Effects of tillage practices and rate of nitrogen fertilization on crop yield and soil carbon and nitrogen

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ABSTRACT

We conducted field experiments since 2006 to determine the effect of tillage practices and rate of nitrogen fertilization on soil properties and crop yield. Four tillage practices and five N rates were used. The results showed that the year-round total yield of wheat and maize under harrow tillage (HT) and rotary tillage (RT) was not significantly different from that of conventional tillage (CT, moldboard tillage) but was higher than that of no-tillage (NT). Reduced tillage (HT and RT) with straw returned and rate of nitrogen (157.5 kg/ha for wheat and 202.5 kg/ha N for maize) were suitable to increase the yield and adjust the soil carbon and nitrogen situation for the winter wheat-summer maize cropping system.

Keywords: wheat; maize; straw returned; N fertilization

Tillage enhances the mineralization of soil organic C and nitrogen (N) by incorporating crop residues, disrupting soil aggregates, and increasing aeration (Tangyuan et al. 2009). But conservation tillage is a complex, fairly flexible agricultural system that can be widely adapted to local conditions (Wall 2007). Nitrogen fertilization improved crop production and some soil quality attributes but also increased the potential for NO_3-N leaching and N_2O-N emissions, especially when it was applied in excess of the crop requirements (Malhi and Lemke 2007). And N is one of the major reasons to support the food for increasing human population (Robertson and Vitousek 2009). However, frequent tillage and excessive nitrogen fertilizer not only reduces the crop productivity but also exacerbates soil erosion, air and water pollution (Hundera et al. 2001, Godfray et al. 2010).

The conservation tillage has received attention; however, uncertainty exists concerning the impact of conservation tillage and nitrogen fertilizer application on the total agricultural environment (Habtegebrial et al. 2007, Malhi and Lemke 2007). Soil C:N ratio is related to N immobilization and mineralization during organic matter decomposition (Bossche et al. 2009). As the changes in soil organic carbon (SOC) and soil total nitrogen (STN) occur slowly (Alvarez and Steinbach 2009), long-term studies are necessary to determine the effects of management factors on SOC and STN. The combined long-term effects of tillage systems and N fertilization on SOC and STN are not well-known. We hypothesized that the tillage system with straw returned and an optimum level of N fertilization would increase the content of C and N in the soil. In this study, we evaluated the effects

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of tillage practices and rate of nitrogen fertilization on the soil chemical and physical properties, and crop yields. The SOC and STN were determined in a 6-year field experiment using a winter wheat (*Triticum turgidum* L.)-summer maize (*Zea mays* L.) crop rotation in North China.

MATERIAL AND METHODS

Field site description. This experiment was conducted in a field in the village of Qianzhuliu, city of Longkou, Shandong province (37°63'N, 120°39'E) from 2006 to 2012. The monthly average temperature and total precipitation in the experimental seasons and 1957–2012 are presented in Table 1.

The crop system consists of winter wheat from October to June and summer maize from June to September. The experimental field has a Hapli-Udic Argosols (Chinese Soil Taxonomy, 2001) soil (47.3, 37.2 and 15.5% of sand, silt and clay, respectively). The important properties of initial values in the 0–20 cm depth (2006) are presented as follows: 6.4 pH, SOC 7.60 g/kg, STN 114.99 mg/kg, available P 36.7 mg/kg, and exchangeable K 91.2 mg/kg.

Experimental procedure. The experiment used a split plot design with four replications using tillage as the main plot and N fertilization as the subplot. The plot size for the main plots and subplots was 75 m × 15 m and 15 m × 15 m, respectively. There were 4 tillage practice treatments: conventional (moldboard) tillage (CT); rotary tillage (RT); harrow tillage (HT), and no tillage (NT). All soil tillage practices were performed each autumn after the harvest of maize with straw returned. In the CT, RT, and HT treatments, the maize residues were mechanically shredded and buried using a moldboard plow, rotary tiller, and disc plow to a depth of approximately 25, 10, and 15 cm, respectively. The subplots consisted of 5 N rates (N0; N1; N2; N3; N4) that were applied as 0, 52.5, 105, 157.5, and 210 kg/ha of N for wheat, and 0, 67.5, 135, 202.5, and 270 kg/ha of N for maize, respectively. In wheat season, 90 kg/ha of P, 110 kg/ha of K and half of the N fertilizer applied prior to any tillage treatment, and the remaining N fertilizer dressed at the BBCH stage 31. The maize crop was fertilized with 90 kg/ha of P, 180 kg/ha of K and half of the N fertilizer at sowing, and the other half of N fertilizer was broadcasted at the stage 31.

