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Long-term N fertilization and conservation tillage practices conserve surface but not profile SOC stocks under semi-arid irrigated corn☆

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ABSTRACT

No tillage (NT) and N fertilization can increase surface soil organic C (SOC) stocks, but these gains are frequently not observed through the soil profile and could be subject to loss through subsequent tillage events. We evaluated a long-term irrigated continuous corn no-tillage (NT) and N rate study near Fort Collins, CO that was split into continuous NT or strip till (ST) treatments after five years. We measured grain and residue yields yearly, and SOC and particulate organic matter C (POM-C) at baseline, 5 yrs and 11 yrs later. Continuous NT depressed grain yields (10%) but not stover yields compared to ST. Continuous NT and increasing N fertilization rate increased surface (0–7.5 cm) SOC stocks 10 and 13%, respectively, compared to baseline. Seven years of ST completely negated initial surface (0–7.5 cm) SOC gain under NT and was only partially explained by POM-C loss (8–25%). All treatments lost between 14 and 19 Mg C ha^{-1} in the soil profile (0–120 cm) compared to baseline with no N or tillage effects. Soil C cycling appears to be rapid in this irrigated system, requiring greater C inputs to maintain SOC stocks. Effective conservation practices will need to balance crop yield, surface erosion protection, and profile-wide SOC stock losses.

1. Introduction

No-tillage management reduces soil disturbance and promotes soil aggregation, increasing surface SOC in most agroecosystems. Although these effects have been well-documented for the surface 30 cm (Halvorson et al., 2002; Ogle et al., 2005; West and Post, 2002), studies that sample below the plow layer find smaller (Angers and Eriksen-Hamel, 2008) or no increase in SOC (Follett et al., 2013; VandenBygaart et al., 2003). In irrigated continuous corn systems NT and N fertilization increase surface (0–30 cm) SOC (Halvorson and Jantalia, 2011), but these effects are frequently not observed over the entire soil profile (Denef et al., 2008; Follett et al., 2013; Schmer et al., 2014). Follett et al. (2013) found no change in SOC through the soil profile to 120 cm with NT compared to an overall loss of SOC under conventional moldboard plough tillage after 8 years in irrigated continuous corn with and without fertilizer. Schmer et al. (2014) found no difference between CT and NT SOC stocks (0–150 cm) after 10 years under irrigated continuous corn near Ithaca, Nebraska. Changes in SOC deeper in the profile indicate substantial C turnover, potentially due to increased moisture availability, rooting depth, and microbial activity (Follett et al., 2013; Schmer et al., 2014). This contrasts with rainfed soil profile SOC under continuous NT management, which showed significant SOC accumulation in the entire 0–150 cm profile (Follett et al., 2013) from root turnover and decomposition (Stewart et al., 2016).

Despite the potential long-term benefits of NT to surface soil properties and nutrient cycling, adoption can be low due to reduced yield from N immobilization, surface temperature reductions, and disease pressure (Grandy and Robertson, 2006; Ogle et al., 2012). A producer may choose periodic tillage or reduced-tillage management to counteract these effects and SOC gains under NT may subsequently be lost by tillage events. Tillage disrupts soil aggregation, reducing physical protection of residues as POM or light fraction, and increasing mineralization of soil organic matter (SOM) (Grandy and Robertson, 2006; Paustian et al., 2000). Although reduced-tillage (RT) and periodic tillage has been well-documented in the rainfed Midwest (Conant et al., 2007; Grandy and Robertson, 2006), there is still a lack of knowledge about the impact of RT on SOC sequestration in the semi-arid western US.

Increasing N fertilization rates may increase (Halvorson and

Abbreviations: CT, conventional tillage; NT, no, tillage; RT, reduced tillage; ST, strip tillage; SOC, soil organic C; SOM, soil organic matter, POM-C particulate organic matter carbon; DOC, dissolved organic carbon; DN, dissolved nitrogen

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Jantalia, 2011), decrease, or not change soil organic C stocks depending on soil depth considered and tillage practices (Brown et al., 2014; Follett et al., 2013; Jantalia and Halvorson, 2011). The net effect of N fertilizer on SOC stocks reflects the relative importance of increasing crop productivity and residue and root C inputs to the soil versus its stimulation of residue and SOC decomposition. N fertilizer can change plant allocation above- and belowground in annual cropping systems, reducing (Durieux et al., 1994; Yu et al., 2014), or having no change in root C inputs to the soil (Russell et al., 2009; Stewart et al., 2016). Residue N content and quality increases with N fertilization, which can promote residue decomposability (Craine et al., 2007; Hobbie et al., 2012; Johnson et al., 2007; Stewart et al., 2015). Residues with a greater N content transition more quickly into labile particulate organic matter (POM) fraction, which is comprised of partially decomposed plant material and fungal hyphae (Stewart et al., 2016). However, under nutrient stress, plants increase root exudation stimulating SOM decomposition (Personeni and Loiseau, 2004; Shahzad et al., 2015) for nutrient acquisition (i.e., Craine et al., 2007). Decomposition of SOC increases with greater inherent soil N status (Stewart et al., 2015). Enhanced residue and SOC decomposition help explain the lack of SOC sequestration with increased N fertilization even when substantial increases in crop residues have been observed (Brown et al., 2014; Russell et al., 2009).

Our objective was to evaluate a long-term irrigated continuous corn no-tillage (NT) and N rate study near Fort Collins, CO that was split five years after inception into continuous NT or strip till (ST) treatments and measure crop yields, stover production, soil profile-wide (0–120 cm) SOC, and surface particulate organic matter C (POM-C) at baseline, 5 yrs. and 11 yrs. later. We hypothesize that treatments with tillage (ST) and without fertilizer should have the lowest SOC stocks from greater SOM decomposition and lower C inputs when no N fertilizer is applied.

2. Material and methods

2.1. Field site & experimental design

The study was located on a Fort Collins clay loam soil (fine-loamy, mixed, mesic Aridic Haplustalfs) with a 1 to 2% slope at the Agricultural Research Development and Education Center (ARDEC) (lat. 40° 39′6″ N, long. 104° 59′57″ W; 1535 m above sea level) near Fort Collins, CO. The study was initiated in 1999 on a field that had previously been continuously cropped to corn for 6 yr using a CT (moldboard plow, 30–38 cm depth) production system and was described in detail in Halvorson and Jantalia (2011) and Follett et al. (2013). The study was a randomized complete block design under no-tillage (NT) with five N rates and three field replicates with 10.7 by 15.2 m plots. In 2006, the NT plots were split in half with half of each plot continuing as NT, and the other half converted to a ST system.

No-till corn was directly planted into the previous year's corn residue each spring using a planter equipped with residue managers, followed by application of herbicides for weed control, and harvest (Halvorson et al., 2006). Starting in 2006, the ST plots were strip tilled to ~23 cm depth with a six-row Orthman 1tRIPr (Orthman Manufacturing Inc., Lexington, NE). Corn was planted in the strip-tilled area followed by application of N, herbicides for weed control, and harvest (Halvorson et al., 2011).

The five N rate treatments averaged 0, 67, 117, 168, 232 kg N ha^{-1} from 2001 to 2012 (Table 1) and were chosen to provide a wide range in N rate while minimizing N leaching due to over fertilization. At this site, optimal N rate from 1999 to 2009 in conventional tillage was 177 kg N ha^{-1} (Jantalia and Halvorson, 2011) and for the continuous NT plots in this study was 239 kg N ha^{-1} (Halvorson and Jantalia, 2011). N source was urea ammonium nitrate (UAN, 32–0–0) from 2001 through 2005 applied preplant in subsurface bands (5 cm) with a liquid fertilizer applicator. In 2006, surface band (split applications) of a polymer-coated urea (ESN) was applied at corn emergence in May and dry granular urea N fertilizer was applied in mid-June. From 2007 to 2012, surface band applications of a polymer-coated urea near the corn row at emergence in May were used. Triple superphosphate (0–46–0) was applied in 1999 (56 kg P ha^{-1}), 2004 (28 kg P ha^{-1}), 2005 (53 kg P ha^{-1}), 2009 (20 kg P ha^{-1}), and 2010 (56 kg P ha^{-1}) to avoid P deficiency in the corn.

