Effects of Tillage and Residue Management on Soil Organic Carbon and Total Nitrogen in the North China Plain

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A suitable tillage-residue management system is needed in the North China Plain (NCP) that sustains soil fertility and agronomic productivity. The objectives of this study were to determine the effects of different tillage-residue managements for a winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) double-crop system on soil organic carbon (SOC) and total N pools. No-tillage with residue cover (NTR), no-tillage with residue removed and manure applied (NTRRM), and conventional tillage with residue removed (CTRR) were investigated for 6 yr, based on a uniform N application among treatments. Soil samples were collected at six depths and changes in SOC and total N pools were analyzed. Treatments of NTRRM and NTR sequestered more SOC and total N in the 0- to 5-cm depth than CTRR. In the subsoil (5–60 cm), annual SOC sequestration was 0.01 and –0.40 Mg ha^{-1} yr^{-1} for NTRRM and NTR, respectively, while CTRR exhibited a significantly positive SOC pool trend. In the whole soil profile (0–60 cm), NTRRM, NTR, and CTRR sequestered SOC at the rates of 0.66, 0.27 and 2.24 Mg ha^{-1} yr^{-1}. When manure was applied to substitute for the N lost from residue removal, the NTRRM tended to accumulate more SOC than NTR, and had similar accumulation as NTR in total N pools, grain yield, and aboveground biomass. Crop residue could be substituted by manure in this double-crop, irrigated system. Conventional tillage, with residue removed, was suitable in soil fertility and agronomic productivity relative to NTRRM and NTR in the NCP.

Abbreviations: BD, bulk density; CTRR, conventional tillage with residue removed; NCP, North China Plain; NTR, no-tillage with residue cover; NTRRM, no-tillage with residue removed and manure applied; SOC, soil organic carbon.

As the largest terrestrial organic C pool, soil contains about 1550 Pg C to 1-m depth, which is twice the amount of C in the atmosphere (Lal, 2008a). Cropland soil has a huge potential as a C sink (0.4–0.8 Pg yr^{-1}), which could decrease CO_2 concentrations in the air and mitigate global emissions (Lal, 2004). As SOC is crucial to soil physical, chemical, and biological properties (Gregorich et al., 1994), more SOC sequestration in soil could help in sustaining soil fertility and agronomic productivity. Generally, no-tillage management has the potential to increase SOC pool by capturing C inputs and decreasing C loss by tillage. According to a review based on 276 paired treatments from 67 long-term experiments, West and Post (2002) concluded that soil could sequester 57 ± 14 g C m^{-2} yr^{-1} after conversion from conventional tillage to no-tillage management if crop residue is left on the surface. While long-term (>10 yr) adoption of conservation tillage could potentially decrease global warming in humid climates, there exists a high degree of uncertainty on the effects of conservation tillage in drier areas (Six et al., 2002), such as the NCP.

Soil type (Blanco-Canqui and Lal, 2008; Christopher et al., 2009) and sampling depth (Gál et al., 2007; Machado et al., 2003; VandenBygaart et al., 2011) could affect the assessment of tillage management on SOC pools. Some researchers have expressed doubt that no-tillage can sequester more SOC than

conventional tillage over the entire soil profile. Baker et al. (2007) highlighted the fact that ignoring the subsoil could create bias in sampling, thereby exaggerating the positive effect of no-tillage management on SOC pool over conventional tillage. Recently, a review of such studies (Luo et al., 2010) analyzed 69 paired-experiments and concluded that no-tillage did not improve the SOC pool more than conventional tillage down to 40-cm depth. They found that the SOC pool increased in the 0- to 10-cm depth by 3.15 ± 2.42 t ha^{-1}, but declined in the 20- to 40-cm depth by 3.30 ± 1.61 t ha^{-1} after adoption of no-tillage. Du et al. (2010) studied SOC and total N responses to conventional tillage with and without residue, as compared to rotary tillage and no-tillage for a wheat–corn double crop system in the NCP. They found that the no-tillage system had higher SOC and total N concentrations in the upper 10 cm but lower concentrations in the 10- to 20-cm depth that offset each other such that total SOC pool in the 0- to 30-cm profile were not different except for the conventional tillage without residue treatment. Syswerda et al. (2011) compared conventional tillage to no-tillage in a corn–soybean–wheat rotation in the northern U.S. Corn Belt. They found that surface SOC concentrations and total C pool under no-tillage were significantly greater than conventional tillage and the gains in C sequestration were not offset by C changes with depth. VandenBygaart et al. (2011) found that despite the concerns with only sampling the surface, deep sampling did not improve the ability to determine differences due to land management in SOC pools.

Furthermore, time is important on the influence of tillage on SOC (Christopher et al., 2009). After no-tillage management adoption or conversion back to conventional tillage, soil needs time to establish a new equilibrium between C inputs and outputs. The time could be 6 to 8 yr for the SOC pool in the 0- to 30-cm depth of tropical soils (Six et al., 2002).

Addition of crop residue plays an important role in SOC sequestration in improving soil structure, soil water-holding capability, and soil erosion prevention (Lal, 2009). Crop residue is important to soil nutrient cycling and soil fertility. Crop residue removal will cause the depletion of soil nutrition (such as N, P, K) which could decrease agronomic productivity and increase soil degradation (Blanco-Canqui et al., 2009; Tarkalson et al., 2009). Lal (2009) estimated that residue contained 18 to 62 kg Mg^{-1} of agronomically important nutrients, depending on the type of residue produced and its nutrient content, which would be equivalent to 83% global fertilizer consumption in 2001.

However, the effect of surface residue on SOC sequestration was limited in no-tillage. Gale and Combadellar (2000) distinguished the beneficial effects of no-tillage on SOC sequestration from residue- and root-derived C by a stimulated experiment. They found only 16% ^{14}C in the surface residue was in the soil after 360 d; in contrast, 42% of root-derived ^{14}C was still in the soil. Kochsiek et al. (2009) found that irrigation could increase the rate of litter-C decomposition which indicated that residue-derived C would be encouraging in respiring as CO_2 in irrigation no-tillage field.

Recently, with the increasing demand of biofuel around the world, concern has been expressed over the use of crop residues for biofuel production (Lal, 2008b; Tilman et al., 2009). So there is much debate about the reasonable utilization of crop residues.

Application of manure could increase SOC, and the nutrient input could improve soil fertility and soil structure (Jarecki et al., 2005; Mikha and Rice, 2004; Rochette and Gregorich, 1998). Jiao et al. (2004, 2006) found that aggregate stability (>2 mm) and nutrient retention were improved when manure and mineral fertilizer were applied in combination at a rate of 30 Mg ha^{-1}, as compared to mineral fertilization alone. Thelen et al. (2010) concluded that manure and compost help NT systems decrease the net global warming potential of CO_2 emissions relative to nonmanure systems; therefore, manure could play a similar role as crop residue by improving soil C and nutrient pools. The use of manure as a substitute for crop residue removal under NT has the potential to optimize the use of residue and manure and sustain agricultural development.

