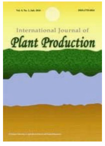

International Journal of Plant Production 10 (3), July 2016
ISSN: 1735-6814 (Print), 1735-8043 (Online)
www.ijpp.info

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Integrative impacts of soil tillage on crop yield, N use efficiency and greenhouse gas emission in wheat-corn cropping system

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Received 14 July 2015; Accepted after revision 3 March 2016; Published online 24 May 2016

Abstract

Wheat-corn cropping system is one of the most important grain production systems in the world. However, the integrative impacts of soil tillage on crop yield, N use efficiency (NUE) and greenhouse gases (GHG_S) emissions are not well documented in this system. Thus, a two-year field experiment was carried out in a typical wheat-corn cropping system with four tillage regimes during the wheat season, including no-tillage (NT), rotary tillage (RT), sub-soiling tillage (ST) and sub-soiling with rotary tillage (SRT) in a randomized block design with three replicates. No-tillage was conducted for all treatments during corn season. Over the two years, the highest yields of wheat, corn and annual were found in the SRT treatment, while the lowest annual yield was found in the NT treatment averagely. Two-year average annual yield in the SRT was 19643.9 kg ha^{-1}, which was 4.8, 5.9 and 7.7% higher than that in the ST, RT and NT treatments, respectively ($P<0.05$). SRT also stimulated plant N uptake with a higher N harvest index and higher partial factor productivity (PFP) than those under the other tillage practices ($P<0.05$). Although SRT stimulated N_2O emission in wheat season, it significantly reduced the emission in corn season compared with the NT ($P<0.05$). Thus, no significant differences in total GHG_S emissions, area-scaled and yield-scaled global warming potential (GWP) were found among the tillage practices. Our results indicate that sub-soiling with rotary tillage might benefit crop production for high yield and N use efficiency with less GHG_S emissions for wheat-corn cropping system in North China Plain.

Keywords: Soil management; Available N; Grain production; N_2O; CH_4; Global warming potential.

Introduction

Wheat (*Triticum. aestivum* L.) and corn (*Zea mays* L.) are the most important food crops, accounting for 26% and 36% of the total grain production in the world, respectively (FAO, 2013). Global grain production needs to increase by 60% from its 2005-2007 productions to meet the food demand for the growing population by 2050 (FAO, 2013). In order to increase crop yield, excessive nitrogen (N) fertilizer has been applied for wheat and corn production, causing serious environmental problem due to a low N use efficiency (NUE) (Cui et al., 2008; Ju et al., 2009). Meanwhile, the radiative forcing of the earth's atmosphere has increased significantly because of the increases in the concentrations of atmospheric GHGs, particularly N_2O and CH_4, which are the second and third important GHGs (IPCC, 2013). Existing evidences demonstrate that agricultural lands are the main sources of anthropogenic emissions of N_2O and CH_4 and agronomy plays an important role in affecting the emissions (Zheng et al., 2007). Wheat-corn cropping system is one of the most important cropping systems in the world, therefore, it is necessary to optimize agronomic practices for high yield and high NUE with less GHGs emissions from this cropping system.

Among the agronomic practices, soil tillage plays significant impacts on crop yields and environmental health by affecting the belowground biotic and abiotic processes (Strudley et al., 2008; Jonard et al., 2013). As compared with conventional tillage, for example, no-tillage could improve the water content of soil status and physical quality under drought conditions, resulting in great increases in wheat yield and water use efficiency (WUE) (He et al., 2009). Other evidence showed that no-tillage might not significantly affect crop yields (Lampurlanés et al., 2002), but it could significantly affect GHGs emissions (Mangalassery et al., 2014). Recently, some observations reported that sub-soiling could increase wheat and corn yields with higher WUE and NUE through breaking soil depth to crop root growth and water and nutrient availabilities (Pikul and Kristian, 2003; Huang et al., 2006; Qin et al., 2008; Hu et al., 2013a). According to our knowledge, existing observations mainly addressed crop yield and resource use efficiency only on one crop growing season and fewer were known about the integrative effects on the cropping system annually. Moreover, the integrative impacts of soil tillage on crop yield and GHGs emissions were not well documented for each crop season and the cropping system to date (Mangalassery et al., 2014; Powlson et al., 2014). Since multiple cropping dominates the production systems of wheat and corn in most developing countries, it is necessary to learn the integrative effects of soil tillage improvement on crop productivity and environmental costs.

China by producing 17.9% of wheat and 23.8% of corn production in the world is one of the largest countries of wheat and corn production (Sadras and Calderini, 2014) and carbon emission (Zou et al., 2015) and wheat-corn cropping system is a dominant cropping system particularly in North China Plain. In order to further enhance crop yields and NUE, great efforts have been made on agronomic innovations such as soil tillage in this region (Bai et al., 2010; Bhatia et al., 2010). Although some field observations have been implemented about tillage impacts on crop yields and GHGs emissions (Han et al., 2007; Rieger et al., 2008; Smith et al., 2012; Tellez-Rio et al., 2015), the integrative effects of tillage were not clear on crop yields, NUE and GHGs emissions. Therefore, a two-year field experiment was conducted for an entire cropping duration and annual crop yields, NUE and GHGs emissions were determined in this experiment. The study objectives were to evaluate the integrative impacts of tillage on crop yields, NUE and GHGs emissions at seasonal and annual scales, so as to provide important references to agronomic innovations for improving regional air quality through reducing GHGs emissions.

Materials and Methods

Experimental site

The field experiment was conducted under a wheat-corn cropping system located in Institute of Agricultural Science of Dongping County, Dongping (35° 89′ N, 116° 36′ E), Shandong Province, China from 2012 to 2014. The experiment location is a typical site of Chinese wheat and corn cropping regions. Wheat-corn cropping system with rotary tillage in wheat season and no-tillage in corn season is typical in North China Plain. The annual average air temperature is 14.4 °C with an average precipitation of 609.2 mm which is concentrated in April–August. During the experiment, the total precipitation from the seeding stage of wheat to maturity stage of corn was 550.0 and 517.1 mm during 2012-2013 and 2013-2014 seasons, respectively (Figure 1). The soil is a cumulated irrigated fluvo-aquic soil in the soil taxonomy classification system of the USA (Soil Survey Staff 1999). Soil organic matter, total N, available N, available phosphorus, available potassium at 0-20 cm depth were 18.6 g kg^{-1}, 1.2 g kg^{-1}, 104.9 mg kg^{-1}, 40.5 mg kg^{-1}, 108.7 mg kg^{-1}, respectively.

