Response of Carbon Dioxide Emissions to Warming under No-Till and Conventional Till Systems

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Differences in soil organic carbon (SOC) distribution, water holding capacity, and soil temperature between no-tillage (NT) and conventional tillage (CT) systems can result in different soil CO_2 emissions which could affect global warming but few studies have addressed this concern. An open warming experiment was conducted in situ by infrared heating of long-term conservation tillage management plots in North China Plain (NCP) to determine the effects of warming on soil CO_2 emissions and the correlation to changes in soil temperature and moisture. This experiment was conducted from February 2010 to June 2012 and included CT and NT plots with and without warming. Warming treatment increased soil temperature by 2.1 and 1.5°C, and decreased volumetric soil-water content by 14 and 10% for CT and NT systems, respectively. Soil CO_2 emissions tended to decrease with time in CT while it consistently increased in NT system over the three wheat seasons and two maize seasons under warming. Our results suggest that differences in soil temperature and soil moisture between the two tillage systems could be enlarged with time by warming, and the potential exist for warming to promote more soil CO_2 emission under NT relative to CT. There is a need to consider the differences in response to global warming between these two tillage systems to properly assess the benefits of NT to C sequestration.

Abbreviations: AGB, aboveground biomass; CN, conventional tillage without warming; CT, conventional tillage, CW, conventional tillage with warming; NCP, North China Plain; NN, no-tillage without warming; NT, no-tillage; NW, no-tillage with warming; SOC, soil organic carbon.

Carbon dioxide efflux from soil is one of the major components of the ecosystem C cycle. Cropland soil has a huge potential to store C (Lal, 2004). With increasing concerns of climate change, soil C sequestration is an important strategy to mitigate CO_2 emissions. Conservation tillage is one of the recommended management practices to increase soil organic C storage in cropland and reduce CO_2 emissions. Numerous studies have found enhanced C sequestration under conservation tillage systems (de Moraes Sá et al., 2013; Kumar et al., 2012; West and Post, 2002) especially in the soil surface layer (Baker et al., 2007; Luo et al., 2010; Hou et al., 2012a). In many less developed regions, such as the NCP (Hou et al., 2012a), differences in C sequestration and SOC pools in the soil surface between CT and NT are enhanced by the fact that the conventional practice is to completely remove plant residues from fields for domestic use. In contrasts, a typical NT system retains residue on the surface thereby confounding inherent differences between tillage systems with residue management differences. Generally, soil CO_2 emissions are considered to be lower under NT management relative to CT management (Dendooven et al., 2012; Ussiri and Lal, 2009). Thus, long-term NT management is thought to partly offset the global warming potential (Piva et al., 2012; Six et al., 2004). Previous studies almost all focus on the role

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of NT system on mitigating climate change, but there are few reports dealing with the influence of climate change on C cycling under NT.

As a soil C loss process, CO_2 emission is important to soil C cycling. The rates of soil respiration are mainly controlled by soil temperature (Rustad et al., 2001), soil moisture (Xu and Qi, 2001; Zhou et al., 2006), and substrate availability (Zhu and Cheng, 2011). The main changes induced by tillage and residue management between CT and NT include soil moisture (Alvarez and Steinbach, 2009), soil temperature (Ussiri and Lal, 2009), soil physical properties (Fernández-Ugalde et al., 2009), and the distribution of SOC (Baker et al., 2007, Hou et al., 2012a). The response of soil CO_2 emission to warming might differ under these two management systems. Mineralization of SOC is a temperature-dependent process and lots of studies have observed soil respiration increase with warming (Rustad et al., 2001; Zhou et al., 2007). Rustad et al. (2001) reviewed the global results of warming experiments and concluded that 9 of 13 studies showed significantly greater soil respiration with warming. The effects of warming on soil temperature changes might not be equal between the two tillage systems depending on the residue cover. Second, influence of soil moisture on respiration is complex and responses of respiration are variable depending on soil moisture (Wan et al., 2002). Suseela et al. (2012) combined four levels of warming and three levels of precipitation and found that soil heterotrophic respiration decreased sharply when soil moisture dropped below 15% or exceeded 26% in grassland. Previous studies considered that NT had a better water-holding capacity relative to CT and this could also result in different responses of soil moisture under warming between the two tillage systems. Third, SOC pool and its composition are also significantly influenced by the conversion from CT to NT, especially in the soil surface layer where SOC pools should be more sensitive to climate change. Luo et al. (2010) reviewed 69 paired CT–NT experiments and concluded that the increase in SOC under NT was mainly in the surface 0 to 10 cm relative to CT. Labile organic C is also significantly greater in NT than CT (Chen et al., 2009) in the surface layer. However, Hou et al. (2012a) found that CT stored more SOC than NT in the subsurface. Based on previous studies, labile organic C is important in sustaining the positive effect of warming on soil respiration (Hartley et al., 2007). So the response of SOC decomposition processes in the soil surface layer could be different between these two tillage systems.