The NCP is one of the most important agricultural regions for supplying food (Du et al., 2010) and the production of crop residue (Liu et al., 2008). Crop residue in this region is essentially completely removed from the surface and used for multiple purposes, including heating and animal feed. The remaining stubble is incorporated annually by conventional tillage. A sustainable agricultural system in this region would provide security for China's food and biofuel production. It is, therefore, necessary to evaluate the effects of no-tillage and residue management on the SOC and total N pools in the NCP.

The objectives of this study were (i) to determine the effects of no-tillage compared to conventional tillage with and without residue on the SOC and total N pools of the soil profile (0–60 cm); (ii) to know whether crop residue could be substituted by manure in no-tillage when applied at an equivalent N rate; and (iii) to develop a sustainable tillage-residue management system based on their effects on SOC and total N pools, and grain yields in the NCP. To evaluate these effects on SOC and total N pools, long-term experiments are needed. Since 2003, the Agriculture Research Service of U.S. Department of Agriculture (USDA-ARS) and the Institute of Geographic Sciences and Natural Resources Research (IGSNRR) of Chinese Academy of Sciences have been conducting a bilateral project on conservation tillage in the NCP.

MATERIALS AND METHODS
Site Description

This study was conducted at Yucheng Comprehensive Experiment Station of China Academy of Science (36°50′ N,116°34′ E,elevation is 20 m), which is along the lower reach of the Yellow River in the NCP. It is located in a semiarid climate, with annual mean temperature of 13.4°C and mean precipitation of 567 mm during the past 25 yr (from 1985–2009). Approximately 70% of annual precipitation occurs between June and September. The soil is classified as a Calcaric fluvisols according to the FAO-Uneson system, surface soil

Table 1. Nutrient management under different treatments for winter wheat and summer maize growing seasons.

Treatments†	Winter wheat	Summer maize
NTRRM	112.5 Kg N ha⁻¹ of mineral fertilizer and 124.5 Kg N ha⁻¹ of urea + 4 Mg ha⁻¹ of dry matter cattle manure	175 Kg N ha⁻¹ of urea
NTR	112.5 Kg N ha⁻¹ of mineral fertilizer and 124.5 Kg N ha⁻¹ of urea + 6 Mg ha⁻¹ of straw	175 Kg N ha⁻¹ of urea + 4 Mg ha⁻¹ of straw
CTRR	112.5 Kg N ha⁻¹ of mineral fertilizer and 172.5 Kg N ha⁻¹ of urea	207 Kg N ha⁻¹ of urea

† NTRRM, no-tillage with residue removed and manure added; NTR, no-tillage with residue; CTRR, conventional tillage with residue removed.

texture is silt loam (sand, 12%; silt, 66%; clay, 22%), according to the USDA classification system, with a pH of 8.6. Winter wheat and summer maize double cropping is predominant in the NCP. Depending on precipitation, winter wheat is irrigated, using local groundwater, two to three times each season (70–80 mm each time), while summer maize is irrigated only in dry summers.

Experimental Design and Management

The long-term conservation tillage experiments had three treatments, based on the same N rate: NTR, NTRRM, and CTRR. There were three replications for each treatment which were arranged randomly. The plot size was 300 m² (7.5 m width × 40 m length). Winter wheat was seeded between 10 and 15 October, and harvested during the first 10 d of June. Then summer maize was seeded 5 d later. After harvest, standing stubble of each treatment was cut to the same height, 15 to 20 cm for wheat and 10 cm for maize, and all other residues were removed for the residue removal treatments (NTRRM and CTRR).

Before the establishment of tillage treatments, the study field was conventionally tilled for 5 yr (from 1998–2003) with winter wheat and summer maize double-cropped. All plots were tilled deeper than 30-cm depth to remove possible plow pans. For the CTRR treatment, a rotary tiller was used with a tillage depth of about 10 to 15 cm which fully incorporated standing stubble into the soil after maize harvest. There was no tillage before maize seeding which is historically common in the NCP. After harvest of NTR treatment, crop residues were chopped into pieces (about 5 cm length) by hand, plots were covered by residue at fixed rates of 4 Mg ha⁻¹ yr⁻¹ (wheat straw) and 6 Mg ha⁻¹ yr⁻¹ (maize stover). For NTRRM treatment, dry cattle (*Bos taurus*) manure at a rate of 4 Mg ha⁻¹ yr⁻¹ was applied on the surface before winter wheat seeding.

The three treatments had the same total N application rate (Table 1), 492 kg N ha⁻¹ yr⁻¹, but part of the N application was from different sources. The N application rate as mineral fertilizer under NTR, NTRRM, and CTRR systems was 412 kg N ha⁻¹ yr⁻¹. But an additional 80 kg N ha⁻¹ yr⁻¹ was applied as mineral fertilizer for CTRR, as dry manure for NTRRM and as residue for the NTR treatments. Details of dry cattle manure and crop residue composition are shown in Table 2. All other management procedures were identical for the three treatments, with herbicide (2,4-Dichlorophenoxyacetic acid butylate) and insecticide (40% dimethoate, *O,O*-dimethyl *S*-[2-(methylamino)-2-oxoethyl] dithiophosphate) spraying in May, and N, P, and K applied as compound fertilizer which is an inorganic chemical fertilizer and contains N (as urea), P (as P_2O_5) and K (as K_2O) at rate of 12: 19: 13, and the application rates were 116 kg N ha⁻¹, 178 kg P ha⁻¹ and 122 kg K ha⁻¹, respectively.

Soil Sampling and Analysis

Soil samples were collected in 0- to 2.5, 2.5- to 5, 5- to 10, 10- to 20, 20- to 40 and 40- to 60-cm depth increments after the harvest of wheat and maize each year. Soil samples were collected at five randomly chosen places in each plot by hand augur (4.6 cm diam.), then mixed together to make a composite sample for each soil depth. Samples were air-dried and passed through a 2-mm sieve for chemical analysis. Soil cores were collected in triplicate from these same six soil depths using stainless steel rings (50 cm³) for bulk density determination.

Soil pH was measured in 1:5 soil/water suspension. Soil organic carbon was determined by oxidation method with $K_2Cr_2O_7$–H_2SO_4 (Lu, 1999). In brief, approximately 0.5 g soil sieved through a 0.25-mm sieve, with roots and stone carefully removed by hand, was digested with 5 mL of 1M $K_2Cr_2O_7$ and 10 mL of concentrated H_2SO_4 at 150°C for 30 min, followed by titration of digests with $FeSO_4$. Soil total N was quantified using a Kjeldahl digestion procedure with NH_4–N analyzed colorimetrically (Gallaher et al., 1976). In this study, we used the data from June and October in 2004 (after wheat and maize harvest, respectively), October 2005, June 2006, October 2007, June 2009 and October 2009. To avoid the effects of differing soil bulk density among treatments, a common equivalent soil mass (Ellert and Bettany, 1995) was used for calculating SOC and total N pools at each depth.

Statistical Analyses

The effects of 6 yr of tillage-residue managements on SOC, total N, soil bulk density, soil C/N ratio, crop yield and aboveground biomass were determined by ANOVA. Significance was determined by LSD at the 0.05 level using SPSS for Windows, version 11.5 (SPSS Inc., Champaign, IL). The change in soil properties with time was determined by Sigmaplot 10.0 software (Systat Inc., Chicago, IL).