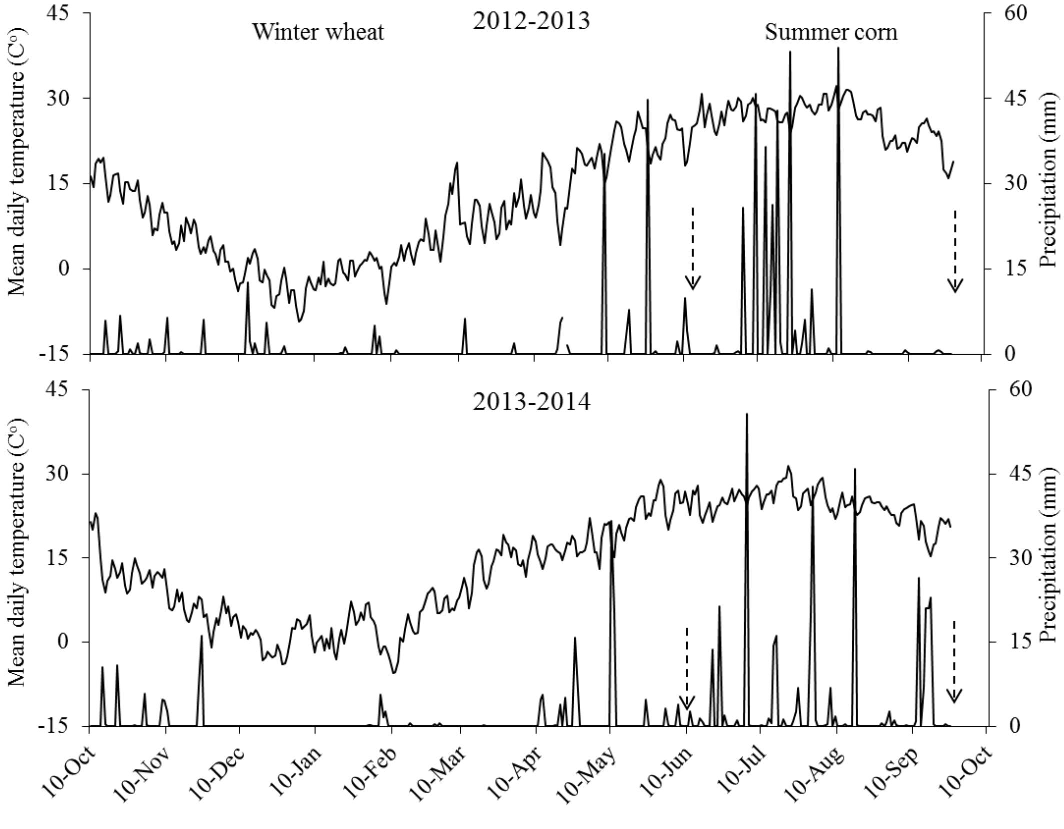

Figure 1. Daily precipitation and mean air temperature during the entire growing period of wheat-corn cropping system in the experimental station (dotted line arrows indicate the time of harvest in each crop).

Experimental Design and management

The experiment was conducted during the wheat growing season with four tillage regimes, including no-tillage (NT), rotary tillage (RT), sub-soiling tillage (ST) and sub-soiling with rotary tillage (SRT). The operation procedures of the four tillage practices are listed in Table 1. For the corn growing season, no-tillage was conducted in all treatments. Only one wheat cultivar, Jimai 22 and one corn cultivar, Zhongdan 909, were used in this experiment. The experiment was a randomized block design with three replicates. Each plot was 55 m long and 5.2 m wide. The distance between treatments was 2 meters and between the replications was 1.5 meters. The wheat sowing dates were

10 October, 2012 and 2013, the harvested dates were 15 June, 2013 and 10 June, 2014, respectively. Two days after harvesting wheat, the corn was sown (on 17 June, 2013 and 12 June, 2014). The corn were harvested on 25 September, 2013 and 26 September, 2014, respectively. During the wheat growing season, the same quantity of chemical fertilizers (135 kg N ha^{-1}, 130 kg P_2O_5 ha^{-1} and 77 kg K_2O ha^{-1}) were applied as base fertilizers and another 90 kg N ha^{-1} was added as a side dressing at the jointing stage. During the corn growing season, 150 kg N ha^{-1}, 140 kg P_2O_5 ha^{-1} and 84 kg K_2O ha^{-1} were used as base fertilizers and 140 kg N ha^{-1} was applied as a side dressing at the jointing stage. Common irrigation and other agronomic managements were also provided in all treatments with the same regime as applied in the local cropping system for high yield.

Table 1. Operation procedure of the four tillage practices.

Tillage practices	Operation procedure
NT	Corn and wheat straw incorporation in field, no-tillage for corn season, strip rotary tillage only on wheat sowing row in wheat season (15 cm in depth)
ST	Corn and wheat straw incorporation in field, no-tillage for corn season, sub-soiling once (35 cm in depth) followed strip rotary tillage only on wheat sowing row for wheat season (15 cm in depth)
RT	Corn and wheat straw incorporation in field, no-tillage for corn season, completely rotary tillage two times for wheat season (15 cm in depth)
SRT	Corn and wheat straw incorporation in field, no-tillage for corn season, sub-soiling once (35 cm in depth) followed completely rotary tillage two times (15 cm in depth)

Plant sampling and N determinations

At maturity, twenty wheat plants and three corn plants were sampled from each treatment in each replicate, respectively. The plants were separated into leaves, stems and spikes. Spikes were further separated into vegetative components and grain. All plant samples were oven-dried to a constant weight at 80 °C and weighed. Nitrogen concentrations of leaf, stem, vegetative components of spike and grain were quantified using the Kjeldahl digestion method (Bremner, 1996). Plant samples were placed in digestion tubes and digested with a salt-catalyst-sulfuric acid mixture by heating the tubes in an aluminum block. One sub-plot of 2 m^2 for wheat and 12 m^2 for corn in area without sampling disturbance were harvested to determine the grain yield and yield components for each replicate. Harvest index (HI) was calculated as grain biomass with total aboveground biomass.

Nitrogen uptake was plant total N content at maturity. Some agronomic indices commonly used to describe NUE include nitrogen harvest index (NHI), partial factor productivity (PFP), agronomic nitrogen use efficiency (ANUE), physiological nitrogen use efficiency (PNUE). In this study, two types of NUE were calculated using the following equations (Cheng et al., 2015; Tomohiro et al., 2015; Xu et al., 2016):

Partial factor productivity (PFP) = Grain yield /Amount of N applied.

Nitrogen harvest index (NHI) = Total N in grain / Total N in the above-ground parts at maturity.

Soil sampling and determinations

The field fresh topsoil (0-20 cm) samples were collected from each treatment on April 30, 2014 and August 14, 2014. In each treatment, nine cores (5 cm in diameter) were taken to a depth of 20 cm and then pooled as a composite sample. All visible roots and fresh litter materials were removed from the samples, passed through a 2-mm sieve as soon as possible and then stored in the refrigerator (4 °C). NH_4^+-N and NO_3^--N were then measured using the sub-samples (<2 mm) of fresh soil extracted with KCl solution by traditional Indophenol blue colorimetric method (Dorich and Nelson, 1983) and Ultraviolet spectrophotometry method (UV-1800, Norman and Stuck, 1981), respectively.

