NITROGEN FERTILIZER SOURCE AND TILLAGE IMPACTS ON SURFACE AND SUBSOIL C UNDER RAINFED CORN

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ABSTRACT

Soil organic carbon (SOC) increases with organic fertilizer and the adoption of no-till. Soil organic C improves the ability of agricultural systems to mitigate and adapt to climate change. This study was conducted to determine the long-term effects of fertilizer type and tillage on profile SOC. The experimental site was a rainfed continuous corn (Zea mays *L.*) system with fertilizer treatments (150 lbs N a^{-1}) of composted organic waste (OrgF), urea (MinF) and no fertilizer addition (Ctrl) and tillage treatments of no-till (NT) and conventional till (CT). Change in SOC and $\delta^{13}C$ was measured through the soil profile after 22 years. The change in SOC was calculated from a baseline sampling at the start of the experiment using equivalent soil mass to determine soil profile changes over time. Long-term addition of OrgF reduced profile C loss (0-60 cm), -1.12 tons C a^{-1} in comparison to Ctrl and MinF where ΔSOC was -8.12 and -13.8 tons C a^{-1}. In the surface 0-15 cm, OrgF increased ΔSOC from the baseline the most (8.11 tons C a^{-1}). No-till sequestered more C in the 0-5 cm layer than CT, while CT sequestered more C than NT in the 5-15 cm layer. The compost $\delta^{13}C$ signature was also evident with depleted soil $\delta^{13}C$ from 0-15 and 30-45 cm. Within the 30-45 cm depth, NT OrgF decreased losses of SOC (-1.70 tons C a^{-1}) compared to CT OrgF (-5.75 tons C a^{-1}). Although $\delta^{13}C$ was elevated with OrgF in the 15-45 cm depths, this did not result in gains in soil C. Although not significant, soil profile C to 45 and 60 cm depths showed greater net gains in soil C with NT OrgF (6.42 and 0.29 tons C a^{-1}) than CT OrgF (1.41 and -3.34 tons C a^{-1}). In summary, surface management effects on soil C were confined to the surface 15 cm even with additional C inputs after 22 years. In these annual cropping systems, considerations need to made for deep-rooted crops and rotations to deliver C inputs into the subsoil; however, this must include no-tillage as tillage loses the benefits of additional C inputs.

INTRODUCTION

The increased concentration of greenhouse gases in the atmosphere has increased the global mean annual temperature since the pre-industrial era and is projected to continue. Efforts to reduce greenhouse gas emissions in the atmosphere are required to mitigate these effects. The largest terrestrial pool of C is the soil with approximately 1550 Pg C in the upper 1 m of soil (Batjes, 2014). It is estimated that over 50% of native SOC has been lost when converted to agricultural systems (Sanderman et al., 2017). Thus, practices that increase SOC in agricultural systems have a significant potential to store C through soil C sequestration which occurs when C replenishment is greater than C loss.

Organic fertilizer addition, such as composted organic waste is known to increase SOC in annual cropping systems (Lynch et al., 2006). In a recent meta-analysis, cattle manure increased SOC stocks compared to an unfertilized control by 3.6 to 7.6 tons C a^{-1} in the upper 20-30 cm

(Maillard and Angers, 2014). This increase in SOC stocks with manure was also greater than mineral fertilizer additions by approximately 1.8 to 4.5 tons C a^{-1} (Maillard and Angers, 2014).

Historically, research has focused on the upper 20-30 cm of soil; however, there is interest in soil C deeper in the soil profile. Over 50% of C in the soil profile is located within 25-100 cm (Batjes, 2014). Further, tillage has less effect on profile SOC stocks, despite widely reported surface SOC gains (Angers and Eriksen-Hamel, 2008). Other research suggests that agricultural practices can alter deep soil dynamics that either increase (Halvorson et al., 2016) or decrease (Stewart et al., 2017) profile C stocks. This study builds on this research and specifically focuses on the relationship between management practices and deep soil carbon in a corn system. There is comparably little known about deep profile effects of manure addition and tillage in rainfed systems.

