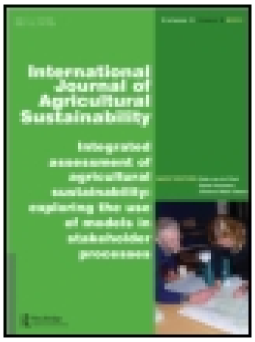

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Soil CO_2 emission and carbon budget of a wheat/maize annual double-cropped system in response to tillage and residue management in the North China Plain

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ABSTRACT

To investigate the impacts of tillage and crop residue managements on soil CO_2 emission and C budget in a wheat (*Triticum aestivum* L.)/maize (*Zea mays* L.) double-cropped system in the North China Plain (NCP), a field experiment was conducted consisting of four treatments: tillage with crop residues retention (CT+), tillage with crop residues removal (CT−), no-till with crop residues retention (NT+), and no-till with crop residues removal (NT−). Daily soil CO_2 fluxes changed with crop growing stage and peaked during the most vigorous growth of period, fluxes in maize season were higher than those in wheat season. Compared to the tilled soils, cumulative CO_2 emissions were significantly lower under no-till treatments. The largest cumulative CO_2 emission occurred under CT+ (65 g CO_2-C m^{-2} y^{-1}) and the smallest was under NT+ (39 g CO_2-C m^{-2} y^{-1}). After 5 years of the experiment, soil organic carbon (SOC) sequestration were greater with crop residues retention (CT+ and NT+) than with crop residues removal (CT− and NT−), the maximum SOC stock was in NT+ (5940 g C m^{-2}) while the minimum was in CT− (3635 g C m^{-2}). NT+ could help to mitigate CO_2 emission in the annual wheat/maize double-cropping system of the area.

KEYWORDS
CO_2 emission; carbon budget; tillage; crop residues management; wheat/maize double-cropping system

Introduction

About 20% of the earth's land area is used for growing crops, and thus farming practices have a major influence on carbon (C) stored in soil and released into the atmosphere as CO_2 (Follett, 2001). As CO_2 emission is produced by the respiration of soil microbes and roots in soil, the processes are strongly influenced by soil condition, for example, temperature, water content, and available nitrogen and dissolved organic matter, which are further strongly influenced by farming practices (e.g. tillage, fertilizer, water, crop residues retention, and manure application). Thus, agricultural soils can act as a net source or sink of C, which is determined by changes in land use and soil management practices (Gregorich, Rochette, Vandenbygaart, & Angers, 2005; Koga, Sawamoto, & Tsuruta, 2006; Lal, 2009, 2011; Paustian et al., 1997). Crop residues as substrate supply strongly affects soil respiration (Gregorich, Rochette, Hopkins, Mckim, & Stgeorger, 2006; Ryan & Law, 2005; Thangarajan, Bolan, Tian, Naidu, & Kunhikishnan, 2013). Tillage-induced physical and environmental conditions play a key role in the emission of biogenic gases from soil (Gregorich et al., 2006). Although the impacts of tillage on soil greenhouse gases (GHG) emissions have been studied more widely than residue management, field studies also report contrasting results for tillage effects on soil CO_2 and N_2O emissions due to site-specific managements and environmental conditions (Jin et al., 2014).

It was widely reported that intensive tillage operations (e.g. plough tillage, PT) often leads to a depletion of soil organic carbon (SOC), resulting in

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large CO_2 emissions from the soil to the atmosphere, in contrast, conservation tillage can reduce C emissions and losses from cultivated lands effectively (Al-Kaisi & Yin, 2005; Jin et al., 2014; Lal, 1997, 2004; Paustian et al., 1997; Reicosky, 1997; Ussiri, David, & Lai, 2009; Utomo, 2014). Arable soil can store C upon conversion from plough tillage to conservation tillage, by reducing soil disturbance, decreasing the fallow period and incorporation of cover crops in the rotation cycle (Lal, 2004). By comparing paired tillage experiments, Paustian et al. (1997) found that the average SOC level was 285 g m^{-2} more under no-till compared with conventional tillage in temperate regions and, on a relative basis, SOC was 8% higher in no-till than in conventional tillage. Arable soils can store SOC upon conversion from plough till to no-till (NT) or conservation tillage by reducing soil disturbance, decreasing the fallow period and incorporation of cover crops in the rotation cycle (Lal, 2004). Many researches indicated that NT sequestrated higher SOC than conventional tillage. For example, Ussiri et al. (2009) reported that after 43 years of continuous maize, the mass of SOC in the top 30 cm soil was significantly greater under NT than under chisel till and PT, and NT reduced CO_2 emission by an average of 0.7 and 0.6 Mg C ha^{-1} y^{-1} during the growing season compared to PT and chisel till, respectively. Ghimire, Adhikari, Chen, Shah, and Dahal (2012) suggested that a rice–wheat system could serve as a greater SOC sink under NT system than conventional tillage in lowlands of Nepal. Zhang, Wang, Chen, Malemela, and Zhang (2013) also reported a wheat–corn system in the NCP with the highest net SOC sequestration rate at 527.7 kg ha^{-1} y^{-1} in NT and the lowest at 234.7 kg^{-1} ha^{-1} y^{-1} in PT(Zhang et al., 2013). For maximum potential C sequestration, multiple cropping sequences coupled with NT are considered most desirable in terms of management strategy. However, some studies do not support the notion of a consistent SOC benefit from conservation tillage (Baker, Ochsner, Venterea, & Griffis, 2007; Govaerts et al., 2006). Govaerts et al. (2006) observed that cumulative soil CO_2 emission was lower under conventional tillage with wheat and maize residues incorporated than that under NT in an irrigated double-cropped system in Mexico. In addition, some studies that have involved deeper sampling generally show no C storage benefit and lower CO_2 emissions for conservation tillage (Baker et al., 2007). Luo, Wang, and Sun (2010) assessed the response of SOC to conversion from conventional tillage to NT based on global data from 69 paired-experiments, and highlighted the role of adopting NT in sequestrating C greatly regulated by cropping systems. Therefore, the benefits of NT on C sequestration may not be the same in different cropping systems due to the specific climate, soil, and farm managements.

