Improving Estimates of the Capacity for No-till Soils in Oklahoma to Sequester Carbon in an Effort to Increase Conversion from Conventional to No-Till Management

FINAL REPORT

Output 16.1.2 of *Program to Improve the Adoption Rates and Efficiency of Best Management Practices to Protect Oklahoma Waters from Nonpoint Source Pollution*

EPA Grant C9-996100-14

FY 2007-2008 319(h) Project 16, Task 1

OCC Task 08-146

Submitted to:

Oklahoma Conservation Commission

Submitted by:

Dr. Chad Godsey, Assistant Professor, Project PI

Department of Plant and Soil Sciences

Oklahoma State University

Stillwater, OK

July 31, 2010

ABSTRACT

Intensive tillage during the last century has greatly reduced organic carbon contents of Oklahoma cropland. Increased awareness and potential of carbon storage in no-till soils has brought about the need to get accurate estimates of carbon sequestration in Oklahoma. Eight locations across Oklahoma were soil sampled to determine the benefits of no-till in regards to carbon sequestration. Locations consisted of side by side no-till and conventional till fields which were sampled at four places. Samples were divided into 0 to 10, 10 to 20, 20 to 40, 40 to 70, and 70 to 110 cm depths and analyzed for total carbon (TC) and total nitrogen (TN). Averaged across locations and depth, the concentration of organic carbon (OC) was 0.7 g kg^{-1} greater in no-till compared to conventional till. As expected, differences between no-till and conventional till were dependant on years in no-till and annual precipitation. The greater the time in no-till management and the higher the annual precipitation, the greater the carbon sequestration compared to conventional till fields.

TABLE OF CONTENTS

Introduction……………………………………………………… ………………………5

Materials and Methods……………………………………………………………………...8
Soil Sampling……………………………………...…………………………8
Soil Analysis………………………………………………………..……………12
Data Analysis…………………………………..……………………………...12

Results………………………………………………………………………………………..12
Organic Carbon Concentration………………… …………………………………12
Total Nitrogen Concentration……………………………………………………15
Organic carbon pool……………………………………………………...…15

Discussion………………………………………………………………………………17
Organic Carbon Concentration………………… …………………………………17
Total Nitrogen Concentration……………………………………………………18
Organic carbon pool……………………………………………………...…19

Conclusion…………………………………………………………………...…20

Literature Cited……………………………………………………………………....21

ACKNOWLEDGMENTS

I would like to acknowledge the Environmental Protection Agency and the Oklahoma Conservation Commission for partial funding of this project. I also would like to thank Mr. Silvano Abreu for his assistance in the project and contribution to the report.

INTRODUCTION

Intensive tillage practices have caused dramatic declines in soil quality (the ability of the soil to sustain biological processes) during the 20th century (Lal and Kimble, 1997). Removal of natural vegetation and use of tillage implements that led to a highly disturbed environment are the main causes of soil degradation. Tillage has been used for centuries as a method to alter the soil structure to prepare the seedbed, incorporate organic material into the soil, accelerate soil warming, and increase soil aeration. The physical act of tillage disrupts the soil and often causes increased decomposition of previously stable soil organic matter (SOM). However, some believe that tillage incorporates organic material that could eventually form SOM (Balesdent et al., 2000), so no loss of SOM would occur. Rather, soil organic matter is simply redistributed in the soil profile.

The most common types of tillage practices that have been studied in agricultural systems include: moldboard plow, chisel plow or reduced tillage like strip tillage, and no-till (NT) (Martens, 2001). Evaluating two long-term (18 and 20 yr old) tillage sites in Michigan, Senthilkumar et al. (2009) found greater decrease in soil carbon (C) when conventional till (CT) was used, while NT had lower decrease and in some cases increased soil C content. Change in soil C under NT was positively correlated to change in silt and clay contents. Conservation tillage, which may include no-till, strip-till, mulch-till, and ridge-till, has many benefits and among them is the positive effect of immobilizing (sequestering) C from the atmosphere. Several authors (i.e. Allmaras, et al., 2000; Follet, 2001; West & Post, 2002; Lal, 2004; Carter, 2005; Lal, 2009) have pointed to NT as a sink of C, based on the increase of SOM content in the vadoze zone (upper 20 cm). At this depth, the absence of plowing, deposition of residues on the soil surface, and slower turnover of the SOM are among the reasons for sequestering C.

Tillage and agriculture have significantly reduced SOM content in soils of Oklahoma. A report from the Oklahoma Conservation Commission (2003) estimates losses of over 113 million tons of soil organic carbon (SOC) in the state of Oklahoma since settlement started in the 1890's. Approximately 74% of the SOC (84.4 million tons) is believed to be lost from tillage. Likewise, a long term experiment in Stillwater, OK, the Magruder Plots, that was initiated in 1892, reports losses from 55 to 67% of the SOM due to continuous winter wheat (*Triticum aestivum*) and CT (Davis, et al., 2003; Girma, et al., 2007).

One limitation in the existing literature is that most studies have only evaluated the increase of SOC associated with NT to a depth of 20 to 30 cm. Recently, some authors (including VandenBygaart, et al., 2003; Qin, et al., 2004; Carter, 2005; Dolan et al., 2006; Baker, et al., 2007) have questioned the higher capacity of NT to sequester carbon based on the shallow sampling depth. Their arguments are based on the following reasons: 1) the absence of soil mobilization causes the formation of a compacted layer below the vadoze zone that restricts root growth at deeper portions of the soil; 2) the high concentration of nutrients and SOM in the upper part of the soil promotes a higher concentration of roots in the most fertile zone of the soil and also inhibits deep root growth; 3) higher SOM content in the upper part increases the soil moisture holding capacity, and more water would be available for plants so that root systems do not have to grow deep in order to absorb water; and 4) maintaining the soil covered by crop residues increases the soil's capacity of reflecting light, defined as albedo, and decreases soil temperature. Therefore, at greater depths, the soils do not warm enough to promote root growing. This last reason is probably the most important according to Baker, et al. (2007). These arguments are supported by Christopher, et al. (2009) that evaluated carbon sequestration at a depth of 60 cm under CT and NT studies in 12 locations of Indiana, Ohio and Pennsylvania. They found higher soil organic carbon (OC) stock under CT in seven locations. According to those authors, 10 years of NT is not sufficient to increase OC in soils under NT; also, the incorporation of crop residue in areas of CT promoted the increase of SOM in the deeper layers of soil in the mentioned zone.