Table 2. Composition of manure and crop residue.

Element	Dry cattle manure	Winter wheat residue	Summer maize residue
		g kg⁻¹	
C	nd†	421.13	375.40
N	19.61	6.80	9.03
P	10.52	0.32	0.67
K	16.74	13.21	26.17

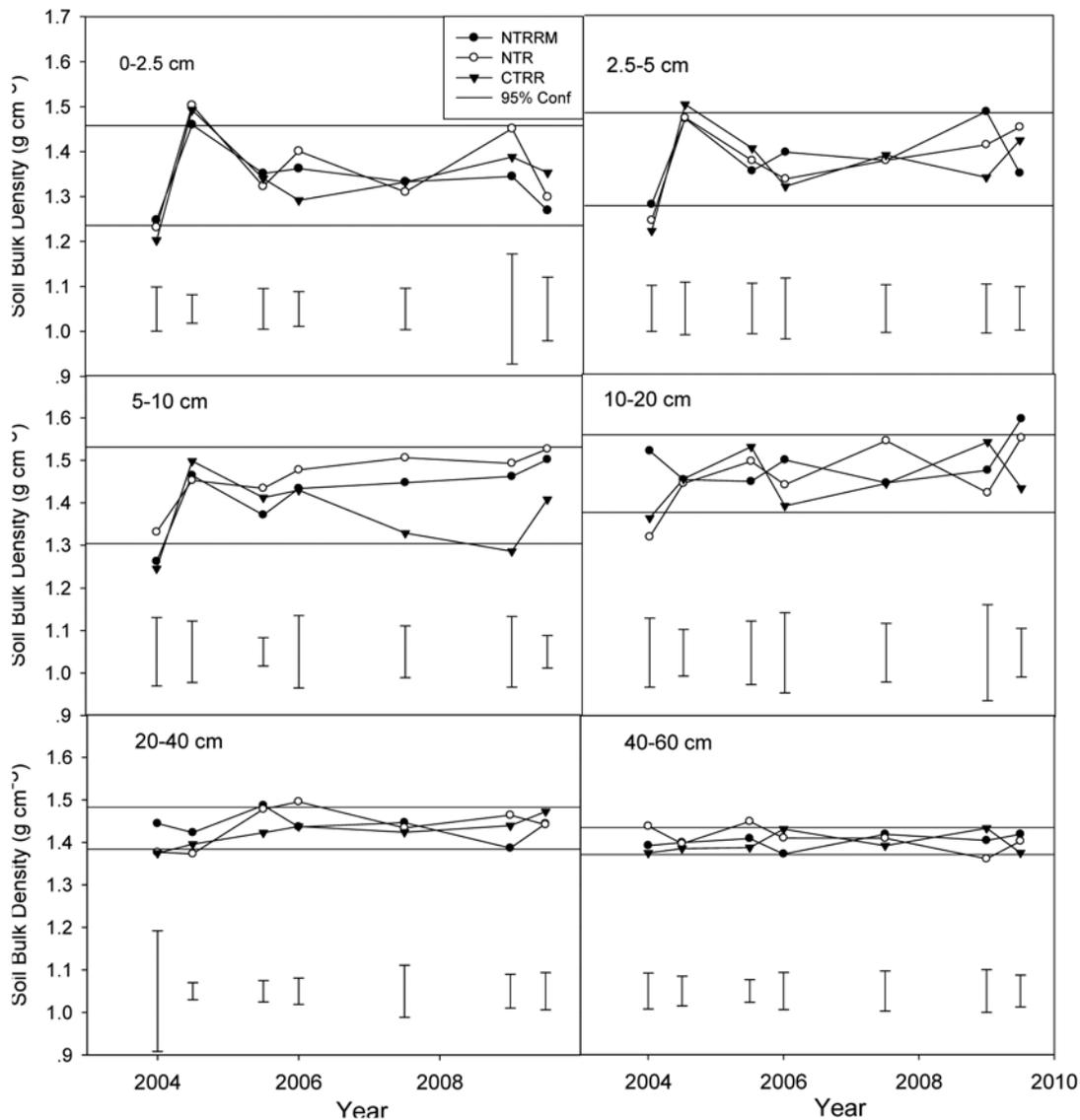† nd stands for no data. Data was measured in 2003.

Fig. 1. Soil bulk density from 2004 to 2009 for no-tillage with residue removed and manure applied (NTRRM), no-tillage with residue cover (NTR), and conventional tillage with residue removed (CTRR) treatments in six depths. Error bars stand for LSD ($P < 0.05$) for comparison among tillage treatments at the same soil layer. Soil bulk density fluctuation ranges shown by the upper and lower horizontal lines which represent 95% confidential interval.

RESULTS

Soil Bulk Density

The impacts of treatments on soil bulk density (BD) at six depths during 2004 to 2009 are shown in Fig. 1. Soil BD under three treatments tended to fluctuate in the upper two depths. Limited differences in BD were observed at 5- to 10-cm depth where the soil was denser in NTRRM and NTR treatments than in CTRR from October 2007 to October 2009. Based on a similar range of fluctuations among treatments in each soil depth, 95% confidence was used to describe the fluctuations of the means of soil BD over the 6 yr. The results showed that the fluctuation ranges tended to decrease with depth. In 0- to 2.5-cm depth, fluctuation range was 0.23 g cm^{-3} (95% confidential interval is 1.23–1.46) and decreased to 0.08 g cm^{-3} in 40- to 60-cm depth (95% confidential interval is 1.37–1.45). In the upper soil depths (0–20 cm), the range was about 0.2 g cm^{-3}. In

the deeper soil depths, however, it was 0.1 g cm^{-3} for 20- to 40-cm or even less at 40- to 60-cm depth.