All corn hybrids had about a 92 to 94 d relative maturity, except in 2007 when an 89d relative maturity corn hybrid was used. Herbicides were used to control weeds with the plots being essentially weed free during the study period. A linear-move sprinkler irrigation system was used to apply water as needed (determined weekly by the feel method 1999–2007 (Klocke and Fischbach, 1998)) and with Watermark soil moisture sensors (Spectrum Technologies Inc., Plainfield, IL) in 2008–2012 during the growing season. Irrigation water was slightly alkaline (pH between 7 and 8) and had NO_3-N content ranging from 1 to 7 mg L^{-1} which resulted in an annual contribution between 7.6 and 24.5 kg N ha^{-1}.

2.2. Plant harvesting & soil sampling

Above-ground corn biomass (grain and stover) was determined in late-September at physiological maturity each year by hand harvesting 15 whole corn plants from a 1.5 m^2 or larger area from each plot (Halvorson et al., 2010; Halvorson and Stewart, 2015). Plants were separated into grain, cobs, and stalks plus leaves for mass determination. The cob and stalk plus leaf residues were combined to obtain total stover residue. Grain yield was determined by harvesting the corn ears from the established harvest area by hand when grain was near 160 g kg^{-1} water content in October, then separating the corn grain from the cob with a mechanical sheller. Grain yields and the stover (cobs, stalks & leaves) are expressed on an oven-dried basis.

Soil samples were collected from the plot area in the fall of 2001 following corn harvest to establish initial SOC and total soil N (TSN) stocks. The same plot area was sampled in 2006, and 2012 to determine the change in SOC and TSN stocks. One soil core (5-cm diameter) sample was collected from near the same location within each plot after harvest, using a GPS to relocate the sampling sites, in increments of 0–7.5, 7.5–15, and 15–30, 30–60, 60–90, 90–120 cm. The ST plots were sampled in the interrow area adjacent to the tilled area. Soil bulk density was determined after grain harvest for each sampling depth in the 0–30 cm using the core method and bulk density below 30 cm was assumed to be a constant from a previous intensive sampling (Follett et al., 2013). Soil bulk density was used to calculate SOC mass and we present SOC on a concentration, soil mass, and equivalent soil mass basis (Ellert and Bettany, 1995). Particulate organic matter was isolated for 2001, 2006, and 2011 using a modified method of Gregorich and Ellert (1993). Briefly, soils were dispersed with a 5 g L^{-1} solution of sodium hexametaphosphate, shaken overnight, rinsed over a 53 μm sieve and oven dried (55C) and ground for further analyses.

2.3. Soil and plant sample C and N analyses

Soil samples were sieved through a 2-mm screen prior to preparation for soil analyses. Soil and plant samples collected for C and N analysis were ground to pass a 150-μm screen and analyzed for total soil C (TSC) and N or plant C and N content using an Elementar vario Macro C-N analyzer (Elementar Americas, Inc., Mt. Laurel, NJ). Soil inorganic C (SIC) was determined on whole soil and POM fraction using the pressure-calcimeter method (Sherrod et al., 2002). Soil organic C was calculated as the difference between TSC and SIC. Cob and stalk plus leaf (stover) N and C were determined on the plants harvested at physiological maturity and grain N and C on grain samples collected at final grain harvest. Total aboveground biomass N and C was determined by summing the cob, stalks plus leaves, and grain.

Table 1
Experimental summary of tillage treatments (continuous no-tillage (NT) and strip-tillage (ST)) N fertilizer rates and source, and yearly precipitation, irrigation, and growing season precipitation (April–September).

year	Tillage treatments	N rates	Fertilizer source[a]	Precip Year total	Irrigation Year total	Growing Season
		kg N ha^{-1}		mm		
2001	NT	0, 67, 101, 134, 168	UAN	187	509	155
2002	NT	0, 67, 101, 134, 202	UAN	178	504	142
2003	NT	0, 67, 101, 134, 224	UAN	228	411	183
2004	NT	0, 67, 101, 134, 224	UAN	240	362	207
2005	NT	0, 67, 101, 134, 246	UAN + PCU	295	388	211
2006	NT, ST	0, 67, 101, 134, 246	PCU + Urea	117	403	69
2007	NT, ST	0, 67, 134, 202, 246	PCU	273	406	195
2008	NT, ST	0, 67, 134, 202, 246	PCU	296	360	272
2009	NT, ST	0, 67, 134, 202, 246	PCU	285	371	245
2010	NT, ST	0, 67, 134, 202, 246	PCU	246	395	196
2011	NT, ST	0, 67, 134, 202, 246	PCU	312	354	255
2012	NT, ST	0, 67, 134, 202, 246	PCU	149	506	133

[a] PCU = polymer-coated urea (44% N); UAN = urea ammonium nitrate (32% N).

2.4. *Statistics*

For all SOC, N, bulk density, C:N data, the main effects of N rate, depth, and year were evaluated using a repeated measures design where both depth and year for each replicate were considered individuals. Crop stover yields, C and N were evaluated using a single repeated measures design with main effects of N rate, depth, and year with field replicates repeated over time. Data were transformed as necessary to meet assumptions of normalcy and equal variance. Differences between main effects were obtained using least-squared mean differences (pdiff option). Individual contrasts within depth were tested after Bonferroni's adjustment at $p = 0.05$. We present least squared means unless otherwise indicated. Nitrogen rates were run separately initially, but due to no significant individual N rate response, were combined and presented as a single N added treatment (Supplemental Table 1).

2.5. *Results*

2.5.1. *Precipitation and irrigation*

Total growing season water averaged 621 ± 45 mm over the study with 412 ± 51 mm coming from irrigation and 209 ± 64 mm from precipitation (Table 1). Growing season precipitation ranged from 87 mm in 2006 to 293 mm in 2011, and irrigation water from 354 in 2011 to 506 in 2012.

2.6. *Grain and stover yields*

For the first 5 years continuous NT grain yields averaged 7344 kg ha^{-1} and were 12% lower than ST from 2006 to 2012 (8313 kg ha^{-1}, $p > 0.001$). From 2006–2012, continuous NT yields were 8% lower than ST (7670 kg ha^{-1}, Table 2). Grain yield increased with increasing N rate, with the addition of 232 kg N ha^{-1} nearly doubling grain yields compared to no N addition (Table 2, $p < 0.001$). However, the first 5 years of NT had a near-linear yield response to N fertilizer rate ($y = 4754.47 + 29.11x + -0.043x^2$, $R2 = 0.98$, $p = 0.013$), while in the last 7 years both the continuous NT and ST treatments reached an optimum of 190 and 203 kg N ha^{-1}, respectively, with no yield benefit of higher N rates. The yield curve was $y = 5454.03 + 44.44x + -0.117x^2$ for ST ($R2 = 0.98$, $p = 0.017$) and $y = 4954.44 + 39.90x + -0.098x^2$ ($R2 = 0.97$, $p = 0.02$) for NT. There was no interaction between N rate and tillage.

Average total stover production ranged from 6147 to 9462 kg ha^{-1} with no difference between tillage treatments or between early and late periods of the study. Stover increased from 0N to N added treatments N ($p > 0.0001$) with no difference between N rates (67 to 232 kg N ha^{-1}) in the later part of the study, or any interaction between rate and tillage (Table 2).

Table 2
Grain yield (kg ha^{-1}), stover (stalk + leaf + cob) biomass (kg ha^{-1}), stover C input (kg C ha^{-1}), and C:N ratios for the initial years of NT (2001–2005) and final years of ST (2006–2012) and NT (2006–2012) under 0, 67, 117, 168 and 232 kg N ha^{-1}. Capital letters within a row indicate significant differences between study periods. Lowercase letters indicate differences between N-rates.