MATERIALS AND METHODS

The experimental site was located at Kansas State University's North Farm in Manhattan, KS (39° 12' 42"N lat, 96° 35' 39"W long; elevation 1020 ft). Annual mean precipitation was 31 inches and mean annual temperature was 53 °F. The soil was a moderately well-drained Kennebec silt loam (fine-silty, mixed, superactive mesic Cumulic Hapludoll). Plots were established in 1990 as split-plot randomized block design with four replications under continuous corn (Zea mays *L.*). Tillage systems were the main plots and N source was the subplot. Tillage systems were conventional tillage (CT) and no-till (NT). Corn was planted through the previous crops' standing residue in the NT plots with minimal soil disturbance. The CT operations consisted of preplant offset disk set to 10 cm depth and postharvest chisel plow to 15 cm.

The subplot treatment, fertilizer source, was applied at a rate of 150 lb N a^{-1}. Mineral fertilizer (MinF) was applied as broadcast urea. The second N treatment was sourced from various types of organic sources high in C. From 1990 to 2001, the original organic fertilizer (OrgF) treatment was fresh beef cattle manure. Each year, the manure was analyzed for total N, NH_4^+, and NO_3^- and application rates were calculated assuming 100% of NH_4^+ and NO_3^- and 35% of organic N was available. Since 2001, mixed source compost (food waste, hay waste, and cattle manure) has been applied (Nicoloso et al., 2018). Prior to application each year, compost was analyzed for total N, organic N, NH_4^+, and NO_3^-. Compost application rate was then calculated assuming 50% of organic N and 100% of mineral N was available during the growing season. A control (Ctrl) treatment consisted of no N application (0 lb N a^{-1}).

Soil cores were collected in fall 2012 with a Giddings Soil Exploration probe (Windsor, CO) to a depth of 120 cm (5 cm diameter). Five cores were collected per plot. Three cores were collected from each plot for lab analyses. Two additional 120 cm cores were collected for bulk density analysis. All undisturbed soil cores were separated into layers 0-5 cm, 5-15 cm, 15-30 cm, 30-45 cm, 45-60 cm, 60-75 cm, 75-90 cm, 90-105 cm, and 105-120 cm in field and stored in bags. Bulk analysis cores were composited into one bag by layer and bulk density cores were bagged individually.

Soil bulk density was determined by gravimetric moisture analysis. Bulk density measurements were averaged by depth for each plot. For analysis of SOC, a subsample was taken from the composited cores and air-dried. Visible roots were removed from the sample and discarded. The soil was then passed through a 2 mm sieve and finely ground with a mortar and pestle.

Soil samples were analyzed for total soil C by dry combustion with a C elemental analyzer (Flash EA 1112 Series, ThermoScientific, Waltham, MA). Soil organic carbon changes were determined on equivalent soil mass to account for soil differences across a landscape or soil bulk density changes induced by management (Ellert and Bettany 1995). The 1992 equivalent soil mass was calculated using bulk density data from 1990 and C treatment data from 1992 (Nicoloso et al., 2018). Change in SOC was measured to 60 cm due to the baseline sampling depth of 90 cm and adjustment in the equivalent soil mass calculations.

Carbon isotope analysis was performed at the KSU Stable Isotope Mass Spectrometry Laboratory on the air-dried, picked and ground subsamples. The analysis was done with a ThermoFinnigan Con Flo III interface and ThermoFinnigan Delta-plus Continuous Flow Stable Isotope Ratio Mass Spectrometer (ThermoFisher Scientific, Waltham, MA).

The main effects of tillage and N management on ΔSOC (1992-2012) were assessed using a repeated measures analysis of SOC stocks with tillage and N management as main effects with plot as a repeated unit. An analysis of variance (ANOVA) was performed, data were checked for normality and transformed as necessary with the ΔSOC analysis log-transformed. The SOC stock change per layer was log-transformed due to non-normal distribution. An ANOVA was used to assess the main treatment effects of tillage and N management and interaction between tillage and N management. Statistics were analyzed on all response variables measuring SOC change and stocks (ΔSOC, bulk density, $\delta^{13}C$) by using SAS PROC MIXED (SAS 9.4). Differences were analyzed with Bonferroni's adjustment and are reported with letters to denote significance. Results were considered statistically significant at $P < 0.10$.