Soil Organic Carbon and Nitrogen Concentration

Regression analysis indicated that the influence of the particular tillage method employed on SOC was related to sampling depth (Fig. 2). The SOC increased rapidly with time in the upper depths (0–2.5, 2.5–5, and 5–10 cm), and had the fastest increase with NTRRM and NTR (1.13 and 1.29 g kg^{-1} yr^{-1}, respectively) at the surface (0–2.5 cm). The SOC also increased with time in the upper depths of CTRR but not as rapidly as for the NTTRM and NTR treatments. As a result, the no-tillage treatments had significantly greater SOC concentrations than CTRR after October 2007 in the 0- to 2.5-cm depth. The rate of growth decreased with depth for both NTRRM (0.69 and 0.19 g kg^{-1} yr^{-1} for 2.5–5 cm and 5–10 cm, respectively) and NTR (0.58 and 0.14 g kg^{-1} yr^{-1} for 2.5–5 cm and 5–10 cm,
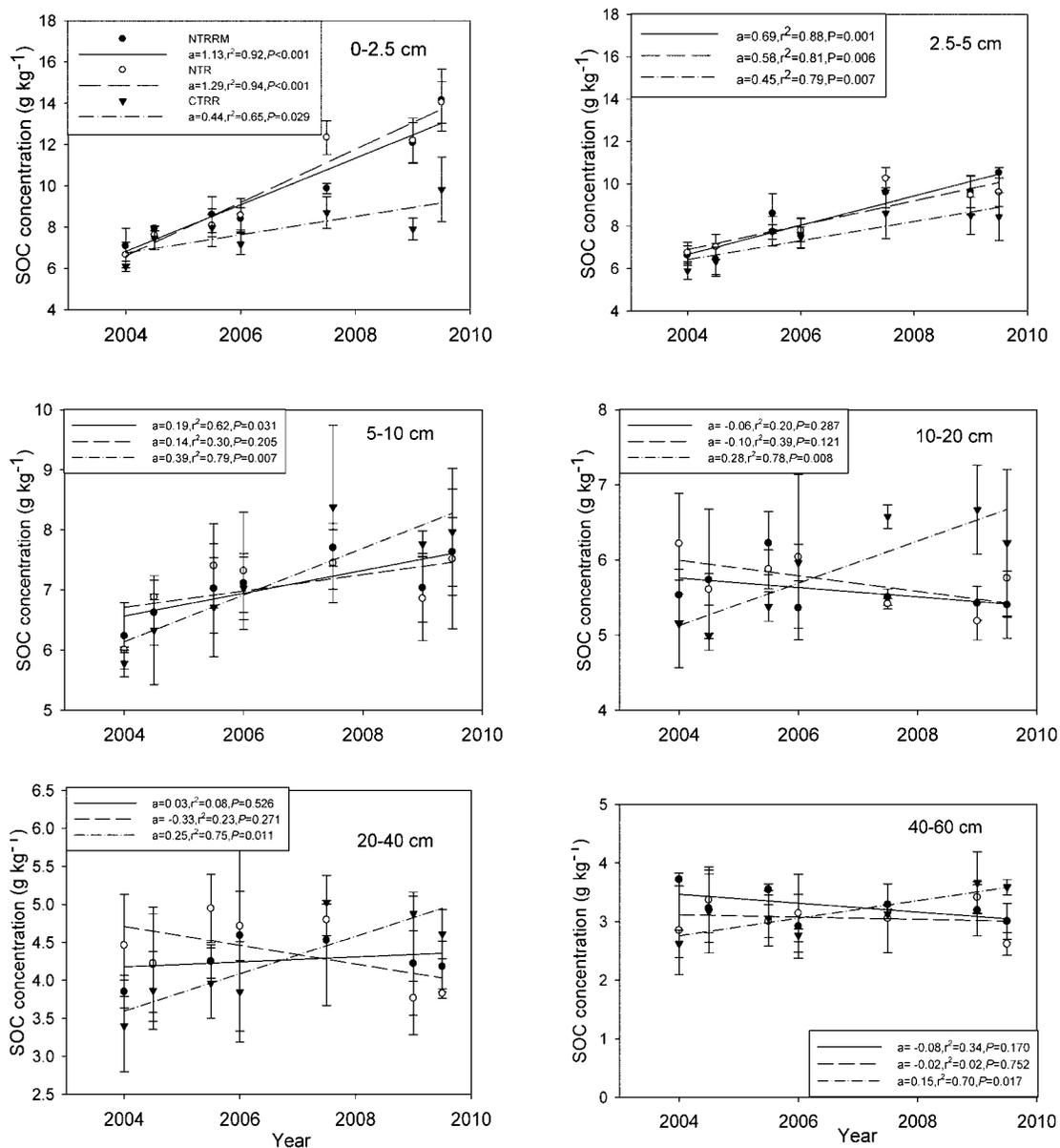
Fig. 2. Change of soil organic carbon (SOC) concentration at six depths with time in three treatments from 2004 to 2009. Solid circles stand for no-tillage with residue removed and manure applied (NTRRM) treatment, hollow circles stand for no-tillage with residue cover (NTR), and solid triangles stand for conventional tillage with residue removed (CTRR) treatment. Solid, long dash and dash-dot lines represent linear regression lines for NTRRM, NTR, and CTRR treatments, respectively. Error bars represent LSD ($P < 0.05$) for comparison among three treatments at same soil layer. The lowercase "a" stands for the linear regression slope which is the annual change of SOC concentration.

respectively). As a result, differences among NTRRM, NTR, and CTRR were not significant for these depths.

The deeper depths (10–20, 20–40, and 40–60 cm) exhibited stable or negative trends for the NTRRM and NTR treatments. The only exception occurred at 20- to 40-cm depth, where a slightly positive growth (0.03 g kg^{-1} yr^{-1}) was detected for NTRRM. In contrast, CTRR exhibited positive growth of SOC for all depth intervals down to 60 cm. The CTRR had similar growth rate of SOC concentration in 0- to 2.5 and 2.5- to 5-cm soil depths (0.44 and 0.45 g kg^{-1} yr^{-1}), but the growth rate exhibited a significant correlation decline with depth down to 0.15 g kg^{-1} yr^{-1} for the 40- to 60-cm depth. As a result, CTRR treatments tended to become greater in SOC concentration than the NTRRM and NTR treatments, but differences were only

significant at the 40- to 60-cm depth at the last sampling (October 2009).