Many long-term studies have been conducted to investigate the response of soil CO_2 emissions to warming with conflicting results. Zhou et al. (2006) observed a positive response of soil CO_2 emissions to warming, whereas De Boeck et al. (2007) and Li et al. (2013) observed neutral response and Liu et al. (2008) and Verburg et al. (2005) observed negative responses. Soil warming increased respiration under both bare soil and wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) cropland (Hartley et al., 2007). Research addressing the combined effects of warming and tillage/residue management systems on soil CO_2 emission is limited. Better understanding of the influence of temperature on C cycling could help us better estimate the contribution and response of tillage and residue management practices to climate change. Therefore, there is a need to evaluate the influence of warming on soil CO_2 emission under a typical NT system in which residue is retained on the surface as compared to a typical CT system in which residue is removed. The objectives of this study were (i) to determine the influence of warming on soil temperature and soil moisture under both CT and NT treatments; (ii) to quantify the responses of soil CO_2 emission to temperature increase. These were determined by artificially warming long-term tillage management plots in situ, in the NCP during the period of February 2010 to June 2012. A previous study (Hou et al., 2012a) reported significant increases in SOC content and pool in the NT surface soil (0–10 cm) relative to CT (from 2003–2009) in these plots.

MATERIALS AND METHODS

Site Description

This study was conducted on long-term (since 2003) conservation tillage fields at Yucheng Comprehensive Experiment Station of China Academy of Science (36°50′ N,116°34′ E, elevation is 20 m). These experimental fields were established as a bilateral project on conservation tillage between the USDA-ARS National Sedimentation Laboratory and the Institute of Geographic Sciences and Natural Resources Research (IGSNRR) of Chinese Academy of Sciences in the NCP. Details of the experimental design and plot maintenance can be found in Hou et al. (2012a, 2012b). It is located in a temperate semiarid climate, with annual mean temperature of 13.4°C and mean precipitation of 567 mm during the past 25 yr (from 1985–2009). Approximately 70% of annual precipitation occurs between June and September. The soil is classified as a calcaric Fluvisols according to the FAO-UNESCO system, and surface soil texture is silt loam (sand, 12%; silt, 66%; clay, 22%) according to the USDA classification system. The surface soil pH is 8.6. Winter wheat and summer double cropping is predominant in the NCP. Depending on precipitation, winter wheat is irrigated using local ground water.

Winter wheat was seeded in early October and harvested in early June. Winter wheat was irrigated two times each season between March to May (70–80 mm each time). For CT system, after maize harvest, the standing stubble of each treatment was cut to about 10 cm and all residues were removed. The CT plots were tilled with a rotary tiller to a depth of about 15 cm which fully incorporated standing stubble into the soil before winter wheat planting. For NT, wheat and maize residues were chopped into pieces (about 5 cm length) by hand and retained on the soil surface with the remaining standing stubble about 10 cm height. The residue mass retained on the surface for NT was about 10 Mg ha^{-1} yr^{-1} with 4 Mg ha^{-1} yr^{-1} of wheat and 6 Mg ha^{-1} yr^{-1} of maize.