Most carbon sequestration studies have been concentrated in the upper US, Canada and Europe. A limited number of studies have been conducted in warmer climatic conditions, like the southern Great Plains, in which they compare tillage systems at greater depths. Studies carried out in warmer climates, such as those in Brazil (Bayer, et al., 2000; Amado, et al., 2004), have shown higher SOM in NT compared to CT in tropical and subtropical conditions up to a 100 cm depth. In that climate, the albedo effect is positive for the NT because soil temperature is more favorable for microbial activity and root growth. A more intensive cropping system promotes the degradation of compacted layers and reduces soil resistance to root growth due to the diversity of rooting systems (Dwyer, et al., 1996). Additionally, mulch on the soil surface reduces the compaction effect caused by machinery traffic (Metay, et al., 2007).

The amount of carbon sequestration by conservation tillage has been calculated by different authors (West and Post, 2002), and there is considerable variation in the estimates. Variations in climate, crops, tillage, and agricultural inputs are among the reasons for the variation in the potential of sequestering carbon (Follet, 2001; Lal, 2004). Estimations vary from 20 to 50 grams C / m^2 / yr. This variation has low precision in local calculations since SOC has high potential to vary within a soil, along the landscape, and especially across soil types and climate conditions. Experiments that account for local carbon sequestration could reduce the variation and allow a more precise estimation of carbon sequestration rates on a smaller scale. West and Post (2002) present a worldwide overview of 276 experiments that evaluated the input of SOM due to the adoption of NT. Only one study in Oklahoma is presented in their review. In the mentioned study, Dao (1998) evaluated an 11 year NT treatment and observed an increase of 65, 16.6, and 7.2% of the SOC concentration in the depths of 0 to 0.05, 0.05 to 0.10, and 0.10 to 0.20 m, respectively, compared to moldboard plow.

The lack of studies that compare NT and CT in climate conditions similar to Oklahoma's climate leads to the necessity for evaluating NT's capacity to sequester carbon in Oklahoma soils. The objective of this study was to evaluate the SOC and total nitrogen (TN) content of soils under NT and CT in Oklahoma.

MATERIALS AND METHODS

Soil sampling

Crop production fields in Oklahoma that have more than a 5 year history of NT production were identified and sampled in Oklahoma (Figure 1). Conventional tilled fields, adjacent to the NT fields and under the same soil series with similar slopes, were also sampled. No-till is defined by having more than 35% of soil coverage (CTIC, 2010) and, for this study, at least 5 years with no soil mechanical disturbance other than planting. A total of eight NT and eight CT fields in six different counties were identified and sampled (Table 1 and Figure 2) between March and July, 2009. Thirty year average monthly precipitation and temperature for each site is shown in Figure 3. Also, total 30 year average annual precipitation for each location is presented in Figure 4.

Figure 1. Collecting soil samples in the spring of 2009.

In each field, soil samples were collected at four points along a linear transect in the field. Sampled points were taken approximately 30 meters in distance from each other. All soil samples were taken within the same soil series. Since NT and CT fields were adjacent to each other, transects were lined up parallel to each other, so samples were obtained at similar positions in the landscape. At each point, two soil cores of 3.8 cm diameter and one core of 7.5 cm diameter were collected to a depth of 110 cm using a tractor mounted hydraulic driven probe. Each core was divided into 0 to 10, 10 to 20, 20 to 40, 40 to 70, and 70 to 110 cm depths. Soil samples from the 3.8 cm cores were combined in one composite sample for each depth and sample point within the transect, dried in a forced-air oven at 50˚C, and ground to pass through a 2-mm sieve. The 7.5 cm cores were divided at the same depths and a sub-sample of 10.0 cm long was obtained from each depth to evaluate bulk density. Samples were oven dried at 105˚C and soil dry mass was obtained to determine bulk density. Bulk density was determined using the Core Method (Grossman & Reinsch, 2002).

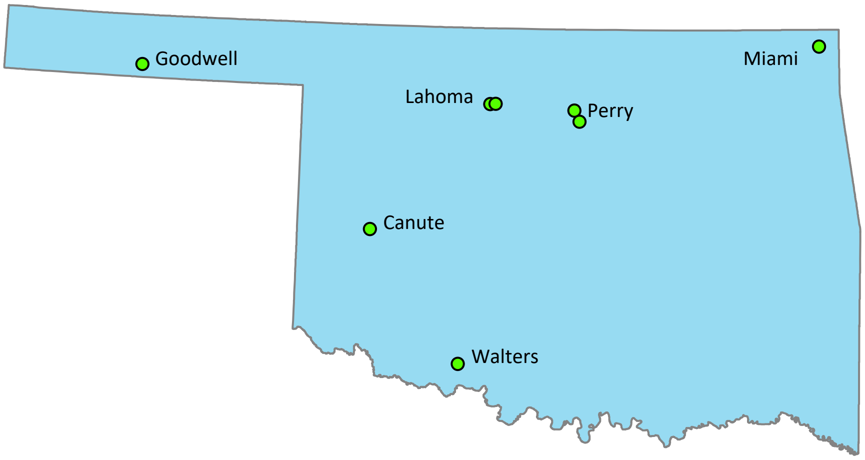

Figure 2. Map of locations sampled. Locations are in areas of highest cropland acres.

Table 1. Soil series, classification, crop rotation characteristics, and time under NT management for each sampled site.