N rate kg N ha^{-1}	2001–2005 NT	2006–2012 ST	2006–2012 NT	2006–2012 avg
grain yield (kg ha^{-1})				
0	4637 a	5353 a	4857 a	5105 a
67	6798 b	8094 b	7344 b	7719 b
117	7596 b	9254 bc	8547 bc	8900 bc
168	8339 c	9297 bc	8531 bc	8914 bc
232	9348 d	9569 c	9070 c	9319 c
Average	7344 A	8313 B	7670 A	
stover yield (kg ha^{-1})				
0	6147 a	6336 a	6262 a	6299 a
67	7418 b	7703 b	8071 b	7887 b
117	7937 b	8503 b	8454 b	8479 b
168	8457 bc	8461 b	8532 b	8497 b
232	9161 c	8217 b	9462 b	8839 b
Average	8071 A	7844 A	8156 A	
stover C yield (kg ha^{-1})				
0	2702 a	2707 a	2698 a	2703 a
67	3274 b	3364 b	3526 b	3445 b
117	3551 bc	3765 bc	3721 bc	3743 bc
168	3770 c	3711 bc	3756 bc	3734 bc
232	4113 c	3633 c	4154 c	3893 c
Average	3585 A	3436 A	3571 A	
stover C:N ratio				
0	102 a	87 a	92 a	90 a
67	92 ab	82 a	84 a	83 a
117	92 a	72 b	70 b	71 b
168	78 ab	60 b	59 b	59 b
232	66 b	65 b	60 b	63 b
Average	86 B	73 A	73 A	

Stover C followed the same pattern, with no differences between tillage, or between early or late periods of the study. All fertilized treatments had greater C compared to no N fertilizer ($p < 0.001$), and 232 kg N ha^{-1} having the greatest C (3893 kg C ha^{-1}) in the later part of the study.

The stover C:N ratio averaged over N rates during the early part of the study (86) was greater than both ST (73) and NT (73) from 2006 to 2012 with no difference between the two ($p > 0.001$, Table 2). N fertilization treatments decreased stover C:N ratio from 90 in the 0 kg N ha^{-1} to 63 in the 232 kg N ha^{-1} treatments.

Table 3
Soil bulk density (g cm^{-3}) for ST and NT in 2001, 2006, and 2012 averaged over N-rate. Lowercase letters within a column indicate significant differences between tillage treatments within depth, and capital letters within a row indicate significant differences between years and tillage within depth.

	NT			ST		Tillage average	
Depth (cm)	2001	2006	2012	2006	2012	NT	ST
	g cm^{-3}						
0–7.5	1.44 A	1.41 A	1.37 A	1.29 B	1.30 B	1.41 a	1.34 b
7.5–15	1.50 AB	1.60 A	1.56 AB	1.51 AB	1.40 B	1.55 a	1.47 b
15–30	1.51 A	1.56 A	1.56 A	1.55 AB	1.51 A	1.54 a	1.52 b

2.7. Bulk density

Strip tillage reduced bulk density in the 0–7.5 and 7.5–15 cm depths compared to NT ($p > 0.001$, Table 3). There was no trend of N rate on bulk density aside from one significant contrast in the surface depth, where 122 > 177 kg N ha^{-1} (1.42 vs 1.32, $p = 0.017$). Bulk density decreased over time in the ST in the surface depth (0–7.5) from 1.44 in 2001 to 1.30 in 2012 ($p > 0.009$).

2.8. Surface SOC content and stocks

Surface (0–7.5) SOC content was greater under NT compared to ST (14.3 vs 13.6 g C kg $soil^{-1}$) averaged over N rates (Table 4). Surface SOC also increased with increasing N fertilization rate (12.3–14.5 g C kg $soil^{-1}$, $p > 0.001$), averaged over tillage systems and years (Table 4). All fertilizer rates except the lowest (67 kg N ha^{-1}) had greater SOC contents compared to the 0 kg N ha^{-1} rate. In the 7.5–15, 15–30, and 90–120 cm depths, SOC content was lower under NT compared to ST ($p > 0.001$). Due to the lack of significance between fertilized N-rates in SOC content of the deeper depths, they were combined for all subsequent analyses and are presented as a single N added treatment.

No-till increased surface (0–7.5 cm) SOC stocks by 10% on average ($p = 0.002$) and N fertilization increased SOC stocks 13% on average over the study (Fig. 1, $p = 0.013$). However, the NT-N added treatment was the only treatment to significantly increase SOC stocks (19%) over the 11 years (0–7.5 cm, $p = 0.0009$, Fig. 1, Fig. 2). Soil organic C change over the study in the other treatments was not different from 0 in the 0–7.5 depths. However, NT-0N increased SOC stocks by 10% in the 0–7.5 depth. ST with N added showed no change in SOC stocks, and ST 0N lost SOC.

Table 4
SOC content (g C kg^{-1} soil) under tillage (ST and NT) and N fertilization rate treatments in 2001, 2006, and 2012. Capital letters within a row indicate significant differences between tillage treatments within depth. Lowercase letters within columns indicate significant differences between N-rates.

Depth (cm)	Average N-rate	NT 2001	NT 2006	NT 2012	ST 2006	ST 2012	N avg	NT avg	ST avg
		g C kg^{-1} soil							
0–7.5	0	11.0	13.1	13.3 a	14.3	**11.4 a**	**12.3 a**	12.5	12.2
	67	13.2	14.0	15.0 a	14.0	**13.2 a**	**13.8 ab**	14.1	13.5
	117	12.8	15.0	17.3 b	15.0	**15.1 b**	**14.6 b**	15.0	14.3
	168	12.2	14.5	17.6 b	15.7	**14.3 ab**	**14.4 b**	14.7	14.1
	232	12.6	15.2	18.1 b	14.8	**13.7 ab**	**14.5 b**	15.3	13.7
	Avg	**12.4A**	**14.4 AB**	**16.3 B**	**14.8 B**	**13.5A**		**14.3A**	**13.6 B**
7.5–15	0	10.9	10.3	8.8	10.2	9.0	10.0	10.0	10.1
	67	11.3	11.1	9.9	11.4	10.2	10.9	10.8	10.9
	117	10.6	10.8	9.4	11.2	10.5	10.5	10.3	10.7
	168	11.1	10.3	9.3	11.0	10.2	10.5	10.2	10.8
	232	10.5	11.1	8.9	10.7	9.6	10.2	10.2	10.3
	Avg	**10.9A**	**10.7A**	**9.2 B**	**10.9A**	**9.9 B**		**10.3A**	**10.6 B**
15–30	0	9.0	9.2	8.0	9.7	7.8	8.8	8.8	8.8
	67	10.0	9.5	8.8	10.5	8.8	9.6	9.4	9.7
	117	9.4	9.6	8.5	10.5	8.7	9.3	9.1	9.5
	168	9.4	8.3	8.8	9.5	8.9	9.0	8.8	9.2
	232	9.6	9.4	7.9	9.7	8.1	9.0	8.9	9.1
	Avg	**9.5A**	**9.2A**	**8.4 B**	**9.9A**	**8.4 B**		**9.0A**	**9.3 B**
30–60	0	3.8	4.0	3.4	4.4	3.4	3.8	3.8	3.9
	67	4.9	5.3	3.7	5.1	3.9	4.7	4.6	4.7
	117	4.9	5.0	4.0	5.3	4.5	4.8	4.6	4.9
	168	4.9	3.7	4.3	4.6	3.6	4.3	4.3	4.4
	232	4.4	4.5	2.8	4.4	4.3	4.1	3.9	4.4
	Avg	**4.6A**	**4.5A**	**3.6 B**	**4.8A**	**3.9 B**		4.2	4.4
60–90	0	2.5	2.3	1.7	2.4	1.6	2.2	2.2	2.2
	67	3.2	2.8	2.2	2.9	2.2	2.7	2.7	2.7
	117	3.1	2.6	2.2	2.6	2.3	2.7	2.6	2.7
	168	3.1	2.8	2.2	2.4	1.8	2.5	2.7	2.4
	232	2.9	2.6	1.7	2.6	2.2	2.5	2.4	2.5
	Avg	**3.0A**	**2.6 B**	**2.0 C**	**2.6 B**	**2.0 C**		2.5	2.5
90–120	0	1.9	1.8	0.7	1.9	1.0	1.6	1.5	1.6
	67	1.9	1.6	0.5	2.2	1.1	1.5	1.3	1.7
	117	1.8	1.7	1.2	1.7	1.0	1.5	1.6	1.5
	168	2.4	1.8	1.2	1.9	1.0	1.8	1.8	1.8
	232	2.2	1.5	1.4	2.1	1.7	1.9	1.7	2.0
	Avg	**2.1A**	**1.7 B**	**1.0 C**	**2.0 B**	**1.2 C**		**1.6A**	**1.7 B**