In this experiment, the total N application rate for NT and CT treatments was 285 kg N ha^{-1} yr^{-1} for wheat and maize. Part or all of the total N, along with P and K, was applied as compound fertilizer which was an inorganic chemical fertilizer containing N (as urea), P (as P_2O_5), and K (as K_2O) as 12:19:13 with application rates of 116 kg N ha^{-1}, 178 kg P ha^{-1}, and 122 kg K ha^{-1} each year. For CT system, the remaining 169 kg N ha^{-1} yr^{-1} was applied as urea. For NT system, the remaining 122 kg N ha^{-1} yr^{-1} of total N was applied as a single urea application and 47 kg N ha^{-1} yr^{-1} as maize residue containing 0.8% N. All other management procedures were identical for the two systems with herbicide (2,4-D butylate) and insecticide (40% dimethoate) spraying in May.

Experimental Design and Management

In this study, a complete randomized block design was used with tillage system as the primary factor and warming as the secondary factor based on the original NT and CT plots. Sixteen 2 by 2 m blocks, four treatments (conventional tillage with and without warming, CW and CN, respectively; no-tillage with and without warming, NW and NN, respectively) replicated four times, were arranged in a 4 by 4 matrix (Fig. 1). All treatments were maintained on the same plots since 2003, each plot was 7.5 m width by 40 m length (300 m^2). There was a 5-m border between adjacent blocks and at least 10 m between plots. The warmed block in each pair was continuously heated using MSR-2420 infrared heater (Kalglo Electronics Inc, Bethlehem, PA) since 4 Feb. 2010. The infrared heater was suspended 3 m aboveground, and did not generate any visible light to influence crop phenology (Sherry et al., 2007). The infrared heater had an average radiation output of about 92 W m^{-2} (details are provided in Hou et al., 2012b). The control (without warming) blocks were the same shape and size as the warmed plots and included a "dummy" infrared heater suspended 3 m aboveground to stimulate shading effects of the infrared heater.

Measurement Protocols

To measure soil respiration (SR), a PVC collar (80 cm^2 in area and 5 cm in height) was inserted 2 to 3 cm into soil at the center of each subplot. For NT system (including NN and NW treatments), the position of each collar was permanent. For CT system (including CN and CW treatments), collars were removed before tillage and inserted at the same position after tillage. At least 1 d before the measurement, living plants inside the collars were removed by hand to exclude aboveground plant respiration. Soil respirations were measured for up to 180 s between 0900 to 1200 h one or two times each month during the growing season using a LI-COR 6400 (Li-Cor, Lincoln, NE) portable photosynthesis system.

Soil temperature (T) at 5-cm depth and volumetric soil moisture (θ) at 0- to 10-cm depth were monitored by PT 100 thermocouples and FDS100 soil moisture sensors (Unism Technologies Incorporated, Beijing), respectively. Two pairs of thermocouples and moisture sensors were arranged symmetrically and vertically to the infrared heater or "dummy" with 1 m distance between the pair in each plot and connected to a datalogger (shown in Fig. 1). Temperature and moisture measurements were taken every 10 min.

The cumulative soil CO_2 emissions by year, and season of maize or wheat, were calculated from daily soil respiration multiplied by the number of days between measurements (Bremer et al., 1998; Zhou et al., 2006).

Statistical Analysis

The main and interactive effects of warming, growing season, and tillage system on soil respiration, soil temperature and soil moisture were determined with a repeated measures ANOVA (RM-ANOVA) using SPSS 11.5 for Windows (SPSS Inc., Champaign, IL).