Town	County	Tillage	Soil Series	Soil classification	Rotation	Yrs of NT
Miami	Ottawa	NT	Taloka silt loam	Fine, mixed, active, thermic Mollic Albaqualfs	soybean / corn / wheat / soybean / corn	5
		CT			wheat / soybean / corn / wheat / soybean / corn	-
Perry 1	Noble	NT	Port silt loam	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	wheat, soybean, corn, wheat	7
		CT			wheat, soybean, corn, wheat	-
Perry 2	Noble	NT	Kirkland silt loam	Fine, mixed, superactive, thermic Udertic Paleustolls	corn / wheat	5
		CT			corn / wheat	-
Lahoma 1	Garfield	NT	Grant silt loam	Fine-silty, mixed, superactive, thermic Udic Argiustolls	wheat / soybean /grain sorghum	12
		CT			continuous wheat	-
Lahoma 2	Garfield	NT	Pond creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls	continuous wheat	5
		CT			continuous wheat	-
Goodwell	Texas	NT	Gruver	Fine, mixed, super active, mesic Aridic Paleustoll	wheat / sorghum / fallow	5
		CT			wheat / sorghum / fallow	-
Canute	Washita	NT	Grandfield	Fine loamy, mixed, super active, thermic, Typic Haplustalfs	cotton	18
		CT			cotton	-
Walters	Cotton	NT	Tillman	Fine, mixed, superactive, thermic Vertic Paleustolls	continuous wheat	12
		CT			continuous wheat	-

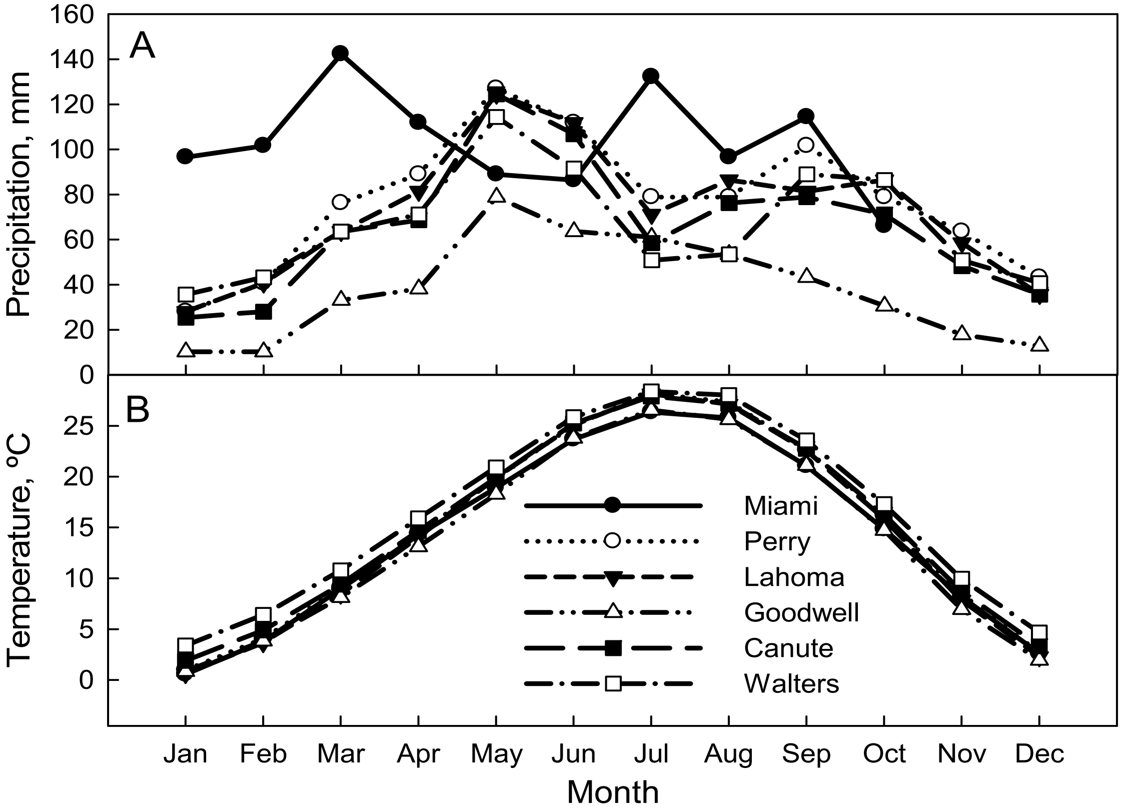

Figure 3. Monthly (30 yr average) precipitation (A) and temperature (B) for studied sites in Oklahoma (http://agweather.mesonet.org/index.php/data/section/climate, 2010).