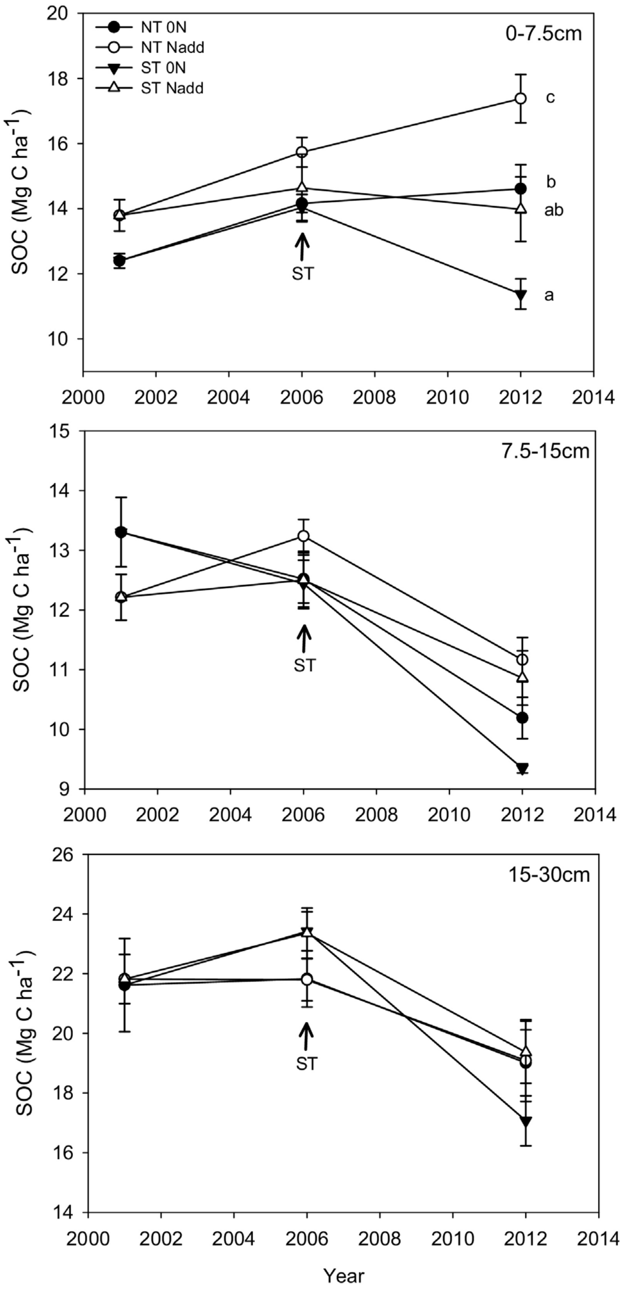

Fig. 1. SOC stocks (Mg C ha^{-1}) by depth for the 0–30 cm depths over time for the continuous NT and the strip-till (ST) under the 0N and N added treatments. Lowercase letters indicate significant differences between treatments within the year 2012. Arrow represents the initiation of ST in 2006.

2.9. Subsurface SOC content and stocks

Soil organic C content was greater under ST compared to NT averaged over N rates in the 7.5–30 cm depths, with no N or tillage effects difference deeper than 30 cm (Table 4). Over the study, all soils deeper than 7.5 cm lost SOC content (g C kg^{-1}soil, Table 4) and SOC stocks (Mg C ha^{-1}, Fig. 2). SOC stocks decreased in the 7.5–30 cm depths and this decrease tended to be greater under the 0N (23–32%) compared to the N added treatments (8–11%, Fig. 2). Net SOC loss throughout the lower depths resulted in a net profile soil C loss between 14 and 19 Mg C ha^{-1} with no difference between tillage or N fertilizer treatments (Fig. 2, Fig. 3).

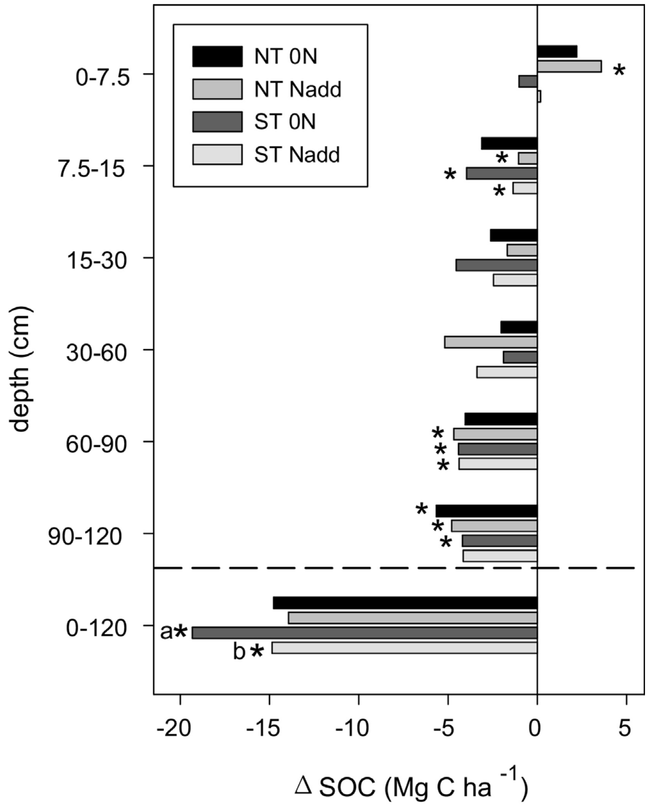

Fig. 2. SOC stock change from 2001–2012 (ΔSOC, Mg C ha^{-1}) between 2001 and 2012 for continuous NT and strip-till (ST) under the 0N and N added treatments by soil depth. Stars indicate a significant difference from zero.

2.10. Changes in nutrient dynamics

Strip tillage had a greater soil C:N ratio compared to NT in the 7.5–15, 15–30, and 90–120 cm depths ($p > 0.008$, Table 5). Soil C:N ratio was greater in the 0–7.5 and 15–30 cm depths under the N added treatments compared to 0N ($p > 0.003$). Surface soil C:N ratios were not affected by N or tillage treatment except in 2006, where ST increased C:N ratio. Soil C:N ratios decreased over time ($p > 0.0001$) in the 7.5–15, 60–90, 90–120 cm, under both tillage treatments, but the decline was greater in NT compared to ST (year*tillage interaction, $p > 0.034$).

2.11. Particulate organic matter

Particulate organic matter C (POM-C) ranged from 0.4 to 3.4 g C kg^{-1} soil and was not altered by N or tillage (Table 6). In the surface depth, POM-C increased from 2001 to 2006, and then decreased to 2011 (Table 6). POM-C decreased 43–47% in the subsurface depths (7.5–15 and 15–30 cm) over the experiment ($p > 0.0001$).

No-till POM-C stocks were 10% greater (2986 kg C ha^{-1}) compared to ST (2680 kg C ha^{-1}) in the 0–7.5 cm depth (Fig. 4, $p = 0.0145$). There was no overall effect of N addition in the 0–7.5 or 7.5–15 cm depths, but N addition decreased POM-C by 16% in the 15–30 cm depth ($p = 0.049$). POM-C peaked in 2006 in the 0–7.5 cm depth, with no difference between 2001 and 2011. In the lower depths (7.5–15 and 15–30 cm) POM-C decreased 51% and 45% from 2001.