Crop residues management also has a significant impact on soil quality and resilience, agronomic productivity, and GHG emissions from soil to the atmosphere (Lal, 1997). The major factors affecting SOC in semi-arid soils are the frequency of summer-fallow in crop rotations and the level of C input into soil through crop residues, and increasing crop residues return to soil have been shown to increase SOC linearly (Rasmussen, Albrecht, & Smiley, 1998). Crop residues serve as a substrate that is converted to microbial biomass and soil organic matter, and has the potential to enhance C storage in agricultural soils (Wright & Hons, 2004), which is also confirmed by some field studies(Jin et al., 2014; Mitchell et al., 2015). An 8-year field experiment conducted by Mitchell et al. (2015) indicates that the increased soil C storage appears to be primarily resulting from crop residues retention to soil (Mitchell et al., 2015). Jin et al. (2014) investigated nine sites across US corn belt and found that removal of corn stover decreased plant C and nitrogen (N) inputs into soils, limiting substrate availability of labile C and N sources for microbial use, and decreased subsequent emissions of CO_2 and N_2O (Jin et al., 2014). However, controversial thought that the CO_2 production from soil increased considerably with the addition of C substrates (e.g. green manure, crop residues, and farmyard manure has been reported by Dash, Roy, Neogi, Nayak, & Bhattacharyya, 2014. Moreover, some experiments indicated that CO_2 emission from the soil can increase from 4 to 11 times after addition of plant residues (Kuzyakov, Friedel, & Stahr, 2000). An important question, 'to what extent can SOC sink capacity potentially offset increases in atmospheric CO_2', has become a hot debate recently (Lal, 2004; Stewart, Paustian, Conant, Plante, & Six, 2009).

Most arable soils now contain a lower SOC pool than their potential as determined by the specific climatic conditions and soil profile characteristics, and the SOC pool can be enhanced by adopting proper management practices (e.g. conservation tillage) (Lal, 2004).Moreover, SOC saturation deficit and the amount of added C influenced residue-C storage in soil fractions due to change in soil management (Stewart et al., 2009). Tillage increases SOC mineralization by disturbing soil and changing soil properties, meanwhile burying crop residues closer to soil in favour of mineralization, intensive tillage also breaks up the soil clods and aggregates to expose fresh surfaces for enhanced gas exchange from the interior where aggregate interior may have a higher CO_2 concentration (Reicosky & Archer, 2007). Tillage alters the SOM decomposition environment by aerating the soil, breaking the aggregates, incorporating residue into the plough layer, and therefore increasing soil and crop residue contact (Ussiri et al., 2009). Cropping intensity, tillage, and residue input all affect SOM (Rasmussen et al., 1998). Because of the highly complex interactions between physical, chemical, and biological variables, GHG fluxes from cropping systems and SOC storage are highly variable temporally and spatially. Thus, more information is needed on the effects of tillage, crop rotation, residue application, and soil variability on C input and output in multiple cropping systems to further our understanding of the potential C sequestration in agro-ecosystems (Ghimire et al., 2012).

In China, with the increasing population and decreasing arable land, multiple cropping systems play an essential role to meet the increasing demand for agricultural products (Zuo et al., 2014). The cropping index was estimated to be greater than 160% across the country indicating the widespread use of annual double- and triple-cropped systems (Liu, 1997; Wu & Zhu, 1999). The North China Plain (NCP) is one of the three major farming areas, which produces more than 75 % of wheat and 35 % of maize grain output of the total production in China (Meng et al., 2012). The cropping system of the NCP is dominated by an annual winter wheat/ summer maize double-cropping system. Conventional farming practices included mouldboard plough tillage with crop residue removal which has led to SOC loss; during the last decades conservation tillage (i.e. no-till) has been gradually adopted for soil conservation (Du, Ren, Hu, & Zhang, 2015). Du et al. (2015) also found that adoption of NT enhanced SOC sequestration in the micro-aggregates of 0–5 cm surface soil of the wheat–corn double-cropping system of the NCP. Zhang et al. (2016) suggested that NT is an efficient and a climate-resilient farming practice with higher ecosystems service values for the NCP; it was mainly attributed to C sequestration from the maize residues (Zhang et al., 2016). With an increasing grain yield, a great amount of wheat straw and maize stover are produced and expected to return to field directly after harvesting grain. The crop residues are either incorporated into soil through tilling, or mulched soil surface with NT. To quantify effects of tillage and crop residues management practices on soil CO_2 emission and C sequestration of the double-cropping system is important for China to take proper measures for mitigating GHG emission from arable soil; it still needs more investigation to understand SOC sequestration potential of farming practices. The objective of this study was to assess the impacts of tillage and crop residues management on CO_2 emissions and C budget in a winter wheat/ summer maize double-cropped system in the NCP.