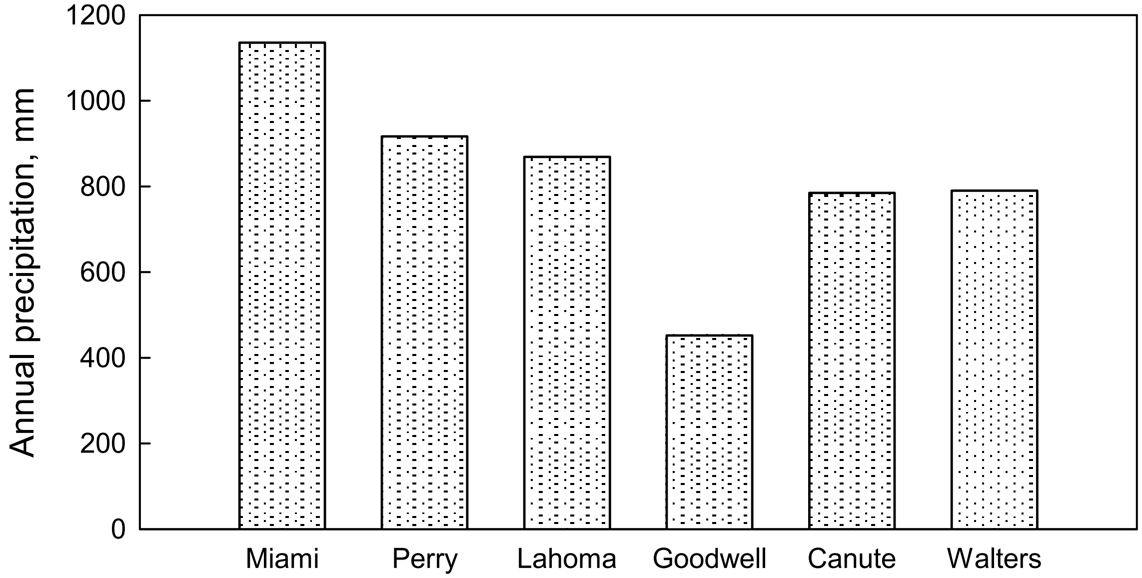

Figure 4. Annual (30 yr average) precipitation for studied sites in Oklahoma (http://agweather.mesonet.org/index.php/data/section/climate, 2010).

Soil analysis

Soil samples were analyzed for total carbon (TC) and total nitrogen (TN) using dry combustion with a LECO FP-2000 CNS analyzer (Westman et al., 2006; ISO/DIS, 1994; Donkin, 1991; Howard & Howard, 1990). In order to account for organic carbon (OC), inorganic carbon (IC) content was determined for all soil samples using a modified pressure-calcimeter method (Sherrod, et al., 2002). With TC and IC results, OC was calculated using equation 1.

$$OC = TC - IC \qquad [1]$$

Data analysis

The experimental design was a randomized complete block design with 2 treatments (NT and CT) and seven replicates (sites). Each site was treated as a block; the main effects were treatment and depth. Sampling points and sites were treated as random variables. Data was analyzed in a PROC MIXED model using SAS (SAS Institute, Cary, NC).

RESULTS

Organic carbon concentration

On average, no-till fields had higher OC concentrations ($p = 0.06$) compared to CT fields. When locations were combined, concentration of OC was 0.7 g kg^{-1} greater in NT when averaged across depths. At individual locations, NT had numerically higher OC concentrations in the soil profile (0 to 110 cm) in six out of eight studied locations (Figure 5).

A significant difference in OC concentrations between depths was observed ($p<0.001$) when locations were combined. Two factors can be identified to correlate with the buildup of OC in NT sites in Oklahoma: precipitation and time under NT management. Soils located at sites where precipitation is higher seemed to have a faster buildup of OC concentration under NT. Miami (1135 mm yr^{-1} and 5 years under NT), located in eastern Oklahoma, and Perry 1 and Perry 2 (917 mm yr^{-1}, 7 and 5 years under NT, respectively), both located in the North-central part of the State, had numerically higher OC concentration in the 0 to 70 cm depth under NT compared to CT. For example, Miami NT (Figure 5) had numerically higher concentrations of OC at 70 cm below the surface compared to CT. In comparison, sites located in drier areas of the state such as Goodwell (452 mm $yr^{-1}$and 5 years under NT), located in the western part of Oklahoma, were not able to increase OC content under NT in a 5 year period. The other factor influencing OC concentration was the age of NT. Older NT sites, such as Lahoma 1 (12 years of NT), Walters (12 years NT), and Canute (18 years NT) had numerically higher OC concentration in soils under NT, especially in the soil surface.