Gas sampling and measurement

The measurements of N_2O and CH_4 were continued from wheat planting in October 2013 to corn harvesting in September 2014. The gas fluxes were measured using a static closed chamber method (Hutchinson and Livingston, 1993). During the entire growing season, a PVC rectangular chamber base (30 cm long, 20 cm wide and 10 cm high) was randomly inserted into the soil to a depth of approximately 10 cm in the space between rows in each plot. The top edge of the base had a groove for filling with water to seal the rim of the chamber. Sampling chamber was made of PVC with a size of 30 cm × 20 cm × 30 cm. Gas samples were taken from 09:00 through 11:00 in the morning to minimize the diurnal variation in flux patterns. To test the linearity of gas accumulation gas samples (20 ml) were taken by syringe at 0, 10, 20 and 30 minutes after chamber closure and then stored in pre-evacuated vials (40 ml) fitted with butyl rubber stoppers. The air temperature inside the chamber was monitored with a mercury thermometer during gas collection. Water content of soil (0-20 cm, w/w) of each plot was measured using the tachometer and sensor (WET brand, made in the UK) after gas sampling. Samples were taken every ten days, except for longer interval in the winter and no sample was collected at the interval of two seasons. Collected gas samples were analyzed with a modified gas chromatograph (GC) (Agilent 7890A, California, USA) equipped with a flame ionization detector (FID) and electron capture detector (ECD) for quantifying CH_4 and N_2O concentrations, respectively. Fluxes were calculated with the linear increase in concentrations of selected sample sets that yield to a linear regression value of $r^2 > 0.90$. Average fluxes and standard errors of CH_4 and N_2O were determined from triplicate plots. Cumulative CH_4 and N_2O emissions per plot were estimated by linear interpolations between every two adjacent sample days of the measurements (Zou et al., 2005).

Global warming potential of CH_4 and N_2O

The global warming potential (GWP) was calculated as CO_2 equivalent (CO_2-eq) on a time horizon of 100-year using 25 as the radioactive forcing potential for CH_4 and 298 for N_2O (IPCC, 2007). The equation was as follows:

Area-scaled GWP (kg CO_2-eq ha^{-1} yr^{-1}) = 25 × CH_4 (kg ha^{-1} yr^{-1}) + 298 × N_2O (kg ha^{-1} yr^{-1}).

Additionally, to associate with GWP and crop production, GWP per unit grain yield, as yield-scaled GWP (g CO_2-eq kg^{-1}), was introduced and calculated following the equation (Pittelkow et al., 2013).

Yield-scaled GWP (g CO_2-eq kg^{-1}) = Area-scaled GWP / Grain Yield

Data analysis

To test the differences among the treatments, the data were analyzed using an analysis of (ANOVA) one & two-way variance (SAS 9.2- 2009 for windows). The treatment means were compared with the least significant difference (Duncan) test ($P<0.05$). The standard deviation of the means was calculated using Microsoft Excel 2010 software for Windows.

Results

Impacts on crop yields

There were significant differences of tillage on yield and yield components across two years observed as follows (Table 2). Wheat yield in the SRT averaged was 8912.4 kg ha^{-1} and averagely was 8.3, 3.5 and 11.9% higher across the two years than that in the ST, RT and NT treatments, respectively. The lowest wheat yield occurred in the NT treatment. The harvest index of SRT and ST systems in both years were significantly higher than that in the NT and RT ($P<0.05$) (Table 2). Tillage impacts on spike number were not consistent, though the lowest spike number with higher grain number was found in the ST treatment. Tillage treatment had no significant effect on 1000-grain weight across the experimental duration.

In corn growing seasons, the highest yields were found in the SRT and ST treatments, while no significant difference was found between the NT and RT treatments (Table 2).

Across the two years, the mean corn yield in the SRT (10731.5 kg ha^{-1}) was 2.1, 8.0 and 4.4% higher than that in the ST, RT and NT treatments, respectively. The lowest ear number was found in the RT treatment, while its 1000-grain weight was significantly higher than the other treatments except for the SRT in 2014. There was no significant impact on the kernel number except for the ST in 2014. And the highest harvest index was found in the SRT treatment.

For the cropping system, the annual yields were significantly higher in 2013-2014 than 2012-2013 for all treatments. Although the difference in annual crop yield was not significant among the treatments in 2012-2013, the highest annual yield existed in the SRT in 2013-2014 ($P<0.05$). The average value of annual yield in the SRT (19463.9 kg ha^{-1}) across the experimental durations was 4.8, 5.9 and 7.7% higher than that in the ST, RT and NT treatments, respectively ($P<0.05$) (Table 2).

Table 2. Impacts of tillage practices on crop yields and their components.

Year	Treatments	Winter wheat					Summer corn					Annual yield (kg ha^{-1})
		Spikes per m^2	Grains per spike	1000-grain Weight (g)	Grain yield (kg ha^{-1})	Harvest index (%)	Ear number ha^{-1}	Kernel number ear^{-1}	1000 Grain weight (g)	Grain yield (kg ha^{-1})	Harvest index (%)	
2012-2013	NT	609.5 ^{a}	36.0 ^{b}	37.5 ^{a}	6844.0 ^{ab}	42.1 ^{b}	84000.0 ^{a}	477.4 ^{a}	262.5 ^{c}	9682.7 ^{b}	55.2 ^{a}	16526.7 ^{a}
	RT	570.7 ^{a}	39.3 ^{ab}	36.7 ^{a}	7172.1 ^{a}	44.2 ^{ab}	77000.0 ^{b}	458.8 ^{a}	293.9 ^{a}	9300.1 ^{b}	44.2 ^{b}	16472.2 ^{a}
	ST	492.6 ^{b}	42.9 ^{a}	35.2 ^{a}	6392.4 ^{b}	48.9 ^{a}	83666.6 ^{a}	471.5 ^{a}	285.1 ^{ab}	10812.6 ^{a}	55.6 ^{a}	17205.0 ^{a}
	SRT	575.6 ^{a}	40.2 ^{ab}	36.3 ^{a}	7381.0 ^{a}	47.5 ^{a}	79000.0 ^{b}	456.4 ^{a}	281.5 ^{b}	9542.7 ^{b}	56.3 ^{a}	16923.7 ^{a}
2013-2014	NT	618.2 ^{ab}	33.2 ^{a}	42.4 ^{a}	9090.9 ^{b}	50.4 ^{b}	92000.0 ^{a}	600.4 ^{ab}	219.3 ^{b}	10873.1 ^{b}	42.7 ^{b}	19964.0 ^{b}
	RT	699.4 ^{a}	28.2 ^{a}	45.3 ^{a}	10043.3 ^{ab}	52.4 ^{b}	82666.7 ^{b}	616.5 ^{a}	236.6 ^{a}	10577.7 ^{b}	47.4 ^{ab}	20621.0 ^{ab}
	ST	599.4 ^{b}	30.2 ^{a}	43.1 ^{a}	10059.6 ^{ab}	57.4 ^{a}	83666.7 ^{ab}	571.5 ^{b}	216.7 ^{b}	10220.0 ^{b}	48.0 ^{ab}	20279.6 ^{b}
	SRT	607.1 ^{b}	30.1 ^{a}	45.9 ^{a}	10443.7 ^{a}	58.6 ^{a}	90000.0 ^{ab}	608.6 ^{ab}	241.7 ^{a}	11920.3 ^{a}	54.0 ^{a}	22364.1 ^{a}
							P value					
Tillage		0.0165	0.6374	0.5383	0.0277	0.0002	0.0067	0.5458	<0.0001	0.056	0.0047	0.0387
Year		0.0013	<0.0001	<0.0001	<0.0001	0.0001	0.0001	<0.0001	<0.0001	<0.0001	0.0072	<0.0001
Tillage × year		0.0839	0.1473	0.5056	0.1621	0.7251	0.3975	0.1384	0.0007	0.0005	0.0153	0.08334

Means of each column followed by similar letters are not significantly different (5%).