Similar to the influences of tillage-residue management treatments on SOC concentrations, N concentrations increased with time, and differences among treatments were mostly in the upper (0–2.5 and 2.5–5 cm) depths (Fig. 3). The growth rate of N concentration was positive in the upper depths but decreased with depth from 0.16, 0.08, 0.04 to 0.01 for NTRRM and 0.11, 0.09, 0.04, 0.02 for NTR for 0- to 2.5, 2.5- to 5, 5- to 10, and 10- to 20-cm depths, respectively. At 0- to 2.5-cm depth, soil N concentration in the NTRRM and NTR fields were both significantly higher than CTRR from October 2007 to October 2009, and N concentration in NTRRM was greater than NTR at 0 to 2.5 cm on October 2009. The three treatments had similar trends during 2004 to 2009 at all soil
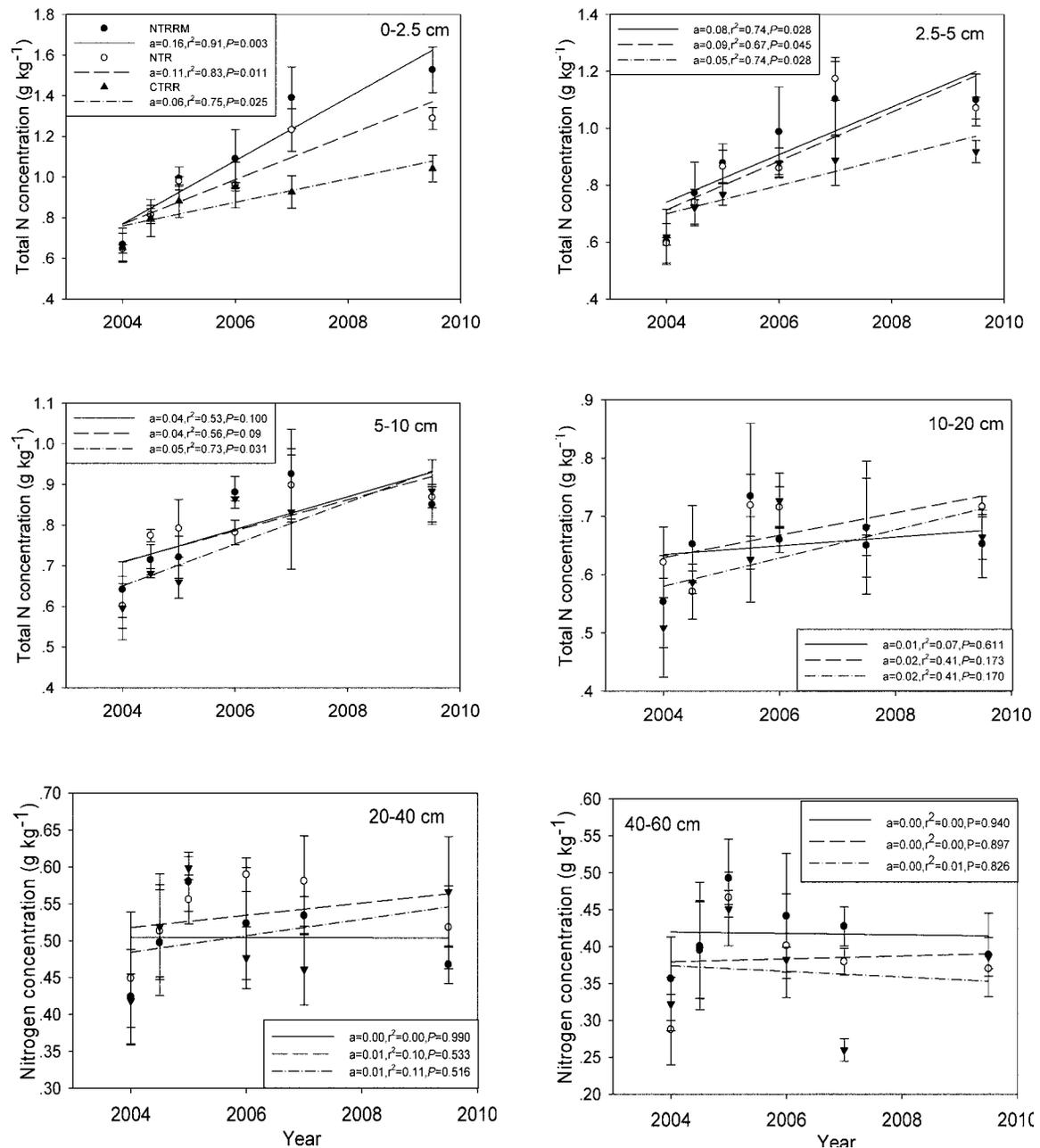
Fig. 3. Change of total N concentration at six depths with year in three treatments from 2004 to 2009. Solid circles stand for no-tillage with residue removed and manure applied (NTRRM) treatment, hollow circles stand for no-tillage with residue cover (NTR), and solid triangles stand for conventional tillage with residue removed (CTRR) treatment. Solid, long dash and dash-dot lines represent linear regression lines for NTRRM, NTR, and CTRR treatments, respectively. Error bars represent LSD ($P < 0.05$) for comparison among three treatments at same soil layer. The lowercase "a" stands for the linear regression slope which is the annual change of SOC concentration.

depths. Positive trends of N concentration were observed at the 0- to 2.5, 2.5- to 5 and 5- to 10-cm depths; however, there was essentially no change in soil N among the treatments or over time at sampling depths below 10 cm.

Soil Organic Carbon and Total Nitrogen Pools

To calculate the SOC and total N pools at each depth interval, a common equivalent mass for all years, depths, and treatments was used to estimate the change in SOC and N mass with time among treatments (Table 3). As observed for the concentration, the SOC pool significantly increased with time for NTRRM and NTR treatments in the upper two depths (0–5 cm) and for all depths (0–60 cm) for the CTRR treatment. Below 10 cm, the NTRRM and NTR treatments exhibited a decrease in SOC pool, but the changes with time were not significant. As a result, NTRRM and NTR both had significantly greater SOC pools than CTRR in the soil surface (0–2.5 cm) by the end of the study and NTRRM had significantly higher SOC pool than CTRR in the 2.5- to 5-cm depth. However, SOC pools in CTRR (14.01 and 10.33 Mg ha^{-1}) were significantly higher than NTR (11.63 and 7.53 Mg ha^{-1}) in 20- to 40 and 40- to 60-cm depths and higher than NTTRM (8.65 Mg ha^{-1}) at

Table 3. Soil organic carbon (SOC) and total N pools in October 2009 and the rate of change from 2004 to 2009.

Depth	NTRRM†	NTR	CTRR	NTRRM	NTR	CTRR
cm	SOC pool in October 2009, Mg ha^{-1} yr^{-1}			SOC change rate from 2004 to 2009‡, Mg ha^{-1} yr^{-1}		
0–2.5	5.00(0.53)a§¶	4.96(0.35)a	3.47(0.55)b	0.40($r^2 = 0.92, P < 0.001$)	0.46($r^2 = 0.94, P < 0.001$)	0.16($r^2 = 0.65, P = 0.03$)
2.5–5	3.82(0.09)a	3.49(0.25)ab	3.07(0.41)b	0.25($r^2 = 0.88, P = 0.001$)	0.21($r^2 = 0.81, P = 0.006$)	0.16($r^2 = 0.80, P = 0.007$)
5–10	5.83(0.44)a	5.74(0.89)a	6.08(0.80)a	0.14($r^2 = 0.61, P = 0.03$)	0.10($r^2 = 0.30, P = 0.20$)	0.30($r^2 = 0.79, P = 0.007$)
10–20	8.62(0.71)a	9.19(0.81)a	9.93(1.57)a	−0.10($r^2 = 0.20, P = 0.31$)	−0.16($r^2 = 0.39, P = 0.13$)	0.45($r^2 = 0.78, P = 0.008$)
20–40	12.71(1.01)ab	11.63(0.19)b	14.01(0.98)a	0.10($r^2 = 0.08, P = 0.53$)	−0.37($r^2 = 0.32, P = 0.18$)	0.75($r^2 = 0.75, P = 0.01$)
40–60	8.65(0.88)b	7.53(0.56)b	10.33(0.38)a	−0.13($r^2 = 0.21, P = 0.30$)	0.04($r^2 = 0.02, P = 0.79$)	0.43($r^2 = 0.70, P = 0.02$)
	Total N pool in October 2009, Mg ha^{-1} yr^{-1}			Total N change rate from 2004 to 2009, Mg ha^{-1} yr^{-1}		
0–2.5	0.54(0.04)a	0.46(0.02)b	0.37(0.02)c	0.06($r^2 = 0.96, P < 0.001$)	0.04($r^2 = 0.90, P = 0.003$)	0.02($r^2 = 0.92, P = 0.02$)
2.5–5	0.40(0.03)a	0.39(0.01)a	0.33(0.01)b	0.03($r^2 = 0.80, P = 0.02$)	0.03($r^2 = 0.77, P = 0.02$)	0.02($r^2 = 0.77, P = 0.02$)
5–10	0.65(0.04)a	0.66(0.02)a	0.67(0.06)a	0.03($r^2 = 0.45, P = 0.14$)	0.03($r^2 = 0.03, P = 0.05$)	0.03($r^2 = 0.03, P = 0.05$)
10–20	1.04(0.09)a	1.14(0.03)a	1.06(0.06)a	0.01($r^2 = 0.07, P = 0.61$)	0.03($r^2 = 0.41, P = 0.17$)	0.04($r^2 = 0.41, P = 0.17$)
20–40	1.42(0.08)a	1.57(0.17)a	1.72(0.23)a	0.00($r^2 = 0.00, P = 0.87$)	0.03($r^2 = 0.15, P = 0.45$)	0.04($r^2 = 0.13, P = 0.47$)
40–60	1.12(0.16)a	1.07(0.00)a	1.11(0.08)a	0.00($r^2 = 0.00, P = 0.93$)	0.01($r^2 = 0.02, P = 0.80$)	−0.01($r^2 = 0.02, P = 0.80$)