The POM C:N was slightly greater under NT compared to ST for all depths (Table 7, $p < 0.021$). Plots with 0N had significantly greater POM C:N compared to those with N added in the 15–30 cm depth, but this difference was slight (1 unit). Over time, C:N increased to 2006, then decreased to 2011, with a greater decrease under ST compared to NT.

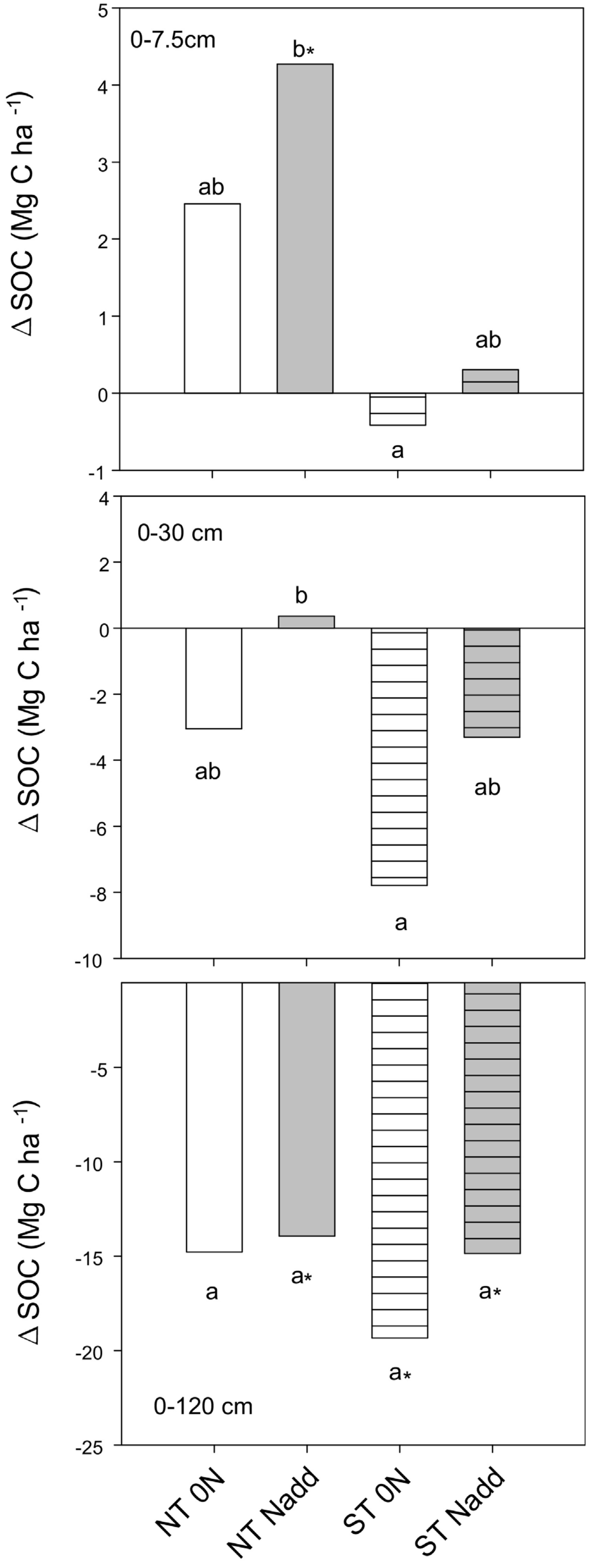

Fig. 3. SOC stock change (ΔSOC, Mg C ha^{-1}) expressed as equivalent soil mass between 2001 and 2012 for the continuous NT and strip-till (ST) under the 0N and N added treatments by soil depth. Stars indicate a significant difference from zero, letters indicate differences between treatments.

2.12. Discussion

2.12.1. Corn yields, stover biomass & stover C

Initial yield suppression after conversion from CT to NT is well documented (Conant et al., 2007; Grandy et al., 2006; Halvorson et al., 2006) and may be due to N immobilization, surface temperature changes, and disease pressure (Grandy et al., 2006; Ogle et al., 2012). Strip-till can maintain soil coverage between rows while creating narrow, residue-free rows for corn planting. Increased surface temperature in-row promotes earlier germination and growth compared to NT and subsequently can increase crop yields. Strip till increased corn grain yields by 10%, compared to continuous NT. Several meta-analyses find corn yields lower under NT compared to CT, even in later experimental years (Ogle et al., 2012; Pittelkow et al., 2015). In the semi-arid system reported here, yield reductions under NT are due to decreased spring temperatures, with residue removal boosting NT yields (Halvorson and Jantalia, 2011; Halvorson et al., 2006; Halvorson and Stewart, 2015).

The N fertilizer requirement shifted over the experiment, with the first 5 years of NT requiring more fertilizer N to maintain grain yields (Halvorson et al., 2006), but in the later part of the study, the N addition of 190–205 kg N ha^{-1} rate maximized yields under both continuous NT and ST treatments. At this site, the interaction of tillage and N fertilizer requirement has been well documented with CT optimizing yields at roughly 177 kg N ha^{-1} (Jantalia and Halvorson, 2011) compared to NT optimizing yields at 239 kg N ha^{-1} after 9 years (Halvorson and Jantalia, 2011). Despite lower yields under NT and a higher N requirement at this site, Archer et al. (2008) found the NT system provided a greater economic benefit compared to CT due to substantial reduction in tractor traffic.

Stover yields increased with N fertilizer rate and are in the range of those published previously from this site from 1999 to 2009 ranging from 5.7–9.0 Mg ha^{-1} across all N rates (Follett et al., 2013; Halvorson and Jantalia, 2011). Corn will consume excess N, lowering both aboveground and root biomass C:N ratio (Russell et al., 2009; Stewart et al., 2016). The variety in N fertilizer rates in this study caused a broad range in stover quantity and quality that will interact with tillage treatments to modify crop residue decomposition and soil organic C accumulation.

2.13. Surface tillage

Conversion from CT to NT resulted in surface SOC accumulation and subsurface (7.5–15 and 15–30 cm) SOC loss as previously observed at this site (Halvorson and Jantalia, 2011) and in other tillage studies (Franzluebbers, 2010; Ogle et al., 2005; Powlson et al., 2014; Schmer et al., 2014). This is due to the lack of tillage incorporation of fresh residues throughout the 0–30 cm layer and the decomposition of previously buried residues. Without new residue inputs to deeper layers, buried residues decomposed and resulted in the loss of 45–51% of POM-C stocks over the study. Residue burial through tillage has been suggested as a more efficient means of C stabilization in some soil systems (Wingeyer et al., 2012).

Seven years of ST after the initial 5 years of NT completely negated surface (0–7.5) SOC gain, but loss of POM-C only explained 8% (0N) and 25% (N added) of the SOC decrease, suggesting substantial mineral-associated C loss. Tillage disrupts soil aggregation, reducing physical protection of residues as POM or light fraction, and increasing mineralization of SOM. Even a single tillage event can increase CO_2 and N_2O emissions and decrease soil aggregation (Grandy et al., 2006). Tillage also disrupts soil macroaggregation and prevents the formation of stable microaggregates, which can protect SOC for centuries (Six et al., 2004, 2002). In a study in Nebraska, USA, Gillabel et al. (2007) found no increase in macroaggregation with irrigation despite more than two-fold increase in residue inputs compared to dryland sites. Tilled, irrigated corn production systems seem to have a particularly low stabilization rate of added residues as SOC (Denef et al., 2008;

Table 5
Soil C:N ratio of the ST and NT treatments in 2001, 2006, and 2012 with (N added) and without N (0N). Lowercase letters within a row indicate significant differences between tillage treatments and within a column indicate differences between N-rates within each depth. Uppercase letters within a row indicate significant differences between year and tillage treatments.