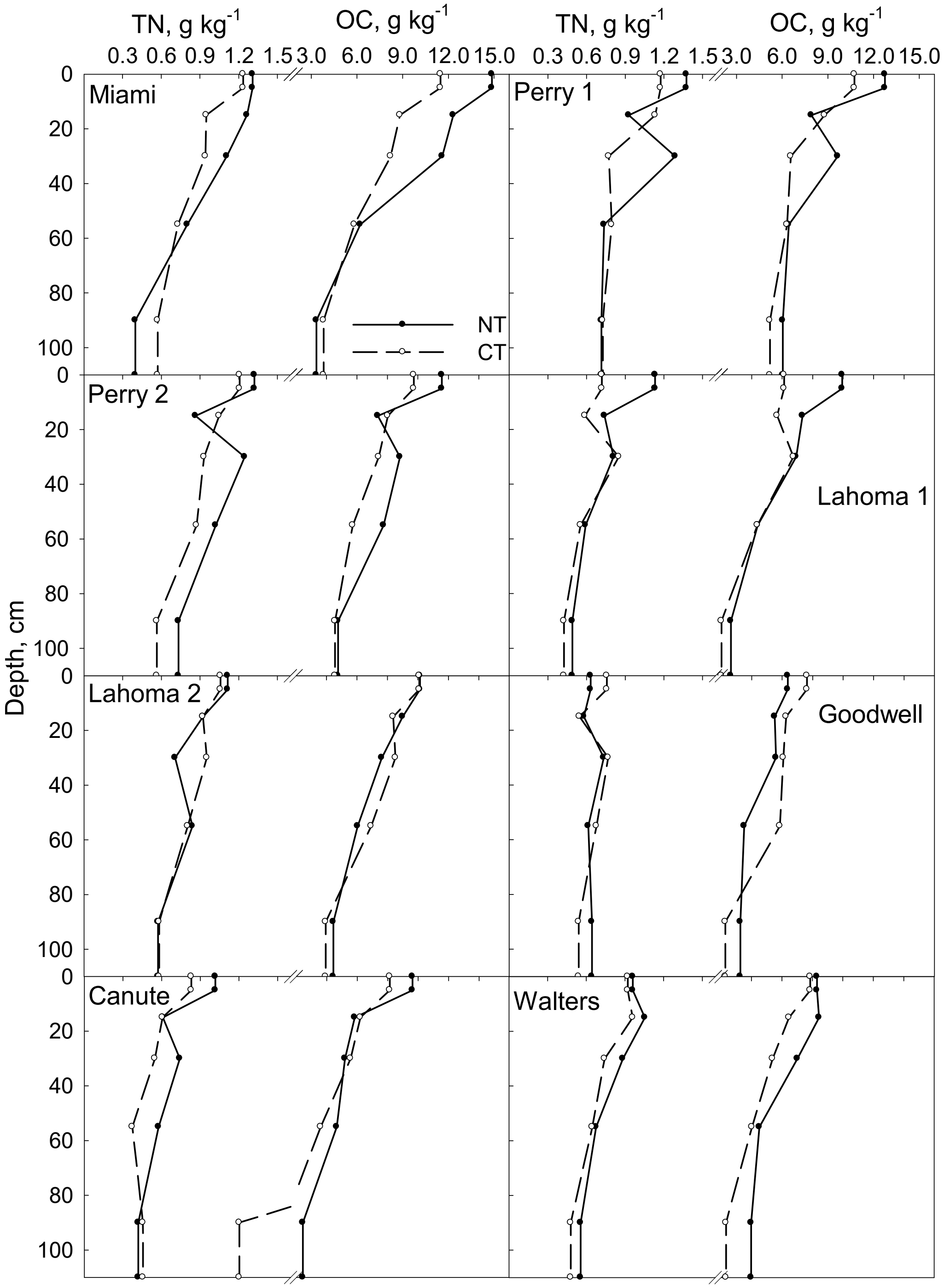

Figure 5. Total nitrogen (TN) and organic carbon (OC) for soils under no-till and conventional till at study locations. Dashed lines represent conventional till results while solids line denote no-till results.

Total nitrogen concentration

Following the same trend as OC, TN was higher in soils under NT compared to CT. When locations were combined, concentration of TN was 0.07 g kg^{-1} greater in NT when averaged across depth. Also, similar to the results of OC, the higher the annual precipitation and the longer NT management, the higher the TN concentration in soil. For example, at the Miami site (Figure 5), five years under NT has resulted in the soil having higher numerical value of TN under NT compared to CT. In Miami, the wettest location, all the depths up to 70 cm had higher TN under NT. In comparison, in Goodwell, the driest location (Figure 5), a lower amount of TN was observed in the NT.

Organic carbon pool

Calculations for the OC pool had similar results as OC concentration (Figure 6). The OC pool across all the sites (Figure 7) was significant (p=0.07), a difference of 8.6 Mg ha^{-1} was observed, with NT being 1.1 times greater than conventional till across the sites. Six sites had numerically higher OC pool in NT compared to CT, while two sites had higher OC pool under CT (Figure 6). Higher numerical differences were found in Walters, where the NT OC pool was 1.3 times larger than CT with a difference of 22.1 Mg ha^{-1}. Similarly, Canute had 16. 3 Mg ha^{-1} more OC in soil under NT. Lahoma 1 had 9.7 Mg ha^{-1} more OC pool than CT. All those locations have been in NT for over 12 years. In sites with less time under NT management but with higher precipitation, the situation is similar. In Miami, the difference is 17.5 Mg ha^{-1} more OC under NT, and the two sites in Perry (Perry 1 and Perry 2) had differences of 15.8 Mg ha^{-1} and 11.7 Mg ha^{-1} respectively, with NT being greater than CT. The two sites where NT had lower OC pool were Lahoma 2, with a difference of 4.0 Mg ha^{-1}, and Goodwell were the difference between tillage was 8.5 Mg ha^{-1}. Both sites have 5 years NT management, compared to the other sites. Goodwell also received the lowest amount of annual precipitation (Figure 4).