Material and methods

Site description

The experiment was carried out at the Yucheng Agriculture Experimental Station of Chinese Academy of Sciences (36°57′ N, 116°36′ E), which is located in the NCP at 26 m above mean sea level, and is part of the Yellow River alluvial plain. The weather is warm-temperate and sub-humid monsoon climate with the long-term average annual precipitation of 593 mm, and mean annual temperature of 13.1°C with a frost-free period of 220 days. The typical cropping system in the NCP is a wheat (*Triticum aestivum* L.) – maize (*Zea mays* L.) annual double-cropping system. Due to the timing of annual precipitation, wheat is usually irrigated and maize is rain-fed (Figure 1). In June of each year, wheat is harvested and maize is directly sown into the wheat stubble under no-till with wheat straw mulching. Maize is harvested in October, and wheat is sown after conventional tillage with maize stover either removed from the field or incorporated into the soil. Wheat is also sown directly into the maize stubble with or without maize residue mulching, namely NT farming is being widely practiced as an alternative to traditional tillage for restoring SOC in the NCP.

Experimental design

The experiment consisted of four treatment combinations with three replications, that is, two levels of tillage and two levels of crop residue. The plots were arranged in a randomized block design. Each plot was 2.58 × 2.58 m in size. The two tillage treatments were conventional tillage (CT) and NT. CT in this experiment followed the typical farmers' practices, whereby the soil is tilled to the depth of 15–20 cm by manual

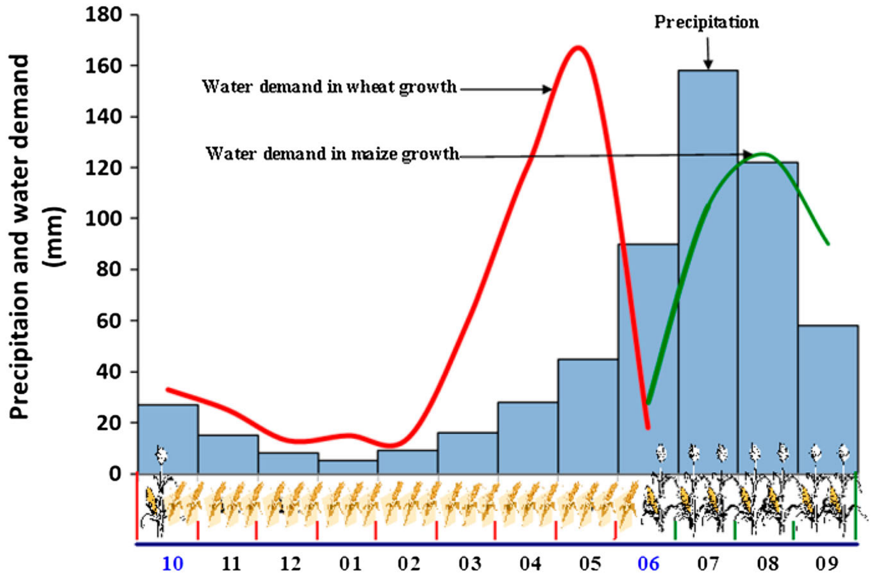

Figure 1. The typical cropping system of annual wheat/maize double cropped in the North China plain.

operation with a shovel after maize harvest each year, with two residue treatments of removal from the field (CT−) and incorporating into the soil (CT+). Under NT, no soil disturbance occurred except for planting. The two residue treatments imposed were (1) all above-ground post-harvest residue was removed (NT−) (i.e. root biomass remained) and (2) residue was retained (NT+). The maize residue was returned to the soil prior to wheat planting and wheat residue was returned prior to maize planting. The maize residues were incorporated into soil of 0–20 cm under the CT treatment and added as mulch to the surface in the NT treatment; the wheat residue was retained on the soil surface in the same plot and subsequently maize was planted directly under NT with wheat stubble. All residues returned to the field were cut to chips.

Wheat was planted in November and harvested early in June the following year; it was followed by maize which was planted within 1–2 days after harvesting wheat in June and harvested in October. Wheat often was irrigated 3–4 times and maize usually rain-fed.

Wheat received 240 kg N ha^{-1} in a split application: the first half was a basal dose that was side-dressed during sowing and the second half was surface-dressed at the boot stage following immediately by irrigation. Maize also received 240 kg N ha^{-1} at 50 days after planting by surface-dressing.