In this study, to estimate the effects of warming on CO_2 emission, each year was separated into wheat and maize growing seasons based on local cropping system. The soil temperature, soil moisture, and soil CO_2 emissions were analyzed by three-

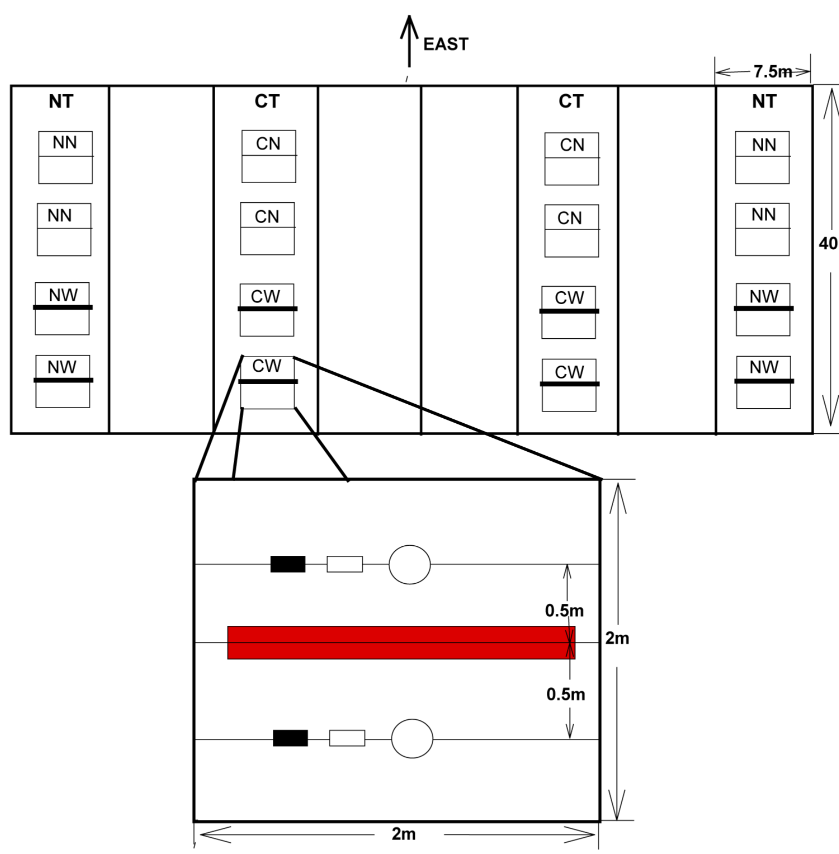

Fig. 1. Layout of the experimental design along with instrumentation of warming treatments. NT and CT indicate no-till and conventional tillage blocks, respectively. In each plot, the thin line indicates the position of the "dummy" infrared heater for control plots while the thick line indicates the position of the real infrared heater in warmed plots. In the cutout, the red rectangular area is the infrared heater, the solid rectangle, open rectangle, and open circle indicate locations of thermocouples, moisture sensors, and soil respiration instruments, respectively.