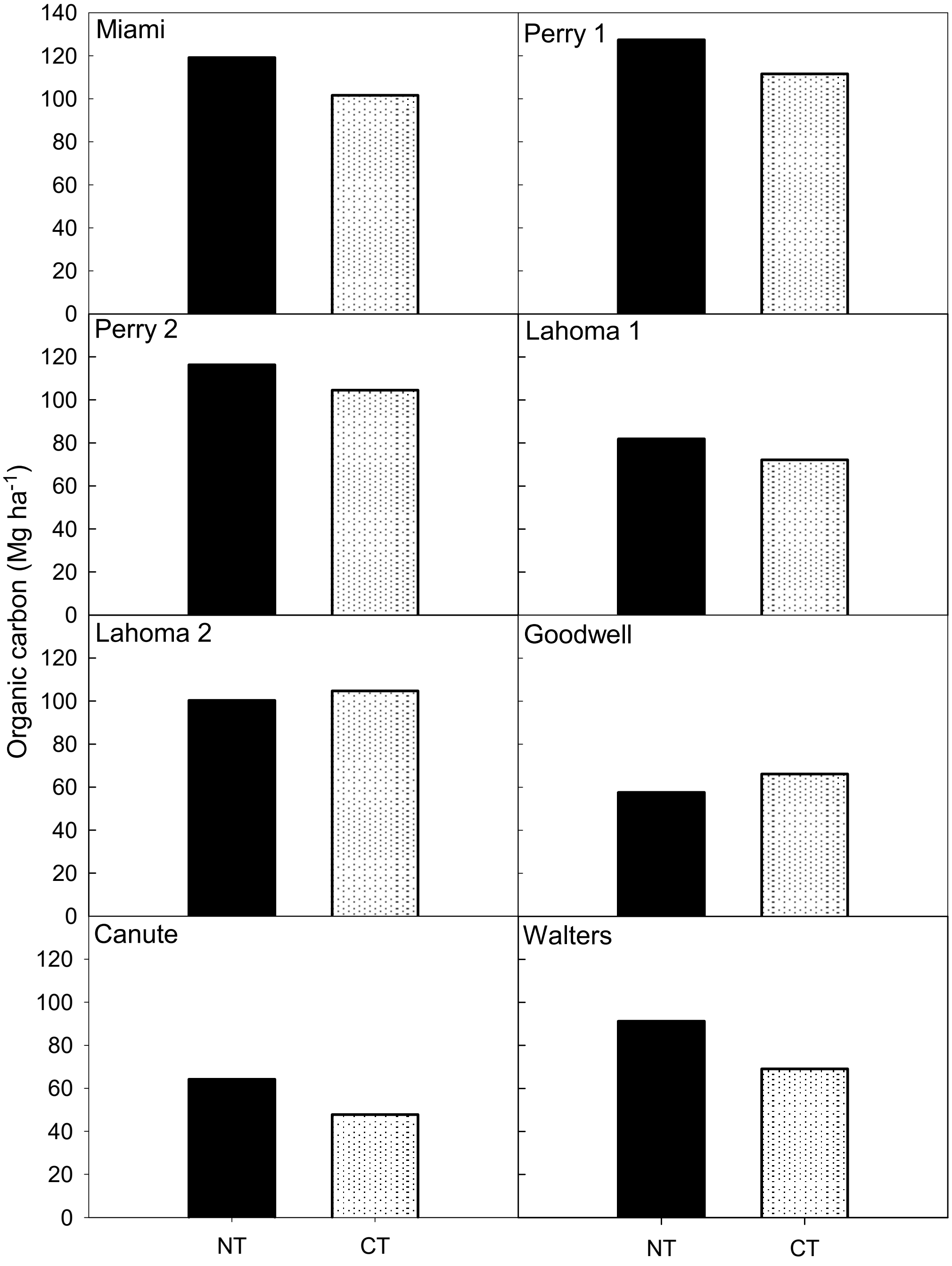

Figure 6. Organic carbon pool for soils under no-till (NT) and conventional till (CT).

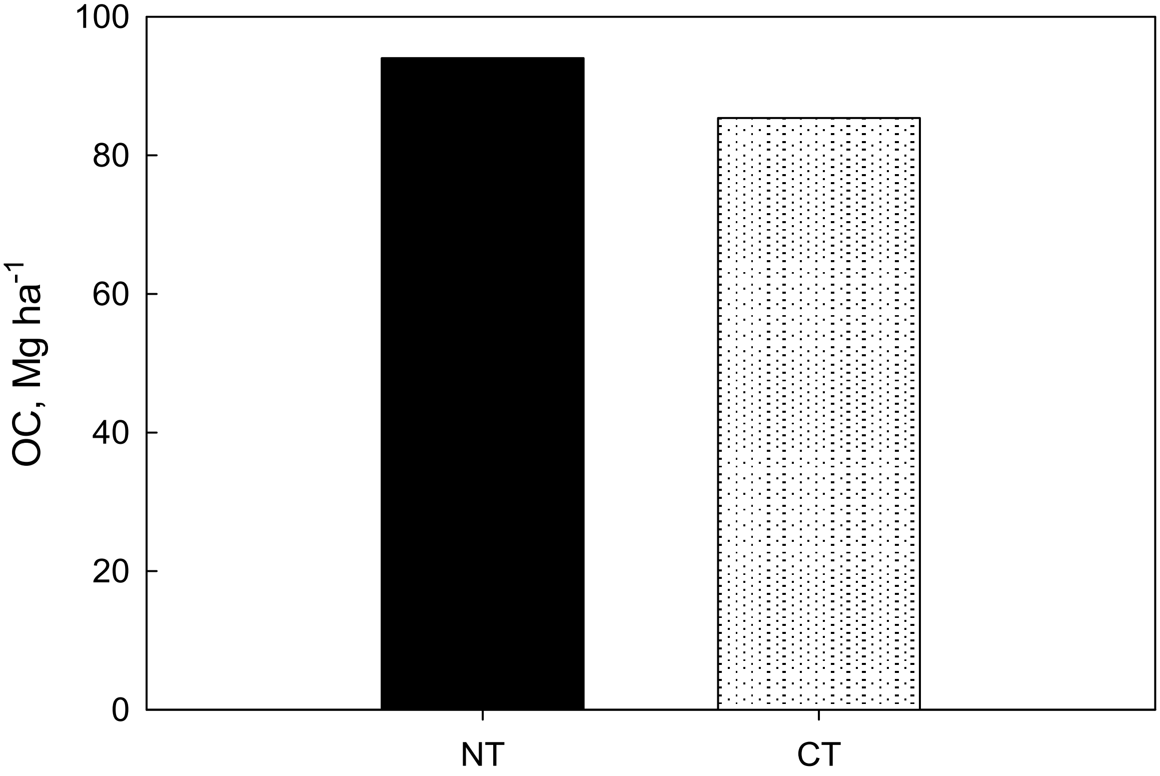

Figure 7. Organic carbon pool of soils under No-till (NT) and conventional till (CT) in Oklahoma.

DISCUSSION

Organic carbon

The results from this state-wide study indicate that NT cropping systems kept in place for at least 5 years tend to increase OC in Oklahoma relative to CT systems (Figure 5). From the sites studied, two factors appear to be important in increasing OC concentration in these soils, and these factors may act synergistically to influence OC: 1) time under NT management and 2) amount of annual precipitation. Sites that have been in NT for over 10 years, such as Canute, Walters, and Lahoma had higher numerical OC concentration in soils under NT compared to CT even though precipitation was under 900 mm yr^{-1} at 2 of the 3 sites. Also, areas where precipitation is higher (above 900 mm yr^{-1}), even if the NT adoption time is less than 10 years (5 years in Miami, 5 and 7 years in Perry), had higher numerical concentration of OC under NT compared to CT. This suggests that in wetter climates, no-till will sequester more carbon than conventional till within at least 5 years. In drier climates, the advantages of NT in sequestering more OC than CT may not be seen until the NT system has been in place for a longer period of time (10 or more years).