Soil and yield analyses. Soil samples were collected in 2011 before wheat sowing and in 2012 before maize sowing. The grain yields of wheat and maize were determined in late June and late September every year, respectively.

Statistical analyses. The data were statistically analyzed using the SPSS 17.0 Statistical Analysis System (Chicago, USA). The differences between the means of the crop yield and soil properties were determined using the least significance difference (*LSD*).

Table 1. Monthly mean temperature and total precipitation in cropping seasons during 2006–2012

Seasons	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Whole season
Mean temperature (°C)													
2006–2007	17.9	9.5	1.5	0.1	4.6	6	12.5	20	24.1	25.6	25.7	22.6	14.2
2007–2008	15.4	8.3	2.6	–1.7	–0.7	7.2	13.6	19.5	22.4	25.7	25.6	22.1	13.3
2008–2009	16.7	8.6	1.7	–0.8	1.8	5.8	13.8	20.2	24.7	25.1	25.7	21.7	13.8
2009–2010	17.1	5.8	6.3	–2.0	0.1	3.1	9.6	19.0	22.8	27.0	25.6	21.1	13.0
2010–2011	13.9	8.9	1.9	–4.2	–0.2	5.4	11.7	18.6	23.1	20.5	25.0	19.6	12.0
2011–2012	14.7	9.6	1.0	–2.2	–1.3	3.7	13.3	20.5	24.0	26.3	25.2	21.6	13.0
1957–2012	16.0	8.5	2.5	–1.8	0.7	5.2	12.4	19.6	23.5	25.0	25.5	21.5	13.2
Rainfall (mm)													
2006–2007	37.6	20.1	13.4	7.7	9.4	14.7	25.3	45.7	73.6	156.5	138.5	52.3	594.6
2007–2008	12.6	3.3	3.7	7.8	21.6	0.0	3.2	24.4	95.7	37.1	192.1	37.3	438.8
2008–2009	7.0	37.7	11.0	2.3	3.2	8.6	51.5	7.5	38.0	113.0	143.7	80.2	503.7
2009–2010	8.6	10.4	5.7	2.8	0.0	74.2	8.9	67.3	22.7	137.7	298.2	99.8	736.3
2010–2011	66.0	0.0	8.1	6.1	0.8	25.1	25.8	92.4	31.4	282.6	119.7	27.0	685.0
2011–2012	5.7	3.0	10.8	0.1	7.9	10.8	53.7	140.1	92.3	431.3	118.9	10.0	884.6
1957–2012	37.4	21.3	13.0	7.8	9.1	14.7	24.7	45.1	74.3	156.9	136.5	59.2	600.1

RESULTS AND DISCUSSION

Crop yield. Variation in wheat and maize grain yields between treatments and seasons was observed (Table 2). The grain yield was significantly lower in the third season compared to the first season. Because maize residues have a slow decomposition rate (Barraco et al. 2007), undecomposed residues in the soil can immobilize a relevant amount of soil mineral N, reducing its availability to wheat sown following maize (Morris et al. 2010). Consequently, the grain yield significantly decreased in the third season maybe due to the immobilization of soil N. The wheat, maize and total grain yields followed the same trends: decreased in the first three seasons and then increased. The effect of the interaction between tillage systems and seasons on grain yields was also significant, suggesting that the effects of conservation tillage including RT and NT on grain yields need long-term studies (Alijani et al. 2012).

For the total yield, no significant difference was observed among CT, HT and RT but that of NT was lowest (Table 2). CT produced the highest mean winter wheat yield, but HT and RT produced higher summer maize yield from 2006 to 2012 compared to other treatments. The positive effect of CT on crop productivity was attributed to better physical and hydrological soil conditions (Mazzoncini et al. 2011). RT and HT did not perform well during the wheat seasons but increased maize yields, leading to higher yields than CT in the total cropping season. There was an increase of wheat grain and total grain when N fertilization was increased from N0 to N3, and an increase of maize grain when N was increased from N0 to N2 (Table 2). The wheat yields treatments at N3 and N4 were 49.06% and 46.10% higher compared to N0 fertilization treatment, respectively. These results may be due to the straw returned to the soil that reduced N fertilizer losses and enhanced mineral N immobilization in the surface soil layers (Grageda-Cabrera et al. 2011). It indicates that the level of applied N can be reduced under suitable tillage or with straw returning (Habtegebrial et al. 2007).