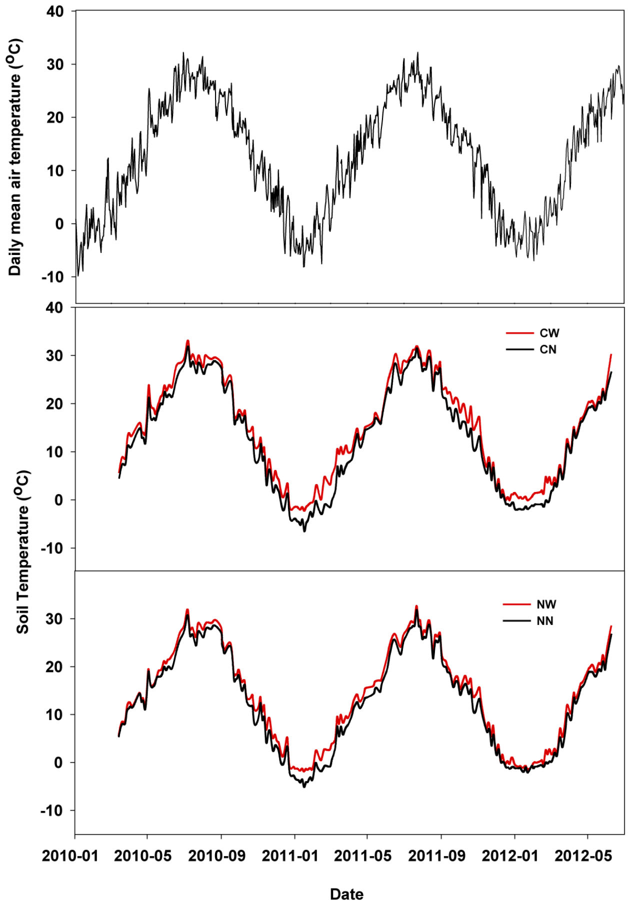

Fig. 2. Daily mean air temperature which was recorded by a weather station about 100 m from the study site, soil temperature for the four treatments (CW and CN stand for conventional tillage with warming and without warming, respectively; NW and NN stand for no-tillage with or without warming, respectively) from February 2010 to June 2012. Warmed plots (CW and NW) are in red lines, and control plots in black lines. The arrows with W and M indicate the wheat season (W) and maize season (M) in the control plots for no-till and conventional tillage treatments from 2010 to 2012.

way ANOVA for changes induced by warming. Wheat season extended from planting in early October to harvest in June, and maize season from planting after the wheat harvest to maize harvest in early October. Details about phenological stages can be found in Hou et al. (2012b).

RESULTS

Soil Temperature and Moisture

Soil temperatures varied with time (Fig. 2). Mean soil temperatures at the depth of 5 cm tended to be higher under CN than NN treatment with a 12.2 and 11.8°C average, respectively, during the study from March 2010 to June 2012. For CW and NW treatments, soil surfaces were significantly ($P < 0.05$) warmer relative to control plots (CN and NN) with average temperature increases of 2.1°C for CT and 1.5°C for NT system, respectively (Table 1). The highest soil temperatures were observed in CW treatment during the three wheat seasons and two maize seasons. As a result of the greater temperature increase in CT system relative to NT, the difference in soil temperature between CT and NT was significantly enlarged from 0.3 (CN vs. NN) to 0.9°C (CW vs. NW) ($P < 0.05$) by warming (Table 2). The increased soil temperatures due to warming tended to be greater for wheat relative to maize seasons with 2.2 and 1.9°C increases in CT, and increases of 1.6 and 1.4°C, respectively, in NT system (Table 1). Soil temperature was significantly affected by warming and year for wheat and maize seasons but not affected by their interactions (W×Y) (Table 3) or tillage system (T).

In contrasts to soil temperature, volumetric soil moisture at 0 to 10-cm depth fluctuated greatly among the seasons by irrigation and precipitation additions (Fig. 3). Usually the lowest soil moisture was observed in June, and the highest in August which is the monsoon season in this region. Throughout the study, warming significantly ($P < 0.001$) decreased the soil moisture of NT and CT treatments (Table 2), with 0.026 and 0.019 $m^3\ m^{-3}$ decreases, respectively. The average soil moisture contents during the study period were significantly ($P = 0.020$) higher in NN than CN treatments with means of 0.193 and 0.188 $m^3\ m^{-3}$, respectively, and also higher in NW than CW ($P < 0.001$) with 0.175 and 0.161 $m^3\ m^{-3}$ means, respectively. The highest soil moisture was always observed in NN treatment during the five growing seasons. The difference between NT and CT system was significantly ($P < 0.001$) enlarged by 0.005 (NN vs. CN) for control and 0.014 $m^3\ m^{-3}$ (NW vs. CW) for warmed treatments. Similar with soil temperature, changes in soil moisture over the three growing seasons were significantly lower under NT than CT (Table 1) ($P < 0.001$). For NT system, warming significantly decreased soil moisture in the wheat seasons, however there was no main effect for maize season (Table

Table 1. Mean soil temperatures (°C) at 5-cm depth in the four treatments (trt) (NW and NN stand for no-tillage with or without warming, respectively; CW and CN stand for conventional tillage with warming and without warming, respectively) during the five growing seasons from 2010 to 2012. Changes in soil temperature, ΔT, within tillage treatments (NW vs. NN, CW vs. CN) and between tillage treatments (NW vs. CW, NN vs. CN) were also calculated. Different letters on means indicate significant differences between treatments within each column ($P < 0.05$).