NT, No-tillage; RT, Rotary tillage; ST, Sub-soiling tillage; SRT, Sub-soiling with rotary tillage.

Impacts on plant nitrogen concentration and use efficiency

The effects of soil tillage on N uptake and use efficiency (NUE) are presented in Table 3. The highest PFP in wheat was detected in the SRT which was 3.8, 4.0 and 14.9% higher than that in the ST, RT and NT treatments, respectively. NHI in the SRT was 4.5, 11.9 and 5.2% higher than that in the ST, RT and NT, respectively. SRT had the highest N concentration in wheat grain, which was 13.0, 19.0 and 5.8% higher than that in the ST, RT and NT treatments, respectively ($P<0.05$). The highest nitrogen uptake among all tillage practices was observed in the SRT which was 4.0, 10.7 and 9.1% higher than that in the ST, RT and NT treatments, respectively.

In corn growing seasons, soil tillage had a significant effect on PFP ($P<0.05$). The highest PFP was detected in the SRT, which was 17.5, 12.7 and 9.6% higher than that in the ST, RT and NT, respectively. NHI in the SRT was 8.7, 6.8 and 11.3% higher than that in the ST, RT and NT treatments, respectively. Compared with the ST treatment, SRT had significantly (11.6%) higher N uptake ($P<0.05$).

Annual PFP in the SRT was 42.9 kg kg^{-1}, which was 10.3, 8.5 and 12.0% higher than that in the ST, RT and NT treatments, respectively. Annual NHI was 5.8, 9.8 and 7.8 % higher and nitrogen uptake was 7.3, 8.5 and 7.2 % higher in the SRT than that in the ST, RT and NT treatments, respectively.

Impacts on N_2O and CH_4 fluxes

The effects of tillage system on N_2O and CH_4 fluxes are presented in Figure 2. Similar fluxes patterns were found for the two gases among all treatments in each crop season (Figure 2). The highest N_2O fluxes occurred in the months with high temperature during the wheat season and the highest values were found in the early stages during the corn season (Figure 2a). The averaged N_2O fluxes were 46.6–85.3 µg N_2O-N m^{-2} h^{-1} in wheat growing season, 63.2–134.2 µg N_2O-N m^{-2} h^{-1} in corn growing season and 64.0–79.1 µg N_2O-N m^{-2} h^{-1} annually. The highest cumulative N_2O emission was found in the SRT in wheat season, while the lowest value occurred in this treatment during the corn season, resulting in no significant difference in annual N_2O emission among all treatments (Table 4).

For the wheat-corn cropping system, each treatment was either a minor source or sink of CH_4 fluxes (Figure 2b). The average fluxes were -16.8– -0.6 µg CH_4-C m^{-2} h^{-1} in wheat growing season, -3.9– 3.2 µg CH_4-C m^{-2} h^{-1} in corn growing season and -12.1– -1.7 µg CH_4-C m^{-2} h^{-1} annually. No significant difference in CH_4 emissions was found among all treatments for each crop growing season (Table 4).

Table 3. Impacts of tillage practices on plant N concentration, uptake and use efficiency in 2013-2014 seasons.

Treatments	Winter wheat							Summer corn						
	Leaf N (%)	Stem N (%)	Spike axis and kernel husks N (%)	Grain N (%)	N uptake (kg ha^{-1})	NHI (%)	PFP (kg kg^{-1})	Leaf N (%)	Stem N (%)	Husks and cob N (%)	Grain N (%)	N uptake (kg ha^{-1})	NHI (%)	PFP (kg kg^{-1})
NT	1.0^{a}	0.6^{b}	0.5^{a}	1.7^{ab}	216.5^{a}	76.3^{ab}	40.4^{b}	1.1^{b}	0.5^{a}	0.1^{a}	1.1^{a}	179.1^{ab}	63.8^{b}	36.7^{b}
RT	1.1^{a}	0.6^{b}	0.5^{a}	1.5^{c}	213.4^{a}	71.7^{b}	44.6^{ab}	1.2^{a}	0.4^{a}	0.1^{a}	1.1^{a}	177.3^{ab}	66.5^{ab}	35.7^{b}
ST	1.2^{a}	0.7^{a}	0.5^{a}	1.6^{bc}	227.1^{a}	76.8^{ab}	44.7^{ab}	1.3^{a}	0.5^{a}	0.1^{a}	1.1^{a}	168.2^{b}	65.3^{ab}	34.3^{b}
SRT	1.0^{a}	0.6^{b}	0.5^{a}	1.8^{a}	236.3^{a}	80.2^{a}	46.4^{a}	1.1^{b}	0.4^{a}	0.1^{a}	1.1^{a}	187.7^{a}	71.0^{a}	40.3^{a}

Means of each column followed by similar letters are not significantly different (5%).

NT, No-tillage; RT, Rotary tillage; ST, Sub-soiling tillage; SRT, Sub-soiling with rotary tillage.

Table 4. Effects of different tillage practices on greenhouse gas emissions, area-scaled global warming potential (GWP) and yield-scaled GWP in wheat-corn cropping system.

Treatments	Wheat growing season				Corn growing season				Annual			
	N_2O (kg ha^{-1})	CH_4 (kg ha^{-1})	Area-scaled GWP (kg CO_2-eq ha^{-1})	Yield-scaled GWP (g CO_2-eq kg^{-1})	N_2O (kg ha^{-1})	CH_4 (kg ha^{-1})	Area-scaled GWP (kg CO_2-eq ha^{-1})	Yield-scaled GWP (g CO_2-Eq kg^{-1})	N_2O (kg ha^{-1})	CH_4 (kg ha^{-1})	Area-scaled GWP (kg CO_2-Eq ha^{-1})	Yield-scaled GWP (g CO_2-Eq kg^{-1})
NT	2.5^{b}	-0.6^{a}	725.0^{b}	76.6^{a}	3.0^{a}	0.1^{a}	892.2^{a}	82.0^{a}	6.0^{a}	-0.5^{a}	1772.7^{a}	88.8^{a}
RT	2.6^{b}	0.1^{a}	792.4^{b}	79.8^{a}	1.9^{ab}	-0.0^{a}	578.0^{ab}	54.8^{ab}	4.9^{a}	0.1^{a}	1462.2^{a}	65.4^{a}
ST	2.4^{b}	-0.7^{a}	711.4^{b}	71.7^{a}	2.6^{ab}	0.1^{a}	770.2^{ab}	75.3^{ab}	5.3^{a}	-0.7^{a}	1575.8^{a}	82.8^{a}
SRT	4.0^{a}	-0.7^{a}	1181.6^{a}	113.5^{a}	1.4^{b}	-0.0^{a}	433.6^{b}	36.4^{b}	5.7^{a}	-0.8^{a}	1676.8^{a}	80.8^{a}

Means of each column followed by similar letters are not significantly different (5%).