The wheat yield was strongly affected by the season × tillage and season × N rate interactions ($P < 0.01$), and the influence of the season × tillage × N rate interaction on wheat yield, maize yield and total yield was significant. The effect of season was maybe because the decomposition of straw returned to soil needs time and the precipitation ranged among experimental seasons.

Soil total C, total N, and C:N ratio. After six years, SOC under NT was greater than under CT, HT and RT before sowing wheat (Table 3). This is in agreement with Mazzoncini et al. (2011). From wheat sowing to harvest, the SOC in the top 40 cm of soil increased with time under HT and RT, which indicated that HT and RT play an important role in organic matter decomposition during the wheat growing season. The SOC of CT at the maize harvest is significantly higher than that of the other tillage methods. Compared

Table 2. Influence of tillage practice and N-rates on grain yield (kg/ha) in cropping seasons during 2006–2012

	Wheat	Maize	Total
Seasons			
2006–2007	7691[a]	9056[a]	16748[a]
2007–2008	6392[c]	8640[b]	15032[c]
2008–2009	5559[d]	7898[d]	13457[e]
2009–2010	6174[c]	8318[c]	14492[d]
2010–2011	6687[b]	8755[ab]	15442[bc]
2011–2012	6796[b]	9006[a]	15802[b]
Tillage			
CT	6774[a]	8586[b]	15360[a]
HT	6576[b]	8895[a]	15471[a]
NT	6314[c]	8201[c]	14515[b]
RT	6536[b]	8767[ab]	15302[a]
N-rates			
N4	7304[a]	9871[a]	17175[a]
N3	7247[a]	9982[a]	17229[a]
N2	6924[b]	9783[a]	16706[b]
N1	6412[c]	8023[b]	14435[c]
N0	4862[d]	5402[c]	10265[d]
$LSD_{0.05}$			
Season (S)	**	**	**
Tillage (T)	**	**	**
N-rates (N)	**	**	**
S × T	**	ns	*
S × N	**	**	**
T × N	ns	ns	ns
S × T × N	**	*	*

CT – conventional tillage; HT – harrow tillage; NT – no tillage; RT – rotary tillage. N0 – 0, N1 – 52.5, N2 – 105, N3 –157.5 and N4 – 210 kg/ha of N for wheat; N0 – 0, N1 – 67.5, N2 – 135, N3 – 202.5 and N4 – 270 kg/ha of N for maize. Within each factor, means in the same column followed by the same letters are not significantly different at $P < 0.05$ (*LSD* test); $^{*}P < 0.05$; $^{**}P < 0.01$; ns – not significant

Table 3. Tillage practice and N-rates on soil organic C (SOC), total N, and C:N ratio before sowing wheat, at wheat harvest (before maize sowing) and at maize harvest in 2011–2012 cropping season (tested soil depth 0–40 cm)

	SOC (%)			Total N (%)			C:N ratio		
	Oct-11	Jun-12	Oct-12	Oct-11	Jun-12	Oct-12	Oct-11	Jun-12	Oct-12
Tillage									
CT	0.59^{c}	0.842^{b}	0.738^{a}	0.075^{b}	0.102^{b}	0.096^{b}	7.869^{d}	8.256^{c}	7.726^{a}
HT	0.74^{b}	0.955^{a}	0.706^{b}	0.075^{ab}	0.098^{c}	0.089^{c}	9.816^{c}	9.753^{a}	7.923^{a}
NT	0.92^{a}	0.858^{b}	0.705^{b}	0.079^{a}	0.105^{a}	0.102^{a}	11.777^{a}	8.173^{c}	6.907^{b}
RT	0.74^{b}	0.925^{a}	0.649^{c}	0.072^{b}	0.106^{a}	0.094^{bc}	10.324^{b}	8.753^{b}	6.960^{b}
$LSD_{0.05}$	**	**	**	**	**	**	**	**	**
N-rates									
N4	0.811^{b}	0.875^{b}	0.708^{b}	0.081^{a}	0.108^{a}	0.104^{a}	9.958^{b}	8.091^{b}	6.817^{c}
N3	0.844^{a}	0.945^{a}	0.704^{b}	0.072^{b}	0.105^{ab}	0.097^{b}	11.612^{a}	8.996^{a}	7.361^{b}
N2	0.771^{c}	0.876^{b}	0.749^{a}	0.076^{b}	0.104^{b}	0.098^{b}	10.131^{b}	8.414^{b}	7.661^{a}
N1	0.710^{d}	0.891^{b}	0.690^{b}	0.068^{c}	0.099^{c}	0.094^{b}	10.441^{d}	9.061^{a}	7.381^{b}
N0	0.601^{e}	0.889^{b}	0.646^{c}	0.064^{d}	0.098^{c}	0.084^{c}	9.541^{c}	9.107^{a}	7.675^{a}
$LSD_{0.05}$	**	**	**	**	**	**	**	**	**