RESULTS AND DISCUSSION

Soil organic C change

The OrgF significantly increased SOC stocks in the 0-5 and 5-15 cm layers (Table 1). Here, OrgF increased SOC by 4.36 and 3.75 tons C a^{-1}, respectively. Soil organic C in the Ctrl and MinF treatments were relatively unchanged and were not significantly different in this layer. In the 15-30 cm depth, no significant differences were detected by N source or tillage. All treatments lost SOC at depths greater than 30 cm. At the 30-45 cm depth, the Ctrl fertilizer treatment lost the least amount of C, approximately -1.13 tons C a^{-1}. The OrgF and MinF lost similar amounts of SOC, -3.72 and -4.04 tons C a^{-1}, respectively. In the 45-60 cm layer, MinF lost the greatest amount of C at -9.37 tons C a^{-1} where OrgF changed by -5.44 tons C a^{-1}. The Ctrl treatment was statistically similar to both the OrgF and MinF treatments, which lost -6.78 tons C a^{-1}. In considering the full profile, 0-60 cm, all treatments lost SOC where OrgF lost the least C, -1.52 tons C a^{-1}, Ctrl changed by -8.12 tons C a^{-1} and MinF changed by -13.8 tons C a^{-1}.

The adoption of NT increased SOC in the surface 0-5 cm by 2.26 tons C a^{-1} above the baseline ($P = 0.052$). This was nearly twice as much SOC as CT, which only accumulated 1.19 tons C a^{-1}. However, SOC increased in the 5-15 cm layer with CT by 1.79 tons C a^{-1} compared to ($P = 0.061$). Inversion of surface soil and residue into the subsurface causes this increase in CT systems (Angers and Eriksen-Hamel, 2008). An interaction between tillage and N management was noted at the 15-30 cm depth, but results were inconclusive after Bonferroni's adjustment. A significant interaction occurred at 30-45 cm. In general, NT MinF and CT OrgF lost the most C within this layer, -4.91 and -5.75 tons C a^{-1}, respectively ($P < 0.001$). The NT Ctrl and OrgF and CT Ctrl and CT MinF were statistically similar, varying between -3.19 and 0.26 tons C a^{-1}.

Table 1. Change in SOC (tons C a^{-1}) for main effects of N management and tillage by soil layer and full profile (0-60 cm) analysis (1992-2012).

		ΔSOC (tons C a^{-1})					
		depth (cm)					
Effect	Treatment	0-5	5-15	15-30	30-45	45-60	0-60
N source	Ctrl	0.05 a	-0.60 a	0.33	-1.13 a	-6.78 ab	-8.12 a
	OrgF	4.36 b	3.75 b	-0.47	-3.72 b	-5.44 a	-1.52 b
	MinF	0.76 a	0.24 a	-1.45	-4.04 b	-9.37 b	-13.8 c
Tillage	NT	2.26 a	0.47 a	-0.71	-3.04	-7.72	-8.74
	CT	1.91 b	1.79 b	-0.34	-2.89	-6.65	-6.91
Effect	df	P-value					
Tillage (T)	1	0.052	0.061	0.669	0.992	0.419	0.319
N source	2	<0.001	<0.001	0.230	0.004	0.015	<0.001
T × N source	2	0.498	0.244	0.076*	<0.001	0.229	0.084

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
**No significance detected after Bonferroni's adjustment*

The C isotope data support the integration of OrgF into SOC up to 45 cm in depth. The OrgF (C3-C) treatment significantly depleted $\delta^{13}C$ in the 0-5 cm, 5-15 cm, 30-45 cm and 105-120 cm depths (Table 2). The Ctrl and MinF treatments were not significantly different within these layers and retained a stronger C4-C isotopic signature. The OrgF was depleted in $\delta^{13}C$ in the 0-5 cm layer, -20.7 ‰ ($P < 0.001$). The Ctrl and MinF averaged -17.1 and -17.6 ‰, respectively in this layer. In the next layer, 5-15 cm, OrgF had a significantly depleted $\delta^{13}C$ value of -18.7 ‰ ($P = 0.043$). The Ctrl and MinF treatments were more enriched in $\delta^{13}C$, averaging -17.1 and -17.4 ‰, respectively. Neither N source nor tillage significantly affected $\delta^{13}C$ in the 15-30 cm depth. In the 30-45 cm depth, OrgF was again significantly depleted in $\delta^{13}C$ from Ctrl and MinF ($P = 0.013$) averaging -16.2 ‰. The Ctrl and MinF treatments were not significantly different, with values of -14.8 and -14.9 ‰, respectively.