The field trial was initiated in 2008. Prior to the experiment, the study field was planted with wheat/maize for the previous decade with tillage after harvesting maize for wheat and NT for maize annually, and all crop residues were removed from the field. The soil is fluvisols according to the FAO-UNESCO system, a silt–loam texture with 12% sand, 66% silt, and 22% clay. At the beginning of the experiment, the soil of the field contained 12.2 g kg-1 of SOC, 0.80 g kg-1 of total nitrogen (N), 2.06 g kg-1 of total phosphorus (P), 22.9 g kg-1 of total potassium (K), and an average pH of 8.4.

Gas sampling and analysis

The CO_2 fluxes of soil surface were measured 19 times in 2010–2011 and 20 times in 2012–2013 using static chambers. The gas was sampled with chambers made of polyvinyl (PVC) pipe. The gas chambers consisted of two parts: a bottom base of 25 cm height and 15 cm diameter and a lid fitted with a gas sampling port equipped with rubber septum. The chambers were inserted 5 cm into the soil. One chamber was installed in each experimental plot for the three replicates of each treatment. The chambers were installed at first in October of 2010. All chambers of each plot were removed from the plot before wheat planting and reinstalled after wheat seeding and were kept in place during the entire growing season.

During gas sampling, the chamber headspace gas was sampled 4 times over a period of 15 min. At 0, 5, 10, and15 min after closing the lid, 25 ml syringes were equipped with a three-way luer lock. The syringes were allowed to equilibrate to ambient temperature for 2 h before being manually injected to gas chromatography (GC 4890, Kyoto, Japan). The gas samples were analysed for CO_2 concentration using GC 4890 equipped with flame ionization detector. Daily flux of gases (F, g CO_2 g m^{-2} d^{-1}) was calculated as:

$$F = \left(\frac{\Delta g}{\Delta t}\right)\left(\frac{V}{A}\right)k, \quad (1)$$

where Δg is the linear change in CO_2 concentration inside the chamber, V is the chamber volume, A is the surface area circumscribed by the chamber, and k is the conversion factor to convert minutes to days. Cumulative emissions of CO_2 during the growing seasons of wheat and maize individually, as well as the two crops together over the double-cropping year, were estimated by integrating over the sampling period using the trapezoidal rule.

Soil sampling and analysis

Three soil cores were collected after maize harvest from each plot at 0–20 cm depths. Soil bulk density was calculated for each treatment after the 5th year of the experiment. They were 1.34, 1.35, 1.74, and 1.75 g cm^{-3} g cm^{-3} for CT−, CT+, NT−, and NT+, respectively. Samples were air-dried, ground gently, and sieved (2 mm). SOC was analysed by using dichromate oxidation and subsequent titration with ferrous ammonium sulphate (Yeomans & Bremner, 1988). Briefly, 0.5 g of soil was digested with 5 mL of 1.0 N KCr_2O_7 and 10 mL of H_2SO_4 at 150°C for 30 min, followed by titration of digests with standardized $FeSO_4$. SOC stock was calculated according to Ghimire et al. (2012), which is given below:

$$\text{SOCstock} = \text{BD} \times \text{SOC} \times \text{D} \times \text{A}, \quad (2)$$

where SOC stock is the SOC stock (g m^{-1}), BD is soil bulk density (g cm^{-3}), SOC is soil organic (g kg^{-1}), D is the thickness of soil sampling layer (cm), and A is the area (m^2). In this experiment, D was 20 cm.

Plant measurements

Wheat grain yield was determined by harvesting the entire crop in each plot and maize grain yield was measured by harvesting plants in two rows in the centre of each plot. After shelling, total grain weight of each sample was recorded. A subsample of about 500 g was taken and dried to a constant weight at 70°C to determine the moisture content of the grain; grain yields are reported on an oven dry basis.

Aboveground dry matter was measured by collecting 20 plants for wheat and 5 plants for maize at random in each plot. These plants were cut at the root–stem junction and ears and other parts were separated for determination of harvest index. After shelling, cobs were combined with the other aboveground plant parts. The aboveground plant matter (straw and stover) and grain were both dried at 70°C and then weighed for dry matter determination. Similar to yield data, total straw and stover dry matter was calculated and expressed on a zero water basis.

Carbon budget

According to the C budget calculation method (Pomazkina, Sokolova, & Zvyagintseva, 2013), the C budget of this study was revised as follows:

$$C = C_{input} - C_{emission}, \quad (3)$$

where C_{input} includes post-harvest aboveground residues and underground roots and $C_{emission}$ refers to cumulative soil CO_2-C emission.

The C input from crop residue was determined for the experimental period from both maize and wheat growth seasons. The C input from maize and wheat residues of each treatment was calculated by using annual residue output and C concentration. The aboveground biomass of both maize and wheat were measured annually as mentioned above. The roots amount of wheat and maize were assessed by using shoot to root ratios (S:R), whereby the S:R ratio for wheat and maize is 1.7 and 2.1, respectively, which are the average of the ratios reported by Buyanovsky and Wagner (1986). These values are close to the crop growth and grain yields obtained in our experimental area in China. The C concentration was 39% and 41% for wheat and maize aboveground residue, respectively (Dong, Hu, Chen, & Zhang, 2009), and 30% and 26% for wheat and maize roots, respectively (Buyanovsky & Wagner, 1986).