NT, No-tillage; RT, Rotary tillage; ST, Sub-soiling tillage; SRT, Sub-soiling with rotary tillage.

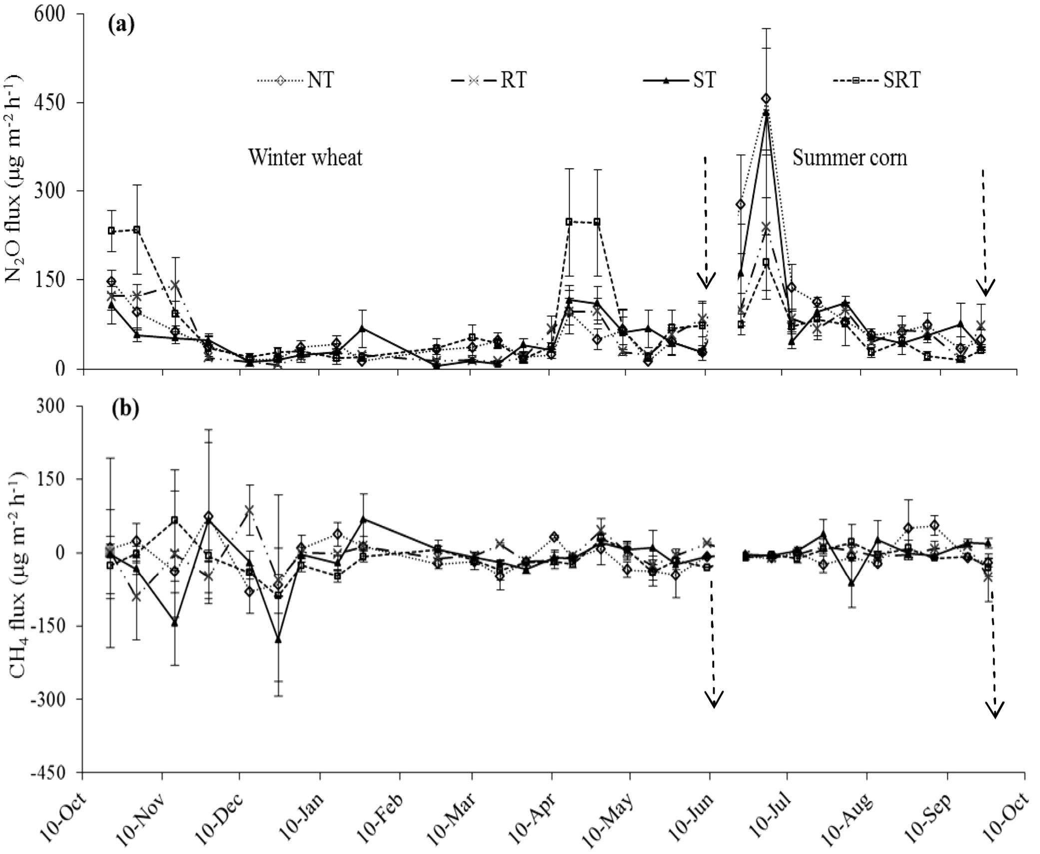

Figure 2. Seasonal N_2O (a) and CH_4 (b) fluxes for the wheat and corn seasons of the wheat-corn cropping system under different soil tillage practices in 2013-2014. NT represents no-tillage; RT, Rotary tillage; ST, Sub-soiling tillage; SRT, Sub-soiling with rotary tillage (dotted line arrows indicate the time of harvest in each crop).

Area-scaled GWP and yield-scaled GWP

Soil tillage had a significant effect on the area-scaled GWP ($P<0.05$) in the wheat growing season. Area-scaled GWP in the SRT was the highest and 66.1, 49.1 and 63.0 % higher than that in the ST, RT and NT, respectively. However, no significant effect of tillage was detected on yield-scaled GWP in wheat growing season ($P>0.05$).

In the corn growing season, NT had the highest area-scaled GWP which was 54.3, 15.9 and 105.8% higher as compared with the RT, ST and SRT respectively (Table 4). Significant differences occurred in yield-scaled GWP between the NT and SRT and the highest value existed in the NT with an order of NT > ST > RT > SRT.

Annually, there was no significant difference in the area-scaled GWP of CH_4 and N_2O emission among all treatments ($P>0.05$). Annual area-scaled GWP contributed mainly by the wheat growing season, averaging approximately 56.1% across all treatments. The contribution of N_2O emission to total GWP was higher than CH_4 emissions in both wheat and corn growing seasons. Although soil tillage had no significant effect on yield-scaled GWP among the treatments annually ($P>0.05$), the highest value occurred in the NT treatment with an order of NT > ST > SRT > RT (Table 4).

Available N and soil water content

Tillage had a significant effect on the concentrations of soil NO_3^--N and NH_4^+- N and water content of soil (Figure 3). For NO_3^--N concentrations, the highest value occurred in the SRT treatment with an order of SRT > ST > RT > NT at wheat flowering stage, while a reverse order was found at corn flowering stage with the highest value occurring in the NT treatment (Figure 3a). Interestingly, reverse tillage impacts were found on NH_4^+- N concentrations as compared with the soil NO_3^--N (Figure 3b). The highest concentrations of NH_4^+- N occurred in the RT treatment at wheat flowering stage and in the SRT treatment at corn flowering stage with an order of SRT > ST > RT > NT (Figure 3b).

Water content of soil at 0-20 cm depth was highest in the NT treatment and the lowest in the SRT treatment during the wheat and corn seasons (Figure 3c). The highest water content of soil was found in the sowing stage and the flowering stage during wheat season. Water content of soil decreased after sowing date and increased 63 days after sowing during corn season.