Observations in our study agree with other long-term studies comparing OC sequestration rates, such as Paustian, et al. (1997) who affirms that lower sequestration rates are often observed in the first 5 years following NT adoption. Ussiri and Lal (2009) reported twice as much OC in the surface 30 cm in NT after 43 years of management compared to CT and moldboard plow management. Additionally, studies carried out in areas of high precipitation (above 1,000 mm yr^{-1}) had reported higher OC sequestration rates compared to lower precipitation zones. Franzluebbers (2010) reports higher OC sequestration rates under NT in higher precipitations states such as Alabama (1391 mm yr^{-1}) and Georgia (1146 mm yr^{-1}) compared to Welasco, Texas (625 mm yr^{-1}). Climate dependent OC sequestration rates have been reported by Havlin et al. (1990) and Franzluebbers and Steiner (2002). Those authors found a positive relationship between crop residue production and OC accumulation, especially in the rooting zone. Our study has found similar results, where areas of higher precipitation (above 900 mm yr^{-1}) have accumulated more OC under NT regardless of time under NT management.

Another important aspect observed at some sites, such as Perry 1 and 2 was a decrease in the OC content occurring in the 10-20 cm layer in NT, while in CT the same sharp decline was not observed. Similar observations were found by Boodey et al. (2010) in Brazil and Christopher et al. (2009). This may be explained by the incorporation of residue in the plowed layer that could promote the increasing of OC at this specific depth.

Total nitrogen

Results of total nitrogen were similar to OC content. Due to the high correlation of nitrogen and soil OC content (Spargo, et al., 2008), TN results are very closely related with OC. Results from our study agree with Spargo et al. (2008). They observed an increase in TN after 14 years of NT in West Virginia. Similar results were also found by

Franzluebbers et al. (1994) in Texas, where NT had 45% more mineralizable N under NT compared to CT treatments. Other US states, such as Michigan (Pierce and Fortin, 1997) and Colorado (Follet and Schimel, 1989) have also observed an increase in TN with NT.

Organic carbon pool

There was a greater pool of OC under NT in Oklahoma compared to CT. Sites located in eastern and central Oklahoma where precipitation is higher have greater accumulation of OC even with <10 yr in NT management. Organic carbon pools are probably larger because the potential to produce biomass is greater due to higher rainfall amounts. West and Post (2002), Franzluebbers and Steiner (2002), and Franzluebbers (2010) have presented data that agree with our observations. Greater differences in the OC pool were observed in the higher rainfall areas (Miami) and in the oldest sites (Walters and Canute).

The use of continuous wheat and low rainfall was not been able to improve OC pool under NT in a short period (5 yr). The site Lahoma 2 had continuous wheat and low rainfall and, consequently, also had lower OC under NT than CT. Our results are in agreement with West and Post (2002) who indicated that continuous wheat NT is not effective in increasing soil OC concentration. Those authors suggest that incorporating a cover crop, especially legumes in a continuous wheat system, would help to increase OC accumulation in the soil.

CONCLUSION

In general, no-till management has increased OC in Oklahoma soils. Time under NT management and precipitation plays an important role in OC sequestration. Areas of higher precipitation have been able to accumulate higher amounts of OC compared to CT management within at least 5 years of the initiation of NT. In dry areas of the state, sites that had only been in no-till for 5 years had lower OC compared to CT, while sites in no-till for at least 10 years had higher OC than comparable CT sites.

Total nitrogen also had increased concentration under NT in most areas of the state. Higher numerical differences of TN were found where higher differences in OC were identified.

Studies in sequential years in the same areas to evaluate the trend of OC sequestration, as well as a more detailed study of depth change in the OC content using a closer depth range should be considered in follow up studies. A component of characterizing OM by using isotope C fractions could be incorporated in the study to evaluate the contribution of different OM origin in the OM pool. Likewise, more studies of OC are needed in order to generate more information and data in the OC sequestration rate/dynamics in soils of Oklahoma.

REFERENCES

Amado, T.J.C., B.H. Campos, C. Bayer. 2004. Materia organica e qualidade do solo sob plantio direto no sul do Brasil. Brazilian J. Soil Sci. 28:113-121.

Allmaras, R.R., H.H. Schomberg, C.L. Douglas Jr., T.H. Dao. 2000. Soil organic carbon sequestration potential of adopting conservation tillage. J. Soil and Water Conserv. 55:365-373.

Baker, J.M., T.E. Ochsner, R.T. Venterea, T.J. Griffis. 2007. Tillage and soil carbon sequestration – What do we really know? Agriculture Ecosyst.Environ. 118:1-5

Balesdent, J. C. Chenu, M. Balabane. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res. 53:215–230.

Bayer, C., J. Mielniczuk, T.J.C. Amado, L. Marin-Neto, S.V. Fernandes. 2000. Organic matter storage in a sandy clay loam Acrisol affected by tillage and cropping systems in southern Brazil. Soil Tillage Res. 54:101-109.

Boodey, R.M., C.P Jantalia, P.C. Conceição, J.A. Zanatta, C. Bayer, J. Mielniczuk, J. Dieckow, H.P. dos Santos, J. E. Denardin, C. Aita, S. J. Giacomini, B.J.R. Alves, S. Urquiaga. 2010. Carbon accumulation at depth in Ferralsols under zero-till subtropical agriculture. Global Change Biol. 16:784-795.

Carter, M.R. 2005. Long-term tillage effects on cool-season soybean in rotation with barley, soil properties and carbon and nitrogen storage for fine sandy loam in the humid climate of Atlantic Canada. Soil Tillage Res. 81:109-120.

Christopher, S.F., R. Lal, U. Mishra. 2009. Regional study of no-till effects on carbon sequestration in the Midwestern United States. Soil Sci. Soc. Am. J.:73(1):207-216.

CTIC – Conservation Technology Information Center. 2010 (Feb 23). http://www.conservationinformation.org

Dao, T.H. 1998. Tillage and crop residue effects of carbon dioxide evolution and carbon storage in a Paleustoll. Soil Sci. Soc. Am. J. 62:250-256.

Davis, R.L., J. J. Patton, R. K. Teal, Y. Tang, M. T. Humphreys, J. Mosali, K. Girma, J. W. Lawles, S. M. Moges, A. Malapati, J. Si, H. Zhang, S. Deng, G. V. Johnson, R. W. Mullen, and W. R. Raun. 2003. Nitrogen Balance in the Magruder Plots Following 109 Years in Continuous Winter Wheat. J. Plant Nut. 26:1561-1580.