Data analysis

The analysis of variance was conducted by using SPSS 20.0 to determine tillage and crop residue effects on

CO_2 fluxes, grain yield, and aboveground biomass, SOC. Means were compared *post hoc* using an LSD test. All tests of significance were made with probability value of 0.05. The figures were drawn using Origin 8.6 (OriginLab Corporation).

Results and discussion

Dynamic CO_2 emissions

The daily CO_2 fluxes during wheat growth season ranged from 0.31 to 4.03 g CO_2-C m^{-2} d^{-1} in 2010–2011 and 0.14 to 3.76 g CO_2-C m^{-2} d^{-1} in 2012–2013. During the maize season, the fluxes ranged from 1.01 to 9.29 g CO_2-C m^{-2} d^{-1} in 2011 and from 2.11 to 10.33 g CO_2-C m^{-2} d^{-1} in 2013. During the wheat season, the lowest fluxes were recorded in over-winter period, while the highest fluxes occurred in grain-filling period. In the maize season, lower fluxes were observed both in seedling period and when the crop was maturing; higher fluxes were measured during tasseling and silking. Similar trends in CO_2 fluxes were observed during the period of crop vigorous growth in both years and the CO_2 fluxes changed with crop growth. Regardless of tillage and crop residues management, larger CO_2 fluxes were observed during vigorous crop growth period, while lower CO_2 fluxes were measured during early crop growth and maturation. The largest CO_2 emission (10.33 g CO_2-C m^{-2} d^{-1}) was measured in maize season under the tilled-with-residue-retained treatment (CT+) (Figure 2). This may be attributed to high soil biological activity and warm soil temperatures as well as root respiratory activity due to crop growth. Photosynthesis supplies C substrate for root metabolism and growth, and a decrease in substrate supply can cause reduced soil respiration within a short time, just as Kuzyakov and Cheng (2001) indicated that cultivation of wheat led to the increasing decomposition intensity of SOC (Kuzyakov & Cheng, 2001). The trend and magnitude of CO_2 flux observed in this experiment are similar to those reported in other studies. For example, Ussiri et al. (2009) reported that the daily CO_2 fluxes ranged from 0.15 to 6.74 g CO_2-C m^{-2} d^{-1}, and the largest CO_2 flux was observed in summer; meanwhile, CO_2 fluxes were also generally lower under NT than PT and chisel tillage with continuous maize a silt loam in Ohio, USA. Soil respiration is strongly linked to plant metabolism (Ryan & Law, 2005). The seasonal change in daily CO_2 fluxes from our experiment coupled with crop growth activity can be attributed

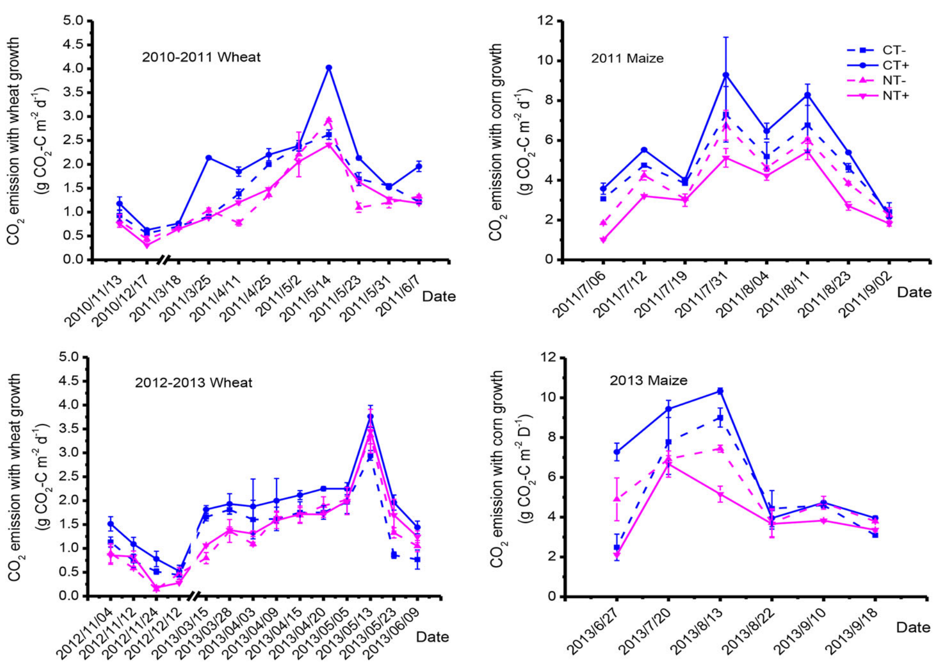

Figure 2. Daily CO_2 fluxes as affected by tillage and crop residue managements. CT+: till with crop residues retained; CT−: till with crop residues removed, NT+: no-till with crop residues retained, NT−: no-till with crop residues removed. Bars represent standard deviation of the mean.

to the vigorous root respiration. Kuzyakov and Cheng (2001) indicated that rhizosphere respiration was tightly coupled with plant photosynthetic activity and soil CO_2 efflux is controlled by photosynthesis cycle together with temperature change. The seasonal variation in CO_2 fluxes coupled with the environmental effects of tillage and crop residue management reflect the controls on crop growth, which further regulates CO_2 production and emission and the moderating effects of soil perturbations on these processes.