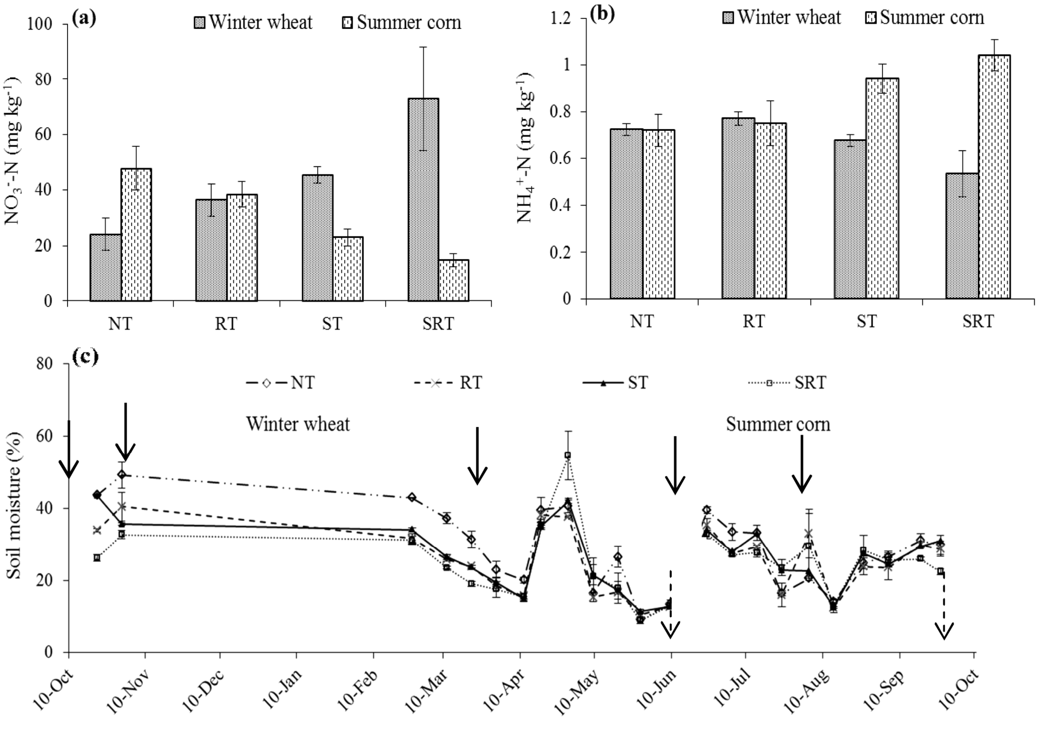

Figure 3. NO_3^--N (a), NH_4^+-N (b) concentrations at the wheat and corn flowering stages and moisture content (c) in the soil at the depth of 0-20 cm under different tillage practices in 2013-2014 (solid line arrows indicate the time of irrigation and the dotted line arrows indicate the time of harvest in each crop).

Discussion

Recently, some studies showed that sub-soiling could increase crop yield by improving infiltration and increasing rooting depth for nutrient uptake (Mohanty et al., 2007; Zink et al., 2011; Kuklík, 2011; Cai et al., 2014). However, other previous observations found that crop yield was not significantly affected by sub-soiling tillage

(Hao et al., 2001). There are still great uncertainties about the impacts of soil tillage on crop yield (Baumhardta and Jones, 2002). In our experiment, no significant effect of sub-soiling was found on wheat and corn yields, however, sub-soiling with rotary tillage (SRT) could significantly enhance wheat and corn yield in wheat-corn cropping system, particularly compared with the no-tillage (NT) (Table 2). Some similar field observations also found similar results that the lowest crop yields were found in wheat and corn under NT (Dong et al., 2005; Bhatia et al., 2010). In agreement with the previous studies, continuous NT decreased crop yield in North China, probably owing to the high precipitation (> 600 mm) (Zheng et al., 2014) and NT was promising only during a drought (< 450 mm) (Wang et al., 2012). In this experimental site, the annual average precipitation was more than 600 mm and the total precipitation from the seeding stage of wheat to the maturity stage of corn were 550.0 mm in 2012-2013 and 517.1 mm in 2013-2014, respectively (Figure 1). Hence, the lowest crop yields in wheat, corn and annual cropping were observed in the NT system.

The N use efficiency (NUE) was often used as indicators of cropping system ability to maintain soil fertility (Grignani et al., 2007). Guo et al. (2014) reported that optimizing agricultural management improved NUE primarily by increasing nitrogen uptake and translocation. Übelhör et al. (2014) showed that fall strip-tillage could improve N-uptake than more intensive strip-tillage, however, Brennan et al. (2014) observed that conventional tillage had the most consistent NUE. Other evidences showed that sub-soiling with controlled-release urea application could improve NUE and boost N uptake of the aboveground portion (Hu et al., 2013b). According to Cassman et al. (1996), the PFP can be increased by increasing the amount, uptake and utilization of indigenous nutrients and also increasing the efficiency of applied nutrients which are taken up by the crop and utilized to produce grain. In our experiment, SRT stimulated plant N uptake and significantly increased PFP. One of the important criterions for cultivar selection for high yield in wheat breeding programs is NHI (Giunta et al., 2007). Meanwhile, significant increases in NHI were observed in the SRT as compared with the RT and NT in winter wheat and summer corn, respectively (Table 3). Our results demonstrate that sub-soiling with rotary tillage might benefit wheat and corn production with high NUE under the wheat-corn cropping system.

Interestingly, there was no significant difference in annual GHGs emissions among the tillage practices, though significant differences were found during each crop season in the present study (Table 4). Tellez-Rio et al. (2015) also reported that tillage systems did not affect total N_2O emissions for an entire cropping duration. In some cases, there was a risk of increasing emission of N_2O under NT or reduced tillage (Six et al., 2004), however, some other studies reported that NT mostly decreased N_2O emission (Kessavalou et al., 1998; Lal, 2004). In the present study, SRT in wheat season and NT in corn season had the highest N_2O emission, likely due to the highest concentrations of NO_3^--N in the soils (Figures 2a and 3a). Although the difference was not significant, the highest annual N_2O emission occurred in the NT among the treatments (Table 4). Soil acted as a source as well as a sink of CH_4 over the cropping system, however, no clear temporal trend was detected in the present experiment (Figure 2a). Meanwhile, no significant difference in CH_4 emissions was observed among the tillage practices (Tellez-Rio et al., 2015). Hu et al. (2013b) reported that compared with corn growing season, wheat growing season had lower CH_4 uptake. Bayer et al. (2012) and Kern et al.

(2012) also found that aerobic soils like that under wheat cultivation acted as a net sink of CH_4 due to presence of methanotropic bacteria. Our results also showed that though tillage had no significant effect on CH_4 emissions in wheat, corn and annual cropping system, the ratio of CH_4 emissions in wheat is less than the corn growing season. Ussiri et al. (2009) found that the GWP associated with N_2O and CH_4 might reduce by 50% in no-tillage as compared with the moldboard and chisel tillage. However, Ahmad et al. (2009) reported that no-tillage didn't significantly affect GWP compared with conventional tillage. In the present study, although significant differences in the area-scaled and yield-scaled GWP were found among tillage practices during wheat or corn season, but no significant difference was found for the entire period of wheat-corn cropping system (Table 4).