CT – conventional tillage; HT – harrow tillage; NT – no tillage; RT – rotary tillage. N0 – 0, N1 – 52.5, N2 – 105, N3 –157.5 and N4 – 210 kg/ha of N for wheat; N0 – 0, N1 – 67.5, N2 – 135, N3 – 202.5 and N4 – 270 kg/ha of N for maize. Within each factor, means in the same column followed by the same letters are not significantly different at $P < 0.05$ (*LSD* test); $^{*}P < 0.05$; $^{**}P < 0.01$

with CT, conservation tillage can significantly reduce the loss of soil carbon during the wheat growing season (Wang et al. 2006). However, time is required to confidently measure the direction of SOC change in response to the soil and crop management practices (Wilhelm et al. 2007).

The STN increased in the top 40 cm of soil under NT, and it maintained a high value throughout the growing season (Table 3). This increase implied a net gain of 187 and 230 kg N/ha at the wheat and maize harvests after six years of NT management, respectively. It also indicates that nitrogen is not fully used under NT. The STN decreased in both the RT and HT treatments from sowing wheat to maize harvesting. Under HT, the STN was higher than the other tillage treatments at the wheat sowing. The higher STN that was observed at wheat harvesting under RT can be associated with a greater biological activity from wheat sowing to harvest. Biological processes such as nitrification increase the transformation of SOM to soil nitrogen (García-Gil et al. 2004).

SOC increased with the N increase from N0 to N3, however no significant differences were found between the N3 and N4 applications at the wheat sowing and maize harvest. In wheat season, SOC and STN significantly increased with the N application rate increased (from N0 to N3). At maize harvesting, the differences of SOC and STN between treatments were smaller, especially when the nitrogen level was less than N3. STN was significantly positively correlated with the SOC, which is in agreement with Thomas et al. (2007). It indicated that, the N3 level during the wheat season and the N2 and N3 levels during the maize season are advantageous to the straw decomposing.

Under NT, the C:N at the 0–40 cm depth was lower than that of the other tillage treatments at the wheat sowing, wheat harvest and maize harvest. Under CT, the C:N increased during the maize season, which indicates that the greater maize nitrogenous fertilizer consumption was caused by higher straw decomposition. The lowest C:N ratio value occurred at wheat sowing under N0, but the C:N ratio increased gradually over time, mainly because straw decomposing brings a large amount of organic carbon into soil. The C:N ratio narrowed over time under all nitrogen treatments, which indicates that N is preferentially retained during decomposition of the residues and potentially increases the cycling of fertilizer N in the soil surface. The C:N ratio was lower during the wheat season, suggesting greater nitrogen use by wheat and soil nitrogen deficiency. Although both SOC and STN were greater in the N4 treatment, the C:N ratio was lower than other treatments, indicating that the nitrogen supply was in excess.

In conclusion, the results showed that conservation tillage with straw returned adjust the soil carbon and nitrogen situations. The recommended 157.5 kg/ha N fertilization for wheat production and 135 or 202.5 kg/ha N fertilization for maize production are sufficient. The year-round total yield of wheat and maize under reduced tillage was not decreased significantly compared to CT, but was better than NT. Using the reduced tillage practice and reducing N fertilizer by 25% both in the wheat and maize season is suggested for sustainable development of crop production with straw returned.

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