Cumulative CO_2 emissions

The annual cumulative CO_2 fluxes were significantly lower in NT (NT+ and NT− on average, 42.43 g CO_2-C m^{-2} y^{-1} in 2010–2011 and 46.96 g CO_2-C m^{-2} y^{-1} in 2012–2013) than the tilled (CT+ and CT− on average, 58.39 g CO_2-C m^{-2} y^{-1} in 2010–2011 and 57.97 g CO_2-C m^{-2} y^{-1} in 2012–2013) treatments. In contrast to the tillage treatments, no significant effect of residue retention could be detected on cumulative CO_2 emission: CO_2 fluxes with residues retained (CT+ and NT+ on average, 51.66 g CO_2-C m^{-2} y^{-1} in 2010–2011 and 54.53 g CO_2-C m^{-2} y^{-1} in 2012–2013) and CO_2 fluxes without residues retained (CT− and NT− on average, 49.15 g CO_2-C m^{-2} y^{-1} in 2010–2011 and 50.40 g CO_2-C m^{-2} y^{-1} in 2012–2013). Overall the till treatment emitted 11.01–15.95 g CO_2-C m^{-2} y^{-1} more than no-till, and soils with crop residue retained emitted 2.51–4.13 g CO_2-C m^{-2} y^{-1} more C than those with crop residue removed. There was, however, a significant interaction between tillage and crop residues: the largest cumulative CO_2 emission was measured under CT+ treatment (emitted 63.94 g CO_2-C m^{-2} y^{-1} and 64.99 g CO_2-C m^{-2} y^{-1} in 2010–2011 and 2012–2013, respectively), while the smallest cumulative CO_2 emission was measured under NT+ treatment (emitted 39.39 g CO_2-C m^{-2} y^{-1} and 44.08 g CO_2-C m^{-2} y^{-1} in 2010–2011 and 2012–2013 respectively), CT+ emitted 20.91–24.55 g CO_2-C m^{-2} y^{-1} more than NT + treatment. In addition, cumulative CO_2 emissions were significantly different between wheat and maize seasons among the treatments. The cumulative CO_2 fluxes were significantly greater in maize than that in wheat season although maize duration (~110 days) is shorter than wheat duration (~230 days) (Figure 3). That may be attributed to the higher temperature coupled with the higher plant photosynthesis in maize growth than in wheat. It was just like as some reported that soil efflux was controlled by photosynthesis together with temperature (Kuzyakov & Cheng, 2001). However, more information is needed to quantify CO_2 fluxes derived from soil, crop residue, and root respiration, and those intensity related with plant photosynthesis.

These data indicate that tillage and tillage by interaction with residue management played a key role in affecting CO_2 emission over one year in a double-cropped system. These trends were observed over both experimental years. Thus, NT+ would result in smaller CO_2 emission from surface soil than CT + . The results also indicate that the effect from single residue application on CO_2 emission was not significant, but the effect of interaction between residue application and tillage was significant. This observation suggests that the effect of residue retention on soil CO_2 emission was substantially influenced by soil tillage.

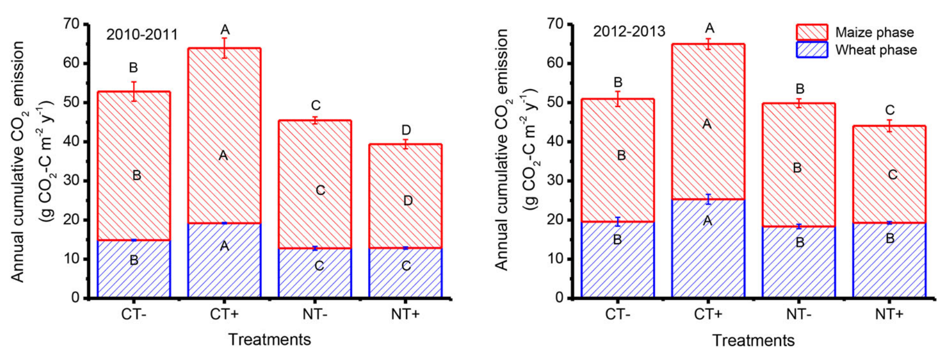

Figure 3. Annual cumulative CO_2 emissions as affected by tillage and crop residue managements. CT+: till with crop residues retained; CT−: till with crop residues removed, NT+: no-till with crop residues retained, NT−: no-till with crop residues removed. Bars represent standard deviation of the mean.

The results presented herein are consistent with other studies. Dong et al. (2009) reported that higher annual CO_2-C production was observed under PT and rotary tillage than that under no-till in a wheat/maize double-cropped system. Similarly, Ussiri et al. (2009) observed that annual CO_2-C production was significantly lower in NT than in PT and chisel till in Ohio, USA. Lower CO_2 emission from soil under no-till crop residues retained than from soils under mouldboard plough with residues retained, could be partially attributed to slower decomposition of crop residues placed on the soil surface in no-till than when they were incorporated with mouldboard plough (Al-Kaisi & Yin, 2005). Ghimire et al. (2012) also demonstrated that interaction effect on SOC storage between tillage and crop residue was significant at 0–15 cm surface soil. Single effect of residue application was not significant but its significance became apparent after its interaction with the tillage system. It means the effect of residue application was greatly modified by the tillage system; because, tillage measures not only induce change in soil C distribution with soil depth but also change in the soil physical conditions, and influenced crop root growth (Luo et al., 2010). Those determine the decomposition of the incorporated crop residues into soil.