Conclusion

Tillage practices significantly affect crop yields and NUE without obvious effect on annual GHGs emissions. Sub-soiling with rotary (SRT) in wheat season and no-tillage in corn season significantly increased crop yields and harvest index at seasonal and annual scales under the wheat-corn cropping system. The annual average yields of two years showed an order of SRT > ST > RT > NT. Furthermore, SRT stimulated plant N uptake with higher NHI and PFP. Although SRT stimulated N_2O emissions in wheat growing season, it significantly reduced the emission in corn growing season (compared with NT), resulting in no significant difference in total GHGs emissions as compared with the other tillage regimes. Meanwhile, no significant differences in the area-scaled and yield-scaled GWP were found among the tillage practices. Thus, sub-soiling with rotary tillage might benefit crop production for high yield and high NUE with less GHGs emissions for wheat-corn cropping system.

Acknowledgements

This work was supported by the Special Fund for Agro-scientific Research in the Public Interest (201503116-10), the National Key Technology Support Program of China (2011BAD16B14), the Chinese Nature Science Foundation (31201179) and the Innovation Program of Chinese Academy of Agricultural Sciences.

References

Ahmad, S., Li, C.F., Dai, G.Z., Zhan, M., Wang, J., Pan, S.G., Cao, C.G., 2009. Greenhouse gas emission from direct seeding paddy field under different rice tillage systems in central China. Soil Tillage Res. 106, 54-61.

Bai, X.L., Zhang, H.L., Chen, F., Sun, G.F., Hu, Q., 2010. Tillage effects on CH_4 and N_2O emission from double cropping paddy field. Trans. CSAE 26, pp. 282-289. (In Chinese)

Baumhardta, R.L., Jonesb, O.R., 2002. Residue management and tillage effects on soil-water storage and grain yield of dryland wheat and sorghum, for a clay loam in Texas. Soil Tillage Res. 68, 71-82.

Bayer, C., Gomes, J., Vieira, F.C.B., Zanatta, J.A., Piccolo, M.D.C., Dieckow, J., 2012. Methane emission from soil under long-term no-till cropping systems. Soil Tillage Res. 124, 1-7.

Bhatia, A., Sasmal, S., Jain, N., Pathak, H., Kumar, R., Singh, A., 2010. Mitigating nitrous oxide emission from soil under conventional and no-tillage in wheat using nitrification inhibitors. Agr. Ecosyst. Environ. 136, 247-253.

Bremner, J.M., 1996. Nitrogen-total. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Part 3 Chemical Methods. SSSA Book Ser. 5. SSSA, Madison, pp. 1103-1108.

Brennan, J., Hackett, R., McCabe, T., Grant, J., Fortune, R.A., Forristal, P.D., 2014. The effect of tillage system and residue management on grain yield and nitrogen use efficiency in winter wheat in a cool Atlantic climate. Eur. J. Agron. 54, 61-69.

Cai, H.G., Ma, W., Zhang, X.Z., Ping, J.Q., Yan, X.G., Liu, J.Z., Yuan, J.C., Wang, L.C., Ren, J., 2014. Effect of subsoil tillage depth on nutrient accumulation, root distribution and grain yield in spring maize. Crop J. 2, 297-307.

Cassman, K.G., Gines, G.C., Dizon, M.A., Samson, M.I., Alcantar. J.M., 1996. Nitrogen use efficiency in tropical lowland rice systems: contribution from indigenous and applied nitrogen. Field Crops Res. 47, 1-12.

Cheng, Y., Zhao, J., Liu, Z.X., Huo, Z.J., Liu, P., Dong S.T., Zhang J.W., Zhao, B., 2015. Modified fertilization management of summer maize (*Zea mays* L.) in northern China improves grain yield and efficiency of nitrogen use. J. Integr. Agr. 14 (8), 1644-1657.

Cui, Z.L., Chen, X.P., Miao, Y.X., Li, F., Zhang, F.S., Li, J.L., Ye, Y.L., Yang, Z.P., Zhang, Q., Liu, C.S., 2008. On-farm evaluation of winter wheat yield response to residual soil nitrate-N in North China Plain. Agron. J. 100, 1527-1534.

Dong, Y.H., Ouyang, Z., 2005. Effects of organic manures on CO_2 and CH_4 fluxes of farmland. Chin. J. Appl. Ecol. 16, 1303-1307. (In Chinese)

Dorich, R.A., Nelson, D.W., 1983. Direct colorimetric measurement of ammonium in potassium chloride extracts of soils. Soil Sci. Soc. Am. J. 47, 833-836.

FAO, 2013. FAO Statistical Yearbook 2013. World Food and Agriculture, Rome, Italy.

Giunta, F., Motzo, R., Pruneddu, G., 2007. Trends since 1900 in the yield potential of Italian-bred durum wheat cultivars. Eur. J. Agron. 27, 12-24.

Grignani, C., Zavattaro, L., Sacco, D., Monaco, S., 2007. Production nitrogen and carbon balance of maize-based forage systems. Eur. J. Agron. 26, 442-453.

Guo, Z.J., Zhang, Y., Zhao, J., Shi, Y., Yu, Z.W., 2014. Nitrogen use by winter wheat and changes in soil nitrate nitrogen levels with supplemental irrigation based on measurement of moisture content in various soil depths. Field Crops Res. 164, 117-125.

Han, B., Li, Z.J., Wang, Y., Ning, T.Y., Zheng, Y.H., Shi, Z.Q., 2007. Effects of soil tillage and returning straw to soil on wheat growth status and yield. Trans. CSAE. 23, 48-53. (In Chinese)

Hao, X., Chang, C., Conner, R.L., Bergen, P., 2001. Effect of minimum tillage and crop sequence on crop yield and quality under irrigation in a southern Alberta clayloam soil. Soil Tillage Res. 59, 45-55.

He, J., Wang, Q.J., Li, H.W., Liu, L.J., Gao, H.W., 2009. Effect of alternative tillage and residue cover on yield and water use efficiency in the annual double cropping system in North China Plain. Soil Tillage Res. 104, 198-205.

Hu, H.Y., Ning, T.Y., Li, Z.J., Han, H.F, Zhang, Z.Z, Qin, S.J, Zheng, Y.H., 2013a. Coupling effects of urea types and subsoiling on nitrogen–water use and yield of different varieties of maize in northern China. Field Crops Res. 142, 85-94.

Hu, X.K., Su, F., Ju, X.T., Gao, B., Oenema, O., Christie, P, Huang, B.X., Jiang, R.F., Zhang, F.S., 2013b. Greenhouse gas emissions from a wheate maize double cropping system with different nitrogen fertilization regimes. Environ. Pollut. 176, 198-207.

Huang, M., Li, Y.J., Wu, J.Z., Chen, M.C., Sun, J.K., 2006. Effects of subsoiling and mulch tillage on soil properties and grain yield of winter wheat. J. Henan Univ. Sci. Technol. 27, 47-77. (In Chinese)

Hutchinson, G., Livingston G., 1993. Use of chamber systems to measure trace gas fluxes. In: Harper L.A. (Ed.), Agricultural ecosystem effects on trace gases and global climate. American Society Agron. Madison, WI, pp. 79-93.