Depth	N-rate	NT			ST				
		2001	2006	2012	2006	2012	N avg	NT avg	ST avg
0–7.5	0N	8.55	8.30	8.64	9.38	8.24	8.61 a	8.50	8.72
	Nadded	9.16	8.45	9.08	9.01	8.54	8.90 b	8.90	8.90
	Average	8.85 AB	8.38 A	8.86 AB	9.20 B	8.39 A		8.70 a	8.81 a
7.5–15	0N	8.73	7.39	6.94	8.05	7.33	7.86 a	7.69	8.04
	Nadded	8.68	7.53	7.23	8.05	7.65	7.97 a	7.81	8.13
	Average	8.71 A	7.46C	7.08C	8.05 B	7.49C		7.75 a	8.08 b
15–30	0N	6.20	7.22	7.23	7.74	7.01	6.93 a	6.88	6.99
	Nadded	8.36	6.93	7.09	7.89	7.27	7.65 b	6.36	7.84
	Average	7.28 A	7.07 A	7.16 A	7.82 A	7.14 A		7.17 a	7.41 b
30–60	0N	6.15	5.89	6.10	7.04	5.78	6.19 a	6.05	6.32
	Nadded	6.98	6.09	6.02	6.97	6.11	6.52 a	6.36	6.68
	Average	6.56 A	5.99 A	6.06 A	7.01 A	5.95 A		6.20 a	6.50 a
60–90	0N	6.10	5.08	4.27	5.96	4.02	5.25 a	5.15	5.36
	Nadded	6.91	4.80	4.63	5.97	4.68	5.65 a	5.45	5.85
	Average	6.51 A	4.94 B	4.45 B	5.97 A	4.35 B		5.30 a	5.61 a
90–120	0N	5.93	3.93	2.22	5.84	3.36	4.53 a	4.03	5.04
	Nadded	6.58	3.74	3.39	5.74	3.48	4.92 a	4.57	5.26
	Average	6.25 A	3.83 BC	2.81 C	5.79 AB	3.42 C		4.30 a	5.15 b

Follett et al., 2013; Gillabel et al., 2007; Schmer et al., 2014). Even minor tillage events in this clay soil can substantially increase SOM decomposition and increase SOC loss.

2.14. Surface N fertilization effects

Nitrogen fertilization increased surface SOC stocks and reduced SOC loss in the 7.5–15 and 15–30 cm depths, through a doubling of stover returned to the soil. In this semi-arid climate with relatively low-C soils, the addition of N increased surface (0–7.5 cm) SOC when combined with NT practices (Halvorson and Jantalia, 2011), but not under CT (Jantalia and Halvorson, 2011). N fertilizer effects on SOC sequestration are a function of two competing processes: its stimulation of SOC decomposition and increase in plant productivity and residue returned to the soil. Surface SOC increase is due to greater crop residue returned to the soil surface under increasing N fertilization rates under NT production systems (Halvorson and Jantalia, 2011; Stewart et al., 2016). However, other studies of continuous corn under CT practices found no appreciable increase in SOC stocks with N fertilization, despite a large increase in C inputs (Brown et al., 2014; Russell et al., 2009). In this case, greater C inputs with N fertilization increased surface C while mitigating SOC loss in the 7.5–15 cm.

Despite a wide range in residue-stover C:N ratios, there was little difference in POM C:N ratio between 0N and N added treatments. Nitrogen addition decreased POM C:N ratio in the 15–30 cm depths, but this decrease was small (1.0 unit) compared to the wide gradient in C:N ratios of the residues (30). POM in this study was highly decomposed and retained little of the original C:N ratio of the residue. Nitrogen addition can stimulate decomposition, resulting in smaller POM pools with lower C:N ratios (Stewart et al., 2016). However, other studies across N-rate under rainfed conventional tillage continuous corn production have found surprisingly little effect of N on POM pools. Across a range in N rates from 0 to 269 kg N ha^{-1}, Brown et al. (2014) found N addition decreased only the coarse POM C:N ratio from 20 to 16, with the two finer POM fractions showing a C:N range of only 1. In a rainfed CC system under NT, Stewart et al. (2016) found no difference in POM C:N ratio over varying N rates (60–180 kg N ha^{-1}).

2.15. Soil profile tillage & N fertilization

Although NT and N fertilizer increased surface SOC over time, there was no overall effect of tillage or N over the entire 0–120 cm profile. After 8 years, Follett et al. (2013) found no effect of N fertilizer (157 and 228 kg N ha^{-1}) when considering the entire soil profile

Table 6
POM-C (g C kg^{-1} soil) of the ST and NT treatments in 2001, 2006, and 2011 with (N added) and without N (0N). Uppercase letters within a row indicate main year effects or interactions between tillage and year within depth. Lowercase letters within a row indicate significant main effects between years or between tillage treatments.

depth (cm)	N rate	2001 NT	2006 NT	2011 NT	2006 ST	2011 ST	N avg	NT avg	ST avg	2001 avg	2006 avg	2011 avg
		g C kg^{-1} soil										
0–7.5	0N	2.4	3.4	2.3	3.3	1.8	2.6 A	2.7	2.5	2.4	3.3	2.1
	Nadded	2.5	3.4	2.8	3.3	2.6	2.9 A	2.9	2.8	2.5	3.3	2.8
	Avg	2.5 A	3.4 A	2.6 A	3.3 A	2.2 A		2.8 a	2.7 a	2.5 ab	3.3 b	2.4 a
7.5–15	0N	2.0	1.3	1.1	1.5	0.7	1.4 A	1.5	1.4	2.0	1.4	0.9
	Nadded	1.8	1.4	1.3	1.4	0.7	1.4 A	1.5	1.3	1.8	1.4	1.0
	Avg	1.9 A	1.4 A	1.2 A	1.5 A	0.7 A		1.5 a	1.4 a	1.9 a	1.4 b	1.0 c
15–30	0N	1.5	1.2	1.0	1.2	0.7	1.2 A	1.2	1.1	1.5	1.2	0.8
	Nadded	1.3	1.0	1.1	1.0	0.4	1.0 A	1.1	0.9	1.3	1.0	0.7
	Avg	1.4 A	1.1 AB	1.0 B	1.1 AB	0.5C		1.2 a	1.0 b	1.4 a	1.1 b	0.8 c

