.....	 0-30 cm.....	
CT	-0.135		-0.273	
RT	-0.084	0.052	-0.250	0.024
NT	-0.036	0.100	-0.138	0.135
Source <i>P</i> values.....			
Tillage (T)	0.3478	0.4162	0.2569	0.1308

1 Table 6. Carbon sequestration rate (C rate) and C rate as difference with CT, under conventional tillage (CT),
 2 reduced tillage (RT), and no-tillage (NT), with 0, or 140 kg N ha⁻¹ at 0-15 and 0-30 cm soil depth in Parsons
 3 experiment.
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Treatments	C rate		RT/NT -CT	
Mg C ha ⁻¹ yr ⁻¹Mg C ha ⁻¹ yr ⁻¹	
 0-15 cm.....	 0-30 cm.....	
CT	0.098		0.184	
RT	0.166	-0.007	0.277	0.002
NT	0.230	0.088	0.327	0.118
0-N	0.130	0.052	0.210 b	0.075
140-N	0.199	0.029	0.315 a	0.046
Source <i>P</i> values.....			
Tillage (T)	0.1400	0.2443	0.1619	0.2422
Nitrogen (N)	0.1029	0.7327	0.0138	0.7267
T x N	0.4498	0.7544	0.1125	0.7356

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Table 7. Carbon sequestration rate (C rate) and C rate as differences with CT, under conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) under continuous sorghum (GS-GS), sorghum-soybean (GS-SB), continuous soybean (SB-SB), wheat-soybean (W-SB), and continuous wheat rotation at 0-5 and 0-15-cm soil depth in Manhattan experiment.

Treatments	C rate		RT/NT -CT	
	Mg C ha ⁻¹ yr ⁻¹		Mg C ha ⁻¹ yr ⁻¹	
 0-15 cm.....	 0-30 cm.....	
CT	0.008 b		0.044 b	
RT	0.109 a	0.101	0.188 a	0.145
NT	0.143 a	0.136	0.183 a	0.139
B-B	-0.107 d	0.154	-0.166 d	0.162
S-S	0.059 c	0.134	0.084 c	0.201
S-B	0.064 c	0.121	0.089 c	0.181
W-B	0.163 b	0.106	0.294 b	0.099
W-W	0.254 a	0.078	0.389 a	0.068
Source <i>P</i> values.....			
Rotation (R)	<.0001	0.3544	<.0001	0.4382
Tillage (T)	<.0001	0.1586	<.0001	0.8801
R x T	0.4847	0.4593	0.4800	0.4702

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1 Table 8. Average grain yield for Tribune, Hays, Parsons, and Manhattan sites.
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Site	Yield		
Mg ha ⁻¹		
	CT	RT	NT
Tribune			
W-S-F: sorghum	2.61	4.22	4.73
W-S-F: wheat	2.43	2.85	3.03
Hays			
W-S-F: sorghum	4.03	4.02	3.89
W-S-F: wheat	2.41	2.37	2.15
Parsons			
S-B: sorghum	3.62	3.46	2.71
S-B: soybean	1.49	1.51	1.48
Manhattan			
S-S	5.40	5.40	5.21
S-B- Sorghum	5.85	5.98	6.15
S-B- Soybean	2.15	2.22	2.49
B-B	1.75	1.75	1.95
W-B- wheat	3.16	3.23	3.09
W-B- soybean	2.42	2.49	2.62
W-W	3.03	2.89	2.29

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