Carbon budget and SOC

Regardless of tillage and crop residue management, there was no significant difference of either treatment on maize grain yield (Table 1). However, a significant effect on wheat grain yield of both tillage and residue management was observed after 5 years of starting the experiment (Table 1). The highest grain yield was recorded under CT+ treatment while the lowest grain yield was under NT+ treatment. The wheat grain yield declined under NT+ and this was likely due to crop residues retained on the soil surface that resulted in reduced seed germination and seedling growth. There was a significant interaction between tillage and residue management on wheat growth and grain yield. Meanwhile, the aboveground residues of maize were not significantly different in both tillage and residue management, while there was a significant difference on wheat, moreover the lowest aboveground residues of wheat was recorded under NT+ after 5 years of the experiment. The different output of crop residue provided generally unequal quantities of crop residue C inputs for CT+ and NT+ and removal from CT− and NT−, which would have a direct consequence on SOC stocks. The C budget for each crop was calculated to determine the contribution of residue to the C cycle. Table 2 shows that CT+ and NT+ treatments had C input at least 7500 kg C ha^{-1} y^{-1}, while CT− and NT − had C input no more than 3000 kg C ha^{-1} y^{-1}, regardless of the magnitude of CO_2 emission as soil respiration. This suggests that crop residue management has a strong, positive effect on SOC storage. The C input with crops residue retention resulted in an increase in SOC sequestration rates in CT+ and NT+ of 9350 kg C ha^{-1} y^{-1} and 7050 kg C ha^{-1} y^{-1}, respectively. Whereas with residues removed the CT − and NT− had annual C sequestration rates of 2251 kg C ha^{-1} y^{-1} and 2368 kg C ha^{-1} y^{-1}, the only C input to soil in the both residue treatments was that from roots. The input C from post-harvest crop residues explains why residue retention increased SOC sequestration in both tillage systems. These results confirmed the suggestion of Rasmussen et al. (1998) that increasing crop yield through improved technology would appear beneficial as long as residues are returned to the soil (Rasmussen et al., 1998). While crop residue plays a key role in the SOC pool, till with crop residues retained resulted in slightly

Table 1. Annual crop grain yield and aboveground residue yield affected by tillage and crop residue management (kg ha^{-1} mean ± SD).

		2010–2011		2012–2013	
		Wheat	Maize	Wheat	Maize
Grain yield	CT−	8043.3 ± 817.9	7944.7 ± 692.7	6512.5 ± 92.0	8753.0 ± 850.3
	CT+	8627.4 ± 1276.7	8671.2 ± 337.5	7076.0 ± 113.7	8582.3 ± 705.5
	NT−	7910.8 ± 1183.0	7648.1 ± 294.2	6256.5 ± 36.0	9198.8 ± 757.3
	NT+	7522.7 ± 483.4	8340.3 ± 517.1	3418.5 ± 49.4	8874.7 ± 386.5
Aboveground residues	CT−	8678.7 ± 882.5	8710.9 ± 759.5	9371.7 ± 132.4	8683.3 ± 843.6
	CT+	9309.0 ± 1377.6	9507.4 ± 370.1	10182.5 ± 163.6	8513.9 ± 699.9
	NT−	8535.8 ± 1276.5	8385.7 ± 322.6	9003.2 ± 51.8	9125.5 ± 751.3
	NT+	8117.0 ± 521.6	9144.6 ± 566.9	4919.3 ± 71.1	8804.0 ± 383.4

Notes: CT+: till with crop residues retained; CT−: till with crop residues removed, NT+: no-till with crop residues retained, NT−: no-till with crop residues removed.

Table 2. Annual C budget and 0–20 cm SOC storage affected by tillage and crop residue management (mean ± SD).

	2010–2011					2012–2013				
	C input ($g\ C\ m^{-2}$)	C emission ($g\ C\ m^{-2}$)	Input–mission ($g\ C\ m^{-2}$)	SOC ($g\ kg^{3}$)	SOC stock ($g\ C\ m^{-2}$)	C input ($g\ C\ m^{-2}$)	C emission ($g\ C\ m^{-2}$)	Input–emission ($g\ C\ m^{-2}$)	SOC ($g\ kg^{3}$)	SOC stock ($g\ C\ m^{-2}$)
CT−	264.0 ± 24.4	52.8 ± 2.3	211.1 ± 23.4	15.3 ± 0.7	4107.0 ± 175.7	276.0 ± 12.1	51.0 ± 3.0	225.1 ± 12.1	14.8 ±0.3	3965.6 ± 79.5
CT+	978.1 ± 92.8	63.9 ± 2.5	914.1 ± 90.3	16.1 ± 0.3	4341.4 ± 82.9	1000.2 ± 40.0	65.0 ± 1.2	935.2 ± 40.9	17.8 ± 0.4	4817.0 ± 94.4
NT−	271.3 ± 20.4	45.5 ± 0.7	225.9 ± 19.8	15.1 ± 0.4	5263.1 ± 150.2	288.5 ± 11.5	49.9 ± 1.7	238.6 ± 11.6	14.6 ± 0.2	5085.5 ± 62.2
NT+	953.0 ± 8.6	39.4 ± 0.9	913.6 ± 9.4	16.3 ± 0.2	5695.6 ± 61.0	749.3 ± 10.3	44.1 ± 1.8	705.2 ± 8.8	17.0 ± 0.9	5939.6 ± 312.8