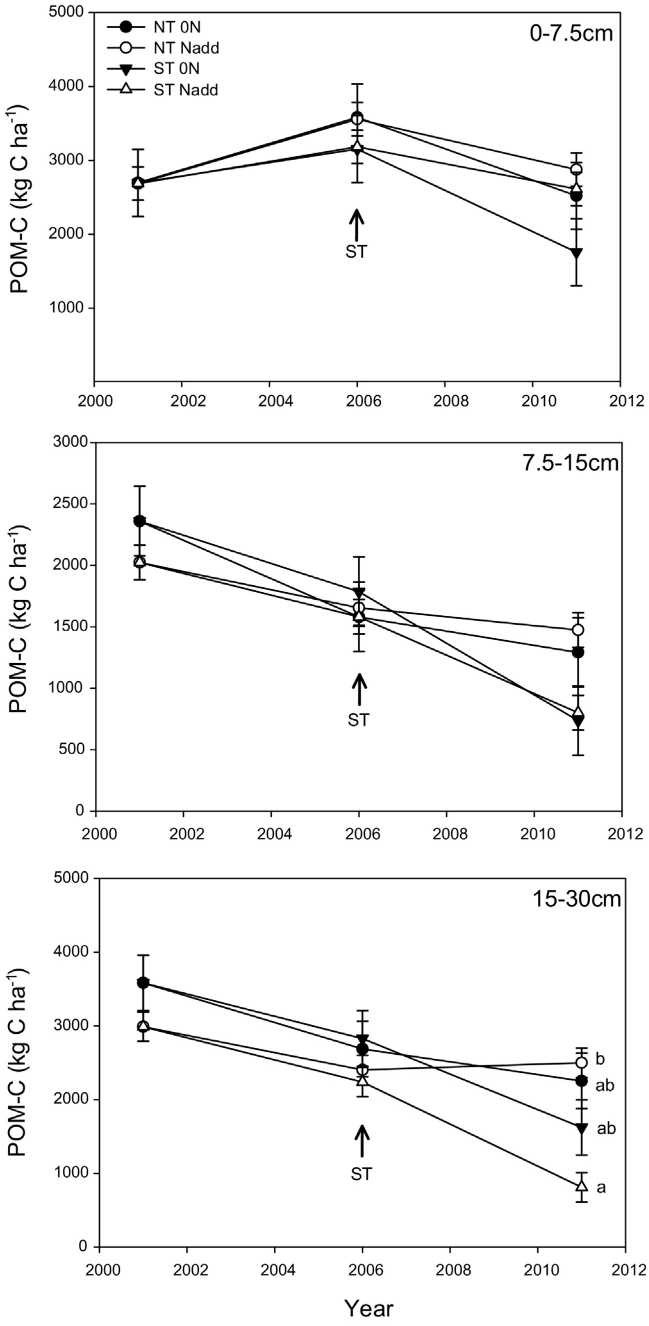

Fig. 4. POM-C stocks (kg C ha^{-1}) by depth for the 0–30 cm depths over time for ST and NT for 0N and N added treatments. Lowercase letters indicate significant differences between treatments within the year 2011. Arrow represents the initiation in ST in 2006.

(0–120 cm), but that NT mitigated SOC loss compared to CT. In contrast, we found that all layers deeper than 7.5 cm lost C resulting in a net profile loss of soil C between 14 and 19 Mg C ha^{-1}, after 11 years. Although a net profile loss of SOC is unusual, other studies have documented that some ploughed systems contained more C compared to NT when the entire plough layer is considered (Gregorich et al., 2009; Ziadi et al., 2014). The authors attributed greater C sequestration under CT to the annual incorporation and burial of residues that were protected from decomposition in the high clay soil. NT can reduce plant growth and yield in cool, wet climates and could be expected to decrease soil C through decreased C inputs (Grandy et al., 2006; Ogle et al., 2012). This does not appear to be the case in this study with no differences in stover returned to the soil throughout the study between ST and NT (Table 2).

Soil C sequestration estimates are sensitive to the use of baseline data and measurement depth reported (Powlson et al., 2014). Many tillage comparisons are made on studies after a certain time period without accounting for initial SOC content. For example at this site, although NT had greater SOC than CT when evaluated across treatments in 2009, when compared to the study's baseline, CT lost SOC and NT maintained SOC stocks (Follett et al., 2013). Many tillage effects are also observed only in the top 30 cm, with SOC stocks deeper in the profile reported more infrequently and with greater variability. When the entire profile is considered, SOC sequestration with NT is much lower, and frequently not-significant (Angers and Eriksen-Hamel, 2008; Denef et al., 2004; Schmer et al., 2014). A recent meta-analysis found the majority of studies show a redistribution of C through the profile with NT, with an accumulation at the surface and a decrease at depth, resulting in a small C gain across the whole profile (Angers and Eriksen-Hamel, 2008).

The overall SOC decrease in layers deeper than 30 cm over time is intriguing and warrants further investigation. Possible explanations include 1) DOC/DN movement through the soil profile stimulating SOC decomposition at deeper depths (priming) or 2) decreased C input from the upper soil layers (from lack of tillage), or decreased root growth with NT. Soil C at depth is highly-processed consisting of microbial products and root exudates associated with clay minerals. Despite its apparent old age, this SOC is highly susceptible to decomposition and priming from the addition of organic C. Fontaine et al. (2007) showed that the addition of fresh C to deep soil horizons can result in a substantial loss of initial SOC. Wet-dry cycles typical under irrigation increase DOC content through soil aggregate and microbial community turnover (Lundquist et al., 1999). Frequent irrigation and flushing of high DOC/DN water through the soil profile could deliver new C deeper in the profile, stimulating microbial decomposition, or loss deeper in the soil profile. Irrigation with high-C waste-water has been shown to produce a similar pattern: increased surface SOC and a decreased SOC content at depth (Jueschke et al., 2008).

Another possible explanation of the SOC decrease at depth is reduced C inputs either from tillage or changes in root distribution (Baker et al., 2007; Ogle et al., 2012). Inversion through conventional tillage redistributes residue C through the plough layer (Angers and Eriksen-Hamel, 2008) and increases C inputs below tillage (Gregorich et al., 2009) where decomposition rates are slower compared to the surface. Under NT, corn root growth is concentrated in the surface due to increased nutrient and water availability (Newell and Wilhelm, 1987; Qin et al., 2005). Root growth under ST may penetrate deeper into the ploughed depths due to lower bulk density and nutrient availability (Ball-Coelho et al., 1998). Further studies will be required to look at these mechanisms of potential C loss.

Conclusions

Long-term NT with N fertilization builds surface SOC, but is susceptible to loss through subsequent tillage, even conservation tillage, in this irrigated semi-arid agroecosystem. Strip tillage increased grain yield to similar values of earlier CT work at this site, but NT yield was depressed on average by 10%. When the entire soil profile was considered, all treatments lost SOC compared to baseline. The mechanisms for this loss need further investigation. This study illustrates the importance of considering the entire soil profile as well as accounting for baseline SOC stocks when evaluating SOC sequestration.

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Table 7

POM-C:N ratio of the ST and NT treatments in 2001, 2006, and 2011 with 0N or Nadded treatments for the top 3 depths.). Uppercase letters within a row indicate main year effects or interactions between tillage and year within depth. Lowercase letters within a row indicate significant main effects between years or between tillage treatments.

depth (cm)	N rate	2001 NT	2006 NT	2011 NT	2006 ST	2011 ST	N avg	NT avg	ST avg	2001 avg	2006 avg	2011 avg
						C:N						
0–7.5	0N	9.5	12.9	11.4	12.1	9.8	10.9 A	11.3	10.5	9.5	12.5	10.6
	Nadded	9.6	12.0	11.5	11.7	9.7	10.7 A	11.0	10.3	9.6	11.8	10.6
	Avg	9.6 A	12.5 B	11.4 B	11.9 B	9.7 A		11.1 a	10.4 b	9.6 a	12.2 c	10.6 b
7.5–15	0N	9.0	10.3	9.0	9.8	6.2	8.8 A	9.3	8.3	9.0	9.9	7.6
	Nadded	8.6	9.4	10.3	9.0	5.1	8.5 A	9.4	7.5	8.6	9.1	7.7
	Avg	8.8 A	9.7 A	9.6 A	9.4 A	5.6 B		9.4 a	7.9 b	8.8 ab	9.6 b	7.6 a
15–30	0N	8.3	9.4	9.5	9.6	7.7	8.8 A	9.1 b	8.5 b	8.3	9.5	8.5
	Nadded	7.9	8.5	10.6	8.3	3.3	7.7 B	9.0 b	6.5 a	7.9	8.4	6.9
	Avg	8.1 A	9.0 A	10.1 A	8.9 A	5.5 B		9.0 a	7.5 b	8.1 a	8.9 a	7.7 a

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.still.2017.04.003.