† NTRRM, no-tillage with residue removed and manure added; NTR, no-tillage with residue; CTRR, conventional tillage with residue removed.
‡ $n = 7$ for SOC and $n = 6$ for total N.
§ Values are means with the standard deviation in parenthesis ($n = 3$).
¶ Different letters in a row designate significant differences ($P < 0.05$) among same soil depth.

the deepest depth (40–60 cm) by October 2009. No differences were observed between NTRRM and NTR in SOC pool.

The three treatments had the same application rates of total N, but with different sources, and thus N availability to plants and mineralization potential could differ between treatments. Similar to what was observed with SOC pools, the total N pool exhibited a significant increase with time for all three treatments in the upper two depths (0–5 cm). However, changes with time, while generally positive, were not significant for all three treatments in the deeper depths. As a result, total N accumulated in the two upper depths was significantly greater for NTRRM and NTR treatments than CTRR. However, in the subsoil (below 5 cm), there were no significant differences in total N pool among treatments.

The SOC and N pools were combined for the two surface depths and compared to the remaining (5–60 cm) and total soil profile (0–60 cm) (Table 4). It is clear that no-tillage, with or without residue, is only impacting the surface depths while conventional tillage is also impacting the deeper depths. Treatments of NTRRM and NTR were both significantly higher in SOC and total N pools than CTRR at the surface (0–5 cm), but CTRR pools were higher below the surface (5–60 cm), for example, SOC. For the whole soil profile (0–60 cm), CTR had higher annual SOC pool change rate (2.24 Mg ha^{-1}) than NTR (0.27 Mg ha^{-1}), and resulted in greater SOC pool (46.89 Mg ha^{-1}) than NTR (42.54 Mg ha^{-1}) in October 2009.

Table 4. Soil organic carbon (SOC) and total N pools in October 2009 and mean rate of change for SOC and total N pools under three treatments in 0- to 5, 5- to 60 and 0- to 60-cm soil depths.

Depth	Treatments†	SOC pool in October 2009	Mean change of SOC from 2004 to 2009‡	Total N pool in October 2009	Mean change of total N from 2004 to 2009
		Mg ha^{-1}	Mg ha^{-1} yr^{-1}	Mg ha^{-1}	Mg ha^{-1} yr^{-1}
0–5	NTRRM	8.82(0.60)a§¶	0.65($r^2 = 0.95, P < 0.001$)	0.94(0.04)a	0.08($r^2 = 0.93, P = 0.002$)
	NTR	8.45(0.43)a	0.66($r^2 = 0.91, P < 0.001$)	0.84(0.02)b	0.08($r^2 = 0.82, P = 0.01$)
	CTRR	6.54(0.96)b	0.32($r^2 = 0.80, P = 0.006$)	0.70(0.05)c	0.04($r^2 = 0.78, P = 0.02$)
5–60	NTRRM	35.80(0.44)b	0.01($r^2 = 0.00, P = 0.97$)	4.23(0.26)a	0.05($r^2 = 0.06, P = 0.63$)
	NTR	34.09(1.46)b	−0.40($r^2 = 0.29, P = 0.22$) #	4.45(0.19)a	0.10($r^2 = 0.24, P = 0.33$)
	CTRR	40.35(1.18)a	1.92($r^2 = 0.87, P = 0.002$)	4.57(0.25)a	0.10($r^2 = 0.10, P = 0.54$)
0–60	NTRRM	44.63(0.27)ab	0.66($r^2 = 0.56, P = 0.05$)	5.17(0.23)a	0.14($r^2 = 0.20, P = 0.36$)
	NTR	42.54(1.45)b	0.27($r^2 = 0.12, P = 0.44$)	5.29(0.21)a	0.18($r^2 = 0.43, P = 0.16$)
	CTRR	46.89(2.61)a	2.24($r^2 = 0.88, P = 0.002$)	5.27(0.25)a	0.14($r^2 = 0.30, P = 0.25$)

† NTRRM, no-tillage with residue removed and manure added; NTR, no-tillage with residue; CTRR, conventional tillage with residue removed.
‡ Annual growth rate by regression line ($n = 7$ for SOC and $n = 6$ for total N).
§ Values are means with the standard deviation in parenthesis ($n = 3$).
¶ Different letters in a column designate significant differences ($P < 0.05$) among treatments for the same soil depth.
# Negative values indicate soil depletion.

Soil Carbon/Nitrogen Ratio

The C/N ratio tended to decrease with time for NTRRM and NTR at all depths, however, the changes with time were not significant for the 6 yr study (Table 5). The changes in C/N ratios with time for CTRR tended to be negligible for most depths and were also not significant for all depths. It is conceivable that differences in C/N ratio among treatments may become significant if the study were performed longer. By October 2009, there were a couple of significant differences observed at deeper depths. The CTRR treatment had significantly higher C/N ratio than NTR in 10 to 20 cm and higher than NTRRM and NTR in 40- to 60-cm depth. In the entire 0- to 60-cm soil profile, CTRR (8.91) tended to be greater than NTRRM (8.64) and NTR (8.06) but differences were not significant at this point.

DISCUSSION
Effects of Tillage Managements on Soil Bulk Density

Soil BD can be affected by tillage managements and is a vital parameter used to estimate SOC and total N pools. Unger and Jones (1998) found similar results after 12 yr of tillage treatments. Their main differences in soil BD were for 4- to 10-cm soil depth which was greater with no-tillage than with stubble mulch tillage among all soil depths down to 65 cm. For the current study, tillage loosened the upper soil (tillage depth was 10–15 cm) under CTRR treatment whereas NTRRM and NTR were denser due to lack of disturbance. The surface was compacted by machinery during seeding twice a year which could reconsolidate the surface soil depths (0–2.5 and 2.5–5 cm) in CTRR and prevent differences among treatments from being significant. Another potential reason for the limited differences among treatments was sampling time with respect to tillage timing. The soil was sampled in June and October, whereas tillage for CTRR treatment occurred after sampling in October, so there were 8 and 12 mo, respectively, of reconsolidation before sampling. Franzluebbers et al. (2007) showed that the decrease in bulk density of the soil surface by paraplowing was inversely related to the time lag between plowing and sampling, and that reductions lasted less than a year. As a result, the influence of tillage on soil BD in this study was insignificant.