Notes: CT+: till with crop residues retained; CT−: till with crop residues removed, NT+: no-till with crop residues retained, NT−: no-till with crop residues removed. C input for CT+ and NT+ included aboveground crop residues and roots and for CT− and NT− only had roots.

higher SOC sequestration than in no-till with crop residue retained in our experiment. However, if the poor wheat germination and seedling emergence under no-till with residues retained would be improved, then the gap in SOC sequestration between till and no-till will be reduced. Even no-till with residues retention would likely exceed tillage with residues retention in terms of C sequestration because of lower CO_2 emission.

The effects of soil tillage and crop residue management on the storage amount of SOC in the 0–20 cm layer are shown in Table 2. As for SOC, a significant effect of crop residue management on SOC was observed for 3 years after starting this experiment, while no significant effect of tillage was measured. The SOC were significantly lower when crop residue was removed than with crop residue retained, and there was no significant difference between till and no-till. The higher SOC concentration in the surface soil layer of CT+ and CT+ was probably attributed to crop residue being retained. Meanwhile, significant differences were observed on SOC stock of both tillage and crop residue managements. The maximum SOC stock value was in no-till with crop residues' retention (5940 $g\ C\ m^{-2}$), while the minimum stock was in till with crop residue removed (3965 $g\ C\ m^{-2}$). The SOC stock under NT was 1122 $g\ C\ m^{-2}$ greater than that under till; SOC stock with crop residues retained was 853 $g\ C\ m^{-2}$ greater than that with crop residues removed after 5 years of starting the experiment. The greater SOC stock under NT could be mainly due to soil bulk density increase with years.

The results of this experiment are consistent with other studies showing that NT management significantly increased SOC storage in surface soils for multi-cropped systems compared with conventional tillage (Wright & Hons, 2004). Also, the NT with crop residue application would result in distinctly higher carbon sequestration at upper soil than under other tillage and residue combination in a rice–wheat cropping system (Ghimire et al., 2012). The results from this study also indicate that SOC stocks increased with crop residues retained and decreased when crop residue was removed. However, it was reported that although SOC changes in response to management practices could be relatively rapid, it can take up to 10 years for management effects to be discerned (Monreal & Janzen, 1993). The crop residue treatment in this experiment had only been in place for 5 years by the time SOC was measured; therefore, the SOC likely had not reached steady state yet and even larger treatment differences may be discerned in the future.

In general, the greater loss of C emission and the removal of crop residues in the CT soil were accompanied by higher crop growth, productivity, and C inputs. This interaction effect highlights that both CO_2 emission from soil respiration and changes in SOC storage resulting from residue application can be regulated by tillage. Thus, whether a cultivated soil acts as a net source or sink of C is determined by both tillage and crop residue management. As long as all crop residues are retained in the system it will act as a sink; but when they are removed from the system it act as a source, either under no-till or conventional tillage. However, more information is needed on the effects of tillage, crop rotation, residue application, soil variability, and climate change on carbon input and output to further understand the potential C sequestration in the wheat/maize double-cropping system of the NCP.

Conclusions

Our results suggest that the wheat/maize double-cropped system in the NCP presents greater benefits of increased C storage in soil with crop residues' retention in the field than removal from the field under both CT and NT soil; the NT+ also had the smallest CO_2 emission. The annual cumulative CO_2 emission is in the following order CT+ (64.4 g C m^{-2} y^{-1}) > CT− (51.9 g C m^{-2} y^{-1}) > NT− (47.7 g C m^{-2} y^{-1}) > NT+ (41.8 g C m^{-2} y^{-1}); meanwhile, the annual sequestrations in the C budget under CT+ (935 g C m^{-2} y^{-1}) and NT+ (705 g C m^{-2} y^{-1}) were greater than under CT− and NT− (225 g C m^{-2} $y^{-1}$and 238 g C m^{-2} y^{-1}, respectively). After 5 years of experiment, SOC stocks were higher in CT+ and NT+ but lower in CT− and NT− due to crop residue retention or removal.

The winter wheat/summer maize double-cropping system with crop residues retained in the field could increase SOC stock. The no-till with crop residues retained had the smallest CO_2 emission and the biggest SOC stock, although it also had the lowest primary productivity matter which resulted from poor germination and seedling in this research that can be improved by effective agronomy measures. Since NT+, an alternative tillage practice, can decrease CO2 emission and increase SOC stock, this practice could help to mitigate greenhouse gases emission and to enhance SOC sequestration in the annual winter wheat/summer maize double-cropping system of the NCP.

Disclosure statement

No potential conflict of interest was reported by the authors.

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