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		NT	NT	NT	ST	ST			
Depth	**N-rate**	**2001**	**2006**	**2012**	**2006**	**2012**	**avg**	**NT avg**	**ST avg**
cm	**kg N ha^{-1}**	---Mg C ha^{-1} soil---							
0-7.5	0	12.4 ± 0.6	14.2 ± 0.8	14.6 ± 2.2	14.0 ± 1.2	11.4 ± 1.4	13.2 ± 1.6	13.7 ± 2.4	12.6 ± 2.4
	67	14.2 ± 1.4	15.8 ± 1.7	15.7 ± 1.8	13.1 ± 2.4	13.1 ± 1.5	14.3 ± 1.9	15.2 ± 2.8	13.5 ± 2.5
	122	14.9 ± 1.9	16.0 ± 1.6	17.4 ± 1.4	15.9 ± 2.8	15.5 ± 4.2	15.8 ± 2.3	16.1 ± 2.9	15.4 ± 2.1
	177	12.6 ± 0.5	15.3 ± 1.4	18.4 ± 2.9	14.1 ± 2.3	14.0 ± 2.1	14.5 ± 2.5	15.4 ± 3.2	13.6 ± 3.2
	237	13.4 ± 0.3	15.9 ± 1.5	17.9 ± 2.8	15.5 ± 5.2	13.4 ± 4.4	14.9 ± 3.1	15.7 ± 3.2	14.1 ± 3.2
	Avg	13.5 ± 1.4	15.4 ± 1.4	16.8 ± 2.4	14.5 ± 2.8	13.5 ± 2.9	14.5 ± 2.5	14.8 ± 2.2	14.0 ± 2.9
7.5-15	0	13.3 ± 1.6	12.5 ± 1.2	10.2 ± 1.0	12.4 ± 1.2	9.3 ± 0.2	11.8 ± 1.9	12.3 ± 1.8	9.3 ± 0.2
	67	13.0 ± 0.7	13.5 ± 0.9	11.7 ± 0.5	12.6 ± 1.3	10.5 ± 1.0	12.4 ± 1.3	12.8 ± 1.0	10.5 ± 1.0
	122	12.4 ± 0.5	13.3 ± 0.7	11.2 ± 1.1	12.5 ± 1.3	11.8 ± 1.2	12.3 ± 1.0	12.3 ± 1.0	11.8 ± 1.2
	177	11.7 ± 1.5	12.6 ± 1.2	11.2 ± 1.1	12.5 ± 1.1	10.8 ± 1.9	11.8 ± 1.4	11.8 ± 1.3	10.8 ± 1.9
	237	11.7 ± 1.2	13.5 ± 0.7	10.7 ± 1.9	12.4 ± 2.6	10.3 ± 1.5	11.7 ± 1.8	11.9 ± 1.6	10.3 ± 1.5
	Avg	12.4 ± 1.3	13.1 ± 0.9	11.0 ± 1.1	12.5 ± 1.4	10.6 ± 1.4	12.0 ± 1.5	12.2 ± 1.4	10.6 ± 1.4
15-30	0	21.6 ± 4.2	21.8 ± 2.8	19.0 ± 3.3	23.4 ± 2.0	17.1 ± 2.5	20.8 ± 3.6	21.0 ± 3.6	20.2 ± 4.0
	67	23.6 ± 0.6	22.2 ± 1.9	20.8 ± 0.2	24.8 ± 3.3	20.6 ± 1.4	22.6 ± 2.1	22.6 ± 1.5	22.7 ± 3.2
	122	21.3 ± 2.5	22.6 ± 1.7	20.2 ± 1.6	23.8 ± 3.0	20.2 ± 1.7	21.6 ± 2.4	21.4 ± 2.2	22.0 ± 3.0
	177	20.9 ± 2.6	20.1 ± 3.0	21.1 ± 3.2	22.2 ± 1.8	20.7 ± 3.0	21.0 ± 2.5	20.7 ± 2.6	21.4 ± 2.4
	237	21.4 ± 2.8	22.3 ± 1.9	18.5 ± 2.8	22.6 ± 2.3	16.0 ± 4.1	20.4 ± 3.5	20.9 ± 2.8	19.3 ± 4.7
	Avg	21.8 ± 2.8	21.8 ± 2.2	19.9 ± 2.4	23.4 ± 2.4	18.9 ± 3.1	21.3 ± 2.9	21.3 ± 2.6	21.1 ± 3.5
30-60	0	18.5 ± 7.5	19.4 ± 3.3	16.5 ± 4.2	21.4 ± 2.0	16.6 ± 5.9	18.5 ± 5.3	18.2 ± 5.7	19.0 ± 4.7
	67	23.8 ± 2.7	25.5 ± 4.4	17.9 ± 8.7	24.7 ± 5.9	18.9 ± 1.6	22.4 ± 5.2	22.8 ± 5.5	21.8 ± 5.1
	122	23.7 ± 6.1	24.3 ± 6.1	19.1 ± 6.4	25.3 ± 7.0	21.5 ± 5.1	22.9 ± 5.8	22.7 ± 6.0	23.4 ± 5.9
	177	23.4 ± 5.4	17.8 ± 7.0	20.7 ± 7.4	22.4 ± 3.8	17.3 ± 1.8	20.8 ± 5.4	21.3 ± 6.2	19.8 ± 3.9
	237	21.1 ± 7.1	21.9 ± 3.9	13.6 ± 1.4	21.2 ± 6.4	20.9 ± 8.7	20.0 ± 6.3	19.4 ± 6.2	21.1 ± 6.8
	Avg	22.1 ± 6.0	21.8 ± 5.3	17.6 ± 5.8	23.0 ± 4.9	19.0 ± 4.9	20.9 ± 5.7	20.9 ± 6.0	21.0 ± 5.2
60-90	0	11.8 ± 1.5	10.8 ± 2.7	7.7 ± 2.6	11.0 ± 2.5	7.4 ± 1.6	10.1 ± 2.6	10.5 ± 2.6	9.2 ± 2.7
	67	14.9 ± 0.6	13.0 ± 1.3	10.3 ± 4.6	13.5 ± 1.2	10.1 ± 1.4	12.8 ± 2.7	13.3 ± 2.9	11.8 ± 2.1
	122	14.4 ± 3.4	11.9 ± 1.6	10.2 ± 1.8	12.4 ± 2.0	10.9 ± 3.0	12.4 ± 2.9	12.7 ± 3.1	11.7 ± 2.4
	177	14.3 ± 2.7	13.0 ± 3.1	10.1 ± 3.3	11.3 ± 1.5	8.4 ± 2.9	11.9 ± 3.3	12.9 ± 3.2	9.9 ± 2.6
	237	13.5 ± 2.3	12.0 ± 2.1	7.7 ± 1.5	11.9 ± 3.3	10.0 ± 4.2	11.5 ± 3.2	11.7 ± 3.1	11.0 ± 3.5
	Avg	13.8 ± 2.4	12.1 ± 2.1	9.2 ± 2.8	12.0 ± 2.1	9.4 ± 2.7	11.7 ± 3.0	12.2 ± 3.0	10.7 ± 2.7
90-120	0	9.1 ± 0.3	8.4 ± 0.8	3.4 ± 0.8	8.9 ± 0.6	4.9 ± 1.4	7.3 ± 2.4	7.5 ± 2.5	6.9 ± 2.4
	67	8.7 ± 0.7	7.4 ± 1.5	2.4 ± 1.5	10.4 ± 1.6	5.4 ± 2.0	7.2 ± 3.0	6.8 ± 2.9	7.9 ± 3.2
	122	8.5 ± 1.0	7.7 ± 2.0	5.6 ± 0.4	8.1 ± 1.4	4.6 ± 0.6	7.2 ± 1.9	7.6 ± 1.7	6.4 ± 2.2
	177	11.3 ± 3.4	8.3 ± 0.4	5.6 ± 2.5	9.0 ± 1.6	4.7 ± 1.4	8.4 ± 3.4	9.1 ± 3.5	6.9 ± 2.7
	237	10.6 ± 0.2	7.0 ± 0.5	6.4 ± 0.7	9.7 ± 1.2	7.8 ± 2.6	8.7 ± 2.0	8.6 ± 2.0	8.8 ± 2.1
	Avg	9.6 ± 1.9	7.8 ± 1.2	4.7 ± 2.0	9.2 ± 1.4	5.5 ± 1.9	7.7 ± 2.6	7.9 ± 2.7	7.4 ± 2.5

Supplemental Table 1 SOC stocks (Mg Cha^{-1} soil) under tillage (ST and NT) and N fertilization rate treatments in 2001, 2006, and 2012.