Dam et al. (2005) observed a larger fluctuation range of BD at the upper 10 cm than 10- to 20- cm soil depths during an 11-yr tillage study. The fluctuation in soil BD with time, as expressed by the 95% confidence interval in Fig. 1, was twice as high at the surface as the 20- to 40 and 40- to 60-cm depths. This indicates that the influence of tillage-residue management system on soil BD was limited to the upper 20 cm depth in this study, which corroborates the study by Dam et al. (2005).

Effects of Tillage-Residue Management on Soil Organic Carbon and Total Nitrogen Pools

Change in SOC pool is a process of soil establishing a new balance between inputs and outputs under different treatments (Lal et al., 1998). Generally, no-tillage with residue left in place has the potential for sequestering more SOC than conventional tillage in the upper soil depths for two reasons: (i) tillage destroys the protection provided by crop residue on the surface; and (ii) increases the oxidization of SOM which could be avoided by no-tillage treatment (Elliott, 1986). Although CTRR got less C input than NTRRM (from cattle manure) and NTR (from crop residue) in this study, it accumulated significantly greater SOC (2.24 Mg ha^{-1} yr^{-1}) than the other two treatments (0.66 and 0.27 Mg ha^{-1} yr^{-1}, respectively) overall in the 0- to 60-cm soil profile. Christopher et al. (2009) reported similar results in a regional study to estimate the change of SOC pool after converting from CT to NT treatment. They found three groups under NT treatment contained significantly less SOC than CT in the 0- to 60-cm soil profile, and considered that time was a limitation for SOC sequestration under NT treatment. Six et al. (2002) also observed that sequestration of SOC after conversion from CT to NT was zero or negative in short-term studies, but accumulation of SOC under NT treatment was positive after 6 to 8 yr at the 0- to 30-cm soil depth. However, Follett et al. (2005) observed that no-tillage could sequester greater SOC than CT after a short-term (5 yr) treatment in Central Mexico. They also found that the deeper depth (15–30 cm) accumulates SOC faster than the upper soil depth (0–15 cm). Therefore, the 6 yr for this study may be enough to establish a new balance in SOC or total N pools.

No-tillage accumulated more SOC than CT only in the surface soil, but a reverse situation was observed below the tillage

Table 5. Soil organic carbon to total N (C/N) ratio in October 2009 and the mean rate of change (n = 6) under three treatments during 2004 to 2009.

Depth	NTRRM†	NTR	CTRR	NTRRM	NTR	CTRR
	C/N ratio in October 2009			Mean change rate of C/N ratio from 2004 to 2009		
cm						
0–2.5	9.26(0.46)a‡§	10.90(0.78)a	9.45(1.42)a	−0.23(r^2 = 0.17, P = 0.42)	0.26(r^2 = 0.36, P = 0.20)	0.02(r^2 = 0.02, P = 0.79)
2.5–5	9.60(0.56)a	8.96(0.53)a	9.17(0.87)a	−0.09(r^2 = 0.03, P = 0.76)	−0.27(r^2 = 0.36, P = 0.21)	−0.02(r^2 = 0.01, P = 0.85)
5–10	8.97(0.16)a	8.65(1.29)a	8.99(0.55)a	−0.17(r^2 = 0.33, P = 0.22)	−0.21(r^2 = 0.43, P = 0.16)	−0.09(r^2 = 0.07, P = 0.60)
10–20	8.28(0.06)ab	8.03(0.52)b	9.33(0.92)a	−0.26(r^2 = 0.50, P = 0.11)	−0.29(r^2 = 0.59, P = 0.07)	−0.16(r^2 = 0.54, P = 0.10)
20–40	8.96(0.85)a	7.45(0.92)a	8.18(0.52)a	−0.10(r^2 = 0.07, P = 0.62)	−0.31(r^2 = 0.45, P = 0.15)	0.04(r^2 = 0.00, P = 0.90)
40–60	7.77(0.38)b	7.07(0.52)b	9.33(0.98)a	−0.15(r^2 = 0.06, P = 0.64)	−0.81(r^2 = 0.54, P = 0.10)	0.50(r^2 = 0.16, P = 0.43)
0–60	8.64(0.41)a	8.06(0.47)a	8.91(0.60)a	−0.15(r^2 = 0.20, P = 0.37)	−0.33(r^2 = 0.57, P = 0.08)	0.08(r^2 = 0.03, P = 0.72)

† NTRRM, no-tillage with residue removed and manure added; NTR, no-tillage with residue; CTRR, conventional tillage with residue removed.

‡ Values are means with the standard deviation in parenthesis (n = 3).

§ Different letters in a row designate significantly differences (P < 0.05) among treatments for the same soil depth.

layer, as has been previously reported (Gál et al., 2007; Machado et al., 2003). Gál et al. (2007) found a remarkable 23% greater SOC under CT treatment than NT in 30- to 50-cm soil depth, but NT gained more SOC than CT in the surface soil, and there was no significant difference between NT and CT in the SOC pools for the 0- to 50-cm soil profile. In this study, similar trends in SOC pools were observed in that accumulations with time at the surface (0–5 cm) were reversed to depreciation with time below 10 cm for NTRRM and NTR. Tillage incorporates crop residues (shallow roots and stubble) from the soil surface into the subsoil where the residues could be mineralized and stabilized as soil organic matter (Angers et al., 1997; Lorenz et al., 2005).

Which factors determine the change of SOC pool in the subsoil? For the effects on SOC pool in the subsoil, belowground biomass plays a main role (Amos and Walters, 2006; Gale et al., 2000). Kong and Six (2010) found that more than 50% of the root-derived C still remained in soil while only 4% residue-derived C was in the soil by the end of the experiment. Many researchers (Ball-Coelho et al., 1998; de Rouw et al., 2010; Qin et al., 2005, 2006) have found that NT crops have greater root density near the surface. These differences in distribution of maize and wheat roots under NT or CT treatments could result in different SOC distributions with depth (Baker et al., 2007). Differences in rooting depth distributions is why VandenBygaart et al. (2011) recommended sampling deeper than 15 cm for perennial crops in Canada. Wu et al. (2008) studied the

change of SOC pools in two long-term (55 and 90 yr) irrigated regions of California. They concluded that long-term irrigation could significantly increase SOC pools in deeper (25–60 cm) soil depths as compared to native soils due to differences in rooting density with depth. In this study, although the surface soil was covered by crop residue under NTR and manure under NTRRM, lack of incorporation into the subsoil meant that these crop roots could not compensate for the SOC losses with depth (de Rouw et al., 2010).