Tillage had a significant influence in the 30-45 cm layer ($P = 0.026$). No-till was slightly more depleted (-15.8 ‰) than CT (-14.8 ‰). At the 120 cm depth, OrgF averaged -20.0 ‰ ($P = 0.059$) where Ctrl and MinF were -16.2 ‰ and -15.9 ‰, respectively. No-till had significantly depleted $\delta^{13}C$ values (-15.8 ‰) at the 30-45 cm depth ($P = 0.025$). This was more depleted than CT, which averaged -14.9 ‰.

Table 2. Soil $\delta^{13}C$ (‰) for 2012 through the soil profile for the main effects of N management and tillage.

		Soil $\delta^{13}C$ (‰)								
		depth (cm)								
Effect		0-5	5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120
N source	Ctrl	-17.1 a	-17.1 a	-16.1	-14.8 a	-14.7	-14.6	-15.2	-15.1	-16.2 a
	OrgF	-20.7 b	-18.7 b	-16.7	-16.2 b	-14.8	-15.5	-15.1	-15.5	-20.0 b
	MinF	-17.6 a	-17.4 a	-16.7	-14.9 a	-14.8	-14.9	-15.4	-15.3	-15.9 a
Tillage	NT	-18.7	-17.3	-16.6	-15.8 a	-14.8	-15.1	-15.0	-15.1	-16.2
	CT	-18.2	-18.1	-16.3	-14.9 b	-14.7	-14.9	-15.4	-15.5	-18.6
Effect	df	P-value								
Tillage (T)	1	0.159	0.143	0.544	0.025	0.695	0.659	0.308	0.268	0.165
N source	2	<0.001	0.043	0.470	0.013	0.964	0.334	0.789	0.670	0.059
T × N source	2	0.852	0.414	0.834	0.158	0.143	0.685	0.581	0.218	0.902

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till

An increase in SOC with OrgF was primarily confined to the surface 15 cm. Although not significant, NT OrgF increased SOC by 0.71 tons C a^{-1} in the 15-30 cm depth, while CT OrgF lost 1.64 tons C a^{-1}. In a previous study at this site, Nicoloso et al. (2018) reported that SOC had saturated in the NT with OrgF in the 0-5 cm layer with subsequent translocation into the underlying 5-15 cm layer. They also found no significant accumulation of SOC below 15 cm with either tillage system. The $\delta^{13}C$ from this study confirms the stabilization of C from OrgF up to 15 cm in depth. The OrgF depleted $\delta^{13}C$ in the 30-45 cm but no significant change in SOC was observed within this layer, though not enough C from OrgF has become stabilized to detect.

No-till over 22 years increased SOC in the surface 0-5 cm by 2.26 tons C a^{-1} while CT only increased surface SOC by 1.91 tons C a^{-1}. On the other hand, CT significantly increased SOC within the 5-15 cm layer so that cumulative SOC from 0-15 cm was not different between tillage systems.

Within the profile 60 cm, all treatments lost SOC except NT OrgF (0.29 tons C a^{-1}). Although not significant, soil profile C to 45 and 60 cm showed greater net gains in SOC with NT OrgF (6.42 and 0.29 tons C a^{-1}) than CT OrgF (1.41 and -3.34 tons C a^{-1}). Considering the main effects through the profile (0-60 cm), the MinF and Ctrl changed by -13.8 and -8.12 tons C a^{-1}, respectively, while OrgF changed by -1.52 tons C a^{-1}. In the 30-60 cm layers, all OrgF and MinF treatments lost SOC regardless of tillage treatment; however, in the 30-45 cm layer, NT was able to significantly reduce C losses (-1.70 tons C a^{-1}) compared to CT (-5.75 tons C a^{-1}). This is similar to another maize tillage and N rate study where NT and N application maintained SOC in the surface but lost SOC below 30 cm (Stewart et al., 2017). It appears that C from OrgF, residue or root decomposition was not able to sustain SOC to this depth in this cropping system.

In summary, surface management effects on soil C sequestration were confined to the surface 15 cm even with additional C inputs. Annual cropping systems, such as this, must consider deep-rooted crops and rotations to maintain deep soil C. However, this must include no-tillage as tillage loses the benefits of additional C inputs.

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