Dolan, M.S., C.E. Clapp, R.R. Allmaras, J.M. Baker, J.A.E. Molina. 2006. Soil organic and nitrogen in a Minnesota Soil as related to tillage, residue and nitrogen management. Soil & Tillage Res*.* 89:221-231.

Donkin, J.M. 1991. Loss-on-ignition as an estimator of soil organic carbon in A-horizon forest soils. Commun. Soil Sci. Plant Anal. 22: 233–241

Dwyer, LM., BL Ma, DW Stewart, HN Hayhoe, D Balchin, JLB Culley, M McGovern. 1996. Root mass distribution under conventional and conservation tillage. Can. J. Soil Sci. 76:23-28.

Follet, R.F. 2001. Soil management concepts and carbon sequestration in cropland soils. Soil Tillage Res. 61:77-92.

Follet, R.F., D.S. Schimel. 1989. Effect of tillage practices on microbial biomass dynamics. Soil Sci. Soc. Am. J. 53:1091-1096.

Franzluebbers, A.J. 2010. Achieving soil organic carbon sequestration with conservation agricultural systems in the southeastern United States. Soil Sci. Soc. Am. J. 74:347-357.

Franzluebbers, A.J. and J.L.Steiner. 2002. Climate influences on soil organic carbon storage with no tillage. P. 71-86. In J.M. Kimble et al. (ed.) Agricultural practices and policies for carbon sequestration in soil. Lewis Public., Boca Raton, FL.

Franzluebbers, A.J., F.M. Hons, 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.

Girma, K., S.L. Holtz, D. B. Arnall, B. S. Tubaña, W. R. Raun. 2007. The Magruder plots: untangling the puzzle. Agron. J. 99:1191–1198.

Grossman, R.B; T.G. Reinsch. 2002. Bulk density and linear extensibility. In: Dane, J.H.; Topp, G.C. Methods of soil analysis. Soil Sci. Soc. Am. book series no. 5.

Havlin, J.L., D.E. Kiessel, L.D. Maddux, M.M. Claassen, J.H. Long. 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci. Soc. Am. J. 54:448-452.

Howard, P.J. and D.M. Howard. 1990. Use of organic carbon and loss-on-ignition to estimate soil organic matter in different soil types and horizons. Biol. Fertil. Soils, 9:306–310.

ISO/DIS 10694. (1994) Soil quality-determination of organic and total carbon after dry combustion. International Organization for Standardization: Geneva, Switzerland, ISO/TC 190/SC.

Lal, R. 2004. Agricultural activities and the global carbon cycle. Nutr. Cycl. Agroecosystems. 70:103-116.

Lal, R. 2009. Challenges and opportunities in soil organic matter research. European Journal of Soil Sci. 60:158-169.

Lal, R. and J.M. Kimble. 1997. Conservation tillage for carbon sequestration. Nut. Cyc. in Agroecosystems 49:243- 253.

Martens, D.A. 2001. Nitrogen cycling under different soil management systems. Adv. Agron. 70:143-192.

Metay, A., J.A.A. Moreira, M. Bernoux, T. Boyer, J.M. Douzet, B. Feigl, C. Feller, F. Maraux, R. Oliver, E. Scopel. 2007. Storage and forms of organic carbon in a no-tillage under cover crops systems in a clayey Oxisol in dry land rice production (Cerrados, Brazil*). Soil Tillage Res.* 94:122-132.

Oklahoma Conservation Commission. 2003. Oklahoma Carbon Sequestration Enhancement Act. Oklahoma Conservation Commission/Carbon Sequestration Advisory Committee.

Paustian, K., O. Andren, H.H. Janzen, R. Lal, P. Smith, G. Tian, H. Tiessen, M. Noordwijk, P.L. Woomer. 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manag. 13:230-244.

Pierce, F.J., M.C. Fortin. 1997. Long-term tillage and periodic plowing of a no-tilled soil in Michigan: impacts, yield, and soil organic matter. In: Paul, E.A.

Paustian, K., Elliot, E.T. Cole, C.V. (eds). Soil organic matter in temperate ecosystems: long-term experiments in North America. CRC Press, Boca Raton, FL, pp 141-149.

Qin, R., P. Stamp, W. Richner. 2004. Impact of tillage on root systems of winter wheat. Agron. J. 96:1523-1530.

SAS Institute. 2002. SAS release 9.1. The SAS Inst., Cary, NC.

Senthilkumar, S., B. Basso, A.N. Kravchenko, G.P. Robertson. 2009. Contemporary evidence of soil carbon loss in the U.S. corn belt. Soil Sci. Soc. Am. J. 73(6):2078-2086.

Sherrod, L. A., G. Dunn, G.A. Peterson, R.L. Kolberg. 2002. Inorganic carbon analysis by modified pressure-calcimeter method. Soil Science Society of America Journal, 66:299-305.

Spargo, J.T., M.M. Alley, R.F. Follet, J. V. Wallace. 2008. Soil nitrogen conservation with continuous no-till management. Nutr. Cycl. Agroecosystems. 82:283-297.

Ussiri, D.A.N, R. Lal. 2009. Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. Soil Tillage Res. 104:39-47.

VandenBygaart, A.J., E.G. Gregorich, D.A. Angers. 2003. Influence of agricultural management on soil organic carbon: a compendium as assessment of Canadian studies. Can. J. Soil Sci. 83:363-380.

West, T.O., W.M. Post. 2002 Soil organic carbon sequestration rates by tillage and crops rotation: a global data analysis. Soil Sci. Soc. Am. J. 66:1930-1946.

Westman, C.J.J., Hytönen, A. Wall, A. 2006. Loss-on-ignition in the determination of pools of organic carbon in soils of forest and afforested arable fields. Commun. Soil Sci. Plant Anal. 37:1059-1075.