In the whole soil profile (0–60 cm), NTRRM and NTR treatments accumulated total N in a similar rate with CTRR during the 6 yr (Table 4). This indicated that dry manure and mineral fertilizer sufficiently replaced the crop residue left on the surface with NTR. Although changes in C/N ratios with time were not significant, there were some interesting trends that could produce differences if continued beyond the 6-yr study period. The NTRRM and NTR treatments exhibited a declining trend in C/N ratio for the whole profile (0–60 cm) although NTR did exhibit a positive change in the 0- to 2.5-cm depth which could be the result of slower mineralization of crop residues in the surface (Blanco-Canqui and Lal, 2008; Torbert et al., 1997). A slight positive change (0.08 yr^{-1}) of C/N ratio was observed for the profile (0–60 cm) in CTRR. Follett et al. (2005) also observed similar trends of C/N ratio change between NT and CT treatments after a 5 yr tillage management. In contrast to Wright et al. (2007) and de Rouw et al. (2010), C/N ratio trended to be greater in CTRR than those in NTRRM and
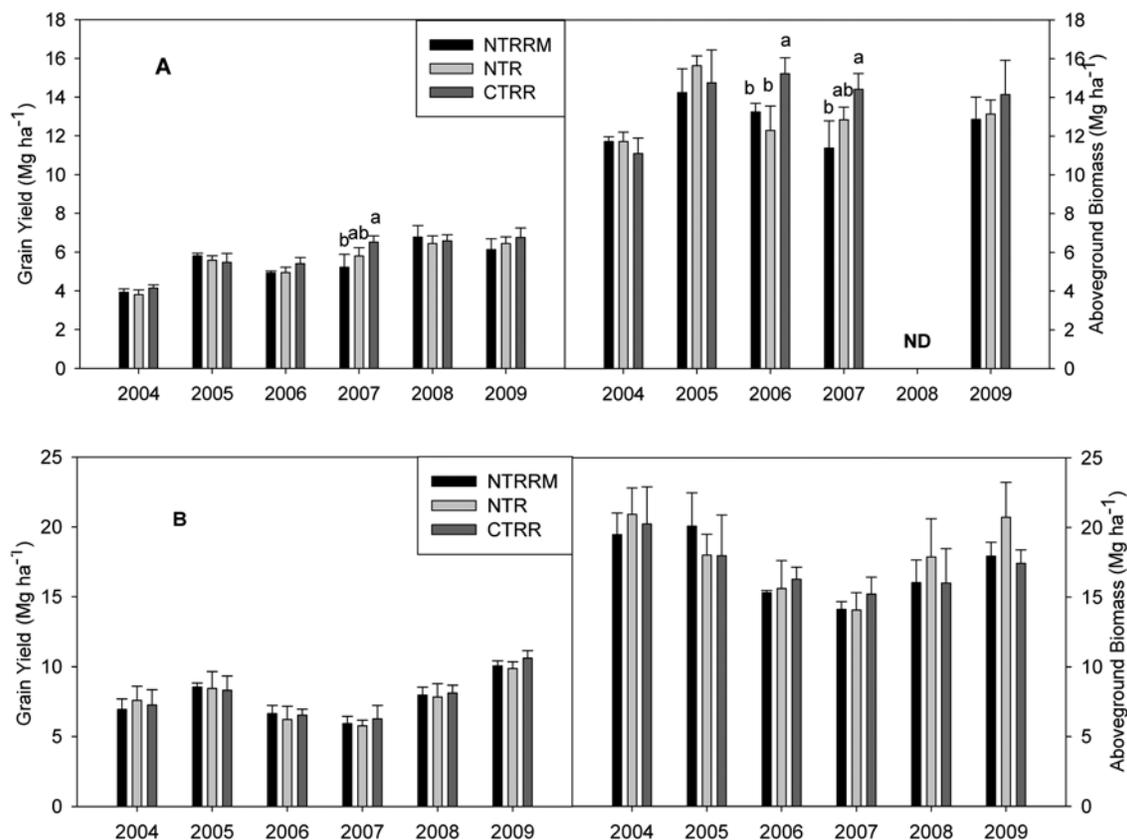

Fig. 4. Effects of tillage-residue management on grain yield and aboveground biomass of (A) wheat and (B) maize from 2004 to 2009. Error bars represent standard deviation. Different letters in a year designate significant differences (P < 0.05) between tillage treatments (P < 0.05); ND stands for no data.

NTR in 0- to 60-cm soil profile in this study but the differences were not significant.

Manure Substituted for Crop Residue in No-Tillage

Application of manure as a nutrient source in no-tillage system could increase the soil C pool (Sainju et al., 2008; Thelen et al., 2010). After 10 yr, Sainju et al. (2008) found that treatments with poultry litter could sequester more SOC and N compared with inorganic N fertilizer regardless of tillage. In this study, the results indicated that a small amount of dry manure (4 Mg ha^{-1} yr^{-1}) could replace crop residue input and compensate for the C, N, and other nutrients lost due to residue removal, thereby enabling similar grain yield and aboveground biomass production as when crop residues are left on croplands (Fig. 4). Reasonable use of crop residue is important for many aspects: forage, biofuel production, protecting soil from erosion (Lal, 2009), and sustainable agriculture. There has been a concern about whether the residue from double-cropped systems should be used to produce biofuels (Lal and Pimentel, 2009; Tilman et al., 2009). These results provide a potential solution for a level double-cropped region where soil erosion is not a concern, but needs more time to assess the long-term effects on soil fertility and agriculture productivity.

CONCLUSIONS

This 6-yr study measured the change of SOC and total N pools under no-tillage with residue replaced by manure, no-till with residue left on the surface, and conventional tillage with residue removed in the NCP, and their impact on crop productivity and biomass production. Soil under NTRRM and NTR treatments had greater SOC and total N than CTRR in the surface (0–5 cm). However, these patterns were not reflective of the subsoil SOC and total N concentrations. As a result, SOC pools for the whole soil profile (0–60 cm) were significantly different in the order CTRR > NTRRM > NTR, whereas differences in total N pools were not significant. These data reveal the importance of quantifying the entire soil profile to validly evaluate the role of tillage and residue management in the NCP.

These data supported the following conclusions for the NCP region: (i) NTRRM and NTR only sequestered more SOC and total N in the surface (0–5 cm) than CTRR; and the subsoil (5–60 cm) exhibited a net loss of SOC in NTR treatments, whereas CTRR could sequester SOC over the entire 60-cm depth; (ii) Using a fixed small amount of manure (4 Mg ha^{-1} yr^{-1}) under no-tillage to substitute for the crop residue removed for the NTR treatment (10 Mg ha^{-1} yr^{-1}) resulted in more SOC sequestration; (iii) CTRR was more effective than NTRRM and NTR in SOC sequestration; and (iv) use of no-tillage with residue or with manure substituting for residue removed did not produce significantly better yields or biomass production than conventional tillage with residue removed and the only occasions in which significant differences were observed, the conventional tillage system was superior.

These results help in understanding and estimating the effects of tillage-residue management on the SOC pools in subsoil and the whole soil profile in the NCP. However, further research should be performed in near future, such as accessing the effects of microbial decomposer communities on SOC losses, and defining the lower limit for using crop residues with no-tillage in this region. Sustainable agriculture in the NCP is important to food security in China; altough, 6-yr study indicated conventional tillage with residue removed was siutable in the NCP, additional long-term studies on the effects of tillage and residue management on SOC pools are seriously needed in the region.

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