IPCC., 2007. Intergovernmental Panel on Climate Change. Fourth Assessment Report: Climate Change 2007: The Physical Science Basis-Summary for Policymakers. http: //www.ipcc.ch/SPM2feb07.pdf.

IPCC., 2013. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Climate Change 2013: The Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jonard, F., Mahmoudzadeh, M., Roisin, C., Weihermüller, L., 2013. Characterization of tillage effects on the spatial variation of soil properties using ground-penetrating radar and electromagnetic induction. Geoderma. 207-208, 310-322.

Ju, X.T., Xing, G.X., Chen, X.P., Zhang, S.L., Zhang, L.J., Liu, X.J., Cui, Z.L., Yin, B., Christie, P., Zhu, Z.L., Zhang, F.S., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. P. Natl. Acad. Sci. USA. 106, 3041-3046.

Kern, J., Hellebrand, H.J., Gömmel, M., Ammon, C., Berg, W., 2012. Effects of climatic factors and soil management on the methane flux in soils from annual and perennial energy crops. Biol. Fertil. Soils. 48, 1-8.

Kessavalou, A., Mosise, A.R., Doran, J.W., 1998. Fluxes of carbon dioxide, nitrous oxide and methane in grass sod and winter wheat-fallow tillage management. J. Environ. Qual. 27, 1094-1104.

Kuklík, P., 2011. Preconsolidation, structural strength of soil and its effect on subsoil upper structure interaction. Eng. Struct. 33, 1195-1204.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science. 304, 1623-1627.

Lampurlanés, J., Angas, P., Cantero-Martinez, C., 2002. Tillage effects on water storage during fallow and on barley root growth and yield in two contrasting soils of the semi-arid Segarra region in Spain. Soil Tillage Res. 65, 207-220.

Mangalassery, S., Sjogersten,S., Sparkes, D.L., Sturrock, C.J., Craigon, J., Mooney, S.J., 2014. To what extent can zero tillage lead to a reduction in greenhouse gas emissions from temperate soils? Sci. Rep. 4, 4586.

Mohanty, M., Bandyopadhyay, K.K., Painuli, D.K., Ghosh, P.K., Misra, A.K., Hati, K.M., 2007. Water transmission characteristics of a Vertisol and water use efficiency of rain-fed soybean (*Glycine max* (L.) Merr.) under subsoiling and manuring. Soil Tillage Res. 93, 420-428.

Norman, R.J., Stucki, J.W., 198l. The derminafion of nitrate and nitrite in soil extracts by ultraviolet spectrophotometry. Soil Sci. Soc. Am. J. 45, 347-353.

Pikul, J.L., Kristian, J.S., 2003. Water infiltration and storage affected by subsoiling and subsequent tillage. Soil Sci. Soc. Am. J. 3, 859-866.

Pittelkow, C.M., Adviento-Borbe, M.A., Hill, J.E., Six, J., van Kessel, C., Linquist, B.A., 2013. Yield-scaled global warming potential of annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input. Agr. Ecosyst. Environ. 177, 10-20.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Change. 4, 678-683.

Qin, H.L, Gao, W.S, Ma, Y.C, Ma, L, Yin, C.M., 2008. Effects of Subsoiling on Soil Moisture under No-tillage 2 Years Later. Agr. Sci. China. 7, 88-95.

Rieger, S., Richner, W., Streit, B., Frossard, E., Liedgens, M., 2008. Growth, yield and yield components of winter wheat and the effects of tillage intensity, preceding crops and N fertilization. Eur. J. Agron. 28, 405-411.

Sadras, V.O., Calderini, D., 2014. Crop Physiology: Applications for Genetic Improvement and Agronomy. pp. 43-46.

Six, J., Ogle, S.M., Breidt, F.J., Conant, R.T., Mosier, A.R., Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Global Change Biol. 10, 155-160.

Smith, K., Watts, D., Way, T., Torbert, H., Prior, S., 2012. Impact of Tillage and Fertilizer Application Method on Gas Emissions in a Corn Cropping System. Pedospher. 22, 604-615.

Strudley, M.W., Green, T.R., Ascough, J.C., 2008. Tillage effects on soil hydraulic properties in space and time: state of the science. Soil Tillage Res. 99, 4-48.

Tellez-Rio, A., García-Marco, S., Navas, M., López-Solanilla, E., Tenorio, J.L., Vallejo, A., 2015. N_2O and CH_4 emissions from a fallow–wheat rotation with low N input in conservation and conventional tillage under a Mediterranean agroecosystem. Sci. Total Environ. 508, 85-94.

Tomohiro, K., Shamitha, R.M., Suhas, P.W., Takeshi, W., 2015. Efficient rates of nitrogenous fertiliser for irrigated sweet sorghum cultivation during the post-rainy season in the semi-arid tropics. Eur. J. Agron. 71, 63-72.

Übelhör, A., Gruber, S., Wilhelm Claupein, W., 2014. Influence of tillage intensity and nitrogen placement on nitrogen uptake and yield in strip-tilled white cabbage (*Brassica oleracea convar. capitata var. alba*). Soil Tillage Res. 144, 156-163.

Ussiri, D.A.N., Lal, R., Jarecki, M.K., 2009. Nitrous oxide and methane emissions from long-term tillage under a continuous corn cropping system in Ohio. Soil Tillage Res. 104, 247-255.

Wang, X., Wu, H.J., Dai, K.A., Zhang, D.C., Feng, Z.H., Zhao, Q.S., Wu, X.P., Jin, K., Cai, D.X., Oenema, O., Hoogmoed, W.B., 2012. Tillage and crop residue effects on rainfed wheat and maize production in northern China. Field Crops Res. 132, 106-116.

Xu, X., He, P., Zhao, S., Qiu, S., Johnston, A.M., Zhou, W., 2016. Quantification of yield gap and nutrient use efficiency of irrigated rice in China. Field Crops Res. 186, 58-65.

Zheng, C.Y., Jiang, Y., Chen C.Q., Sun, Y.N., Feng, J.F., Deng, A.X., Song, Z.W., Zhang, W.J., 2014. The impacts of conservation agriculture on crop yield in China depend on specific practices, crops and cropping regions. Crop J. 2, 289-296.

Zheng, Q.X., Guang, X.X., Zhao, L.Z., 2007. Nitrous oxide and methane emissions as affected by water, soil and nitrogen. Pedospher. 17, 146-155.

Zink, A., Fleige, H., Horn, R., 2011. Verification of harmful subsoil compaction in loess soils. Soil Tillage Res. 114, 127-134.

Zou, J., Huang, Y., Jiang, J., Zheng, X., Sass, R.L., 2005. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: effects of water regime, crop residue and fertilizer application. Global Biogeochem. Cy. 19, GB2021.

Zou, X.X., Li, Y.E., Li, K., Cremades, R., Gao, Q.Z., Wan, Y.F., Qin, X.B., 2015. Greenhouse gas emissions from agricultural irrigation in China. Mitig. Adapt. strat. gl. 20, 295-315.