Trt	2010		2011		2012	2010–2012	ΔT	ΔT
	Wheat	Maize	Wheat	Maize	Wheat		Within	Between
NW	11.6(0.6)†a	25.6(1.3)ab	7.8(0.5)a	24.5(1.4)b	8.7(0.6)ab	13.5(0.9)a	1.5 $P < 0.01$	0.9 $P = 0.132$
NN	10.1(0.8)b	24.2(1.3)c	5.7(0.6)b	23.3(1.4)b	7.4(0.7)b	11.8(1.0)b		0.3 $P = 0.583$
CW	12.3(0.8)a	26.2(1.5)a	8.3(0.9)a	26.3(1.5)a	9.7(0.7)a	14.3(1.1)a	2.1 $P < 0.01$	
CN	10.2(0.6)b	24.6(1.0)abc	5.6(0.6)b	24.3(1.2)b	7.9(0.6)ab	12.2(0.8)b		

† Standard error shown in parentheses.

Table 2. Mean soil moisture (% by volume) at 0- to 10-cm depth in the four treatments (trt) (NW and NN stand for no-tillage with or without warming, respectively; CW and CN stand for conventional tillage with warming and without warming, respectively) during the five growing seasons from 2010 to 2012. Changes in soil moisture, Δθ, within tillage treatments (NW vs. NN, CW vs. CN) and between tillage treatments (NW vs. CW, NN vs. CN) were also calculated. Different letters on means indicate significant differences between treatments within each column ($P < 0.05$). Negative sign indicates a decrease in soil moisture.

Trt	2010		2011		2012	2010–2012	Δθ Within	Δθ Between
	Wheat	Maize	Wheat	Maize	Wheat			
NW	17.0(2.6)†b	24.5(2.3)ab	17.3(1.5)b	23.1(2.4)a	13.2(1.6)b	17.5(2.1)c	−1.9 $P < 0.001$	−1.4 $P < 0.001$
NN	19.0(1.8)a	26.0(1.3)a	19.2(0.9)a	24.3(2.4)a	15.3(1.7)a	19.3(1.6)a		−0.5 $P = 0.02$
CW	15.4(0.8)b	22.9(2.5)b	15.0(0.9)c	21.0(1.5)b	13.0(0.9)b	16.1(1.3)d	−2.6 $P < 0.001$	
CN	18.4(1.5)a	25.1(2.0)a	17.9(1.6)b	23.0(1.9)a	15.6(0.9)a	18.8(1.4)b		

† Standard error was shown in parentheses.

2). For CT system, warming significantly ($P < 0.05$) decreased soil moisture for both wheat and maize seasons, while significant effects of warming on soil moisture were only observed in wheat season for NT system. As factors, warming and year significantly affected soil moisture in wheat season, but not their interactions (W×Y) (Table 3) or tillage system (T).

Soil Respiration

Soil respiration of control and warmed plots in the three growing seasons ranged from 9.75 to 0.35 μmol m^{-2} s^{-1} (both in 2010). The highest CO_2 effluxes of 2010 and 2011 were both recorded in July, while the lowest were in March and November, respectively (Fig. 4). Soil respiration followed crop growth patterns with peaks in the middle of each wheat and maize season.

There was no significant effect of warming on soil respiration for wheat and maize seasons or its interactions with tillage (W×T), year (W×Y), or their combination (Table 3). Soil respiration during wheat growing seasons was significantly affected by tillage ($P = 0.008$). Over the three wheat growing seasons, soil respiration tended to be stimulated under CT (including CN and CW treatments) relative to NT (NN and NW). Significant season effects on soil respiration were observed for both wheat ($P = 0.009$) and maize ($P = 0.048$) seasons.

Between warmed and control plots, there was a similar temporal pattern in soil respiration from March to June for each wheat season. A "time lag" was observed in that soil respiration was stimulated earlier in warmed plots than control plots during the wheat season for both CT and NT systems (Fig. 4). The highest soil respiration for warmed plots usually occurred at the end of April or the beginning of May, which were all earlier than the peak response for control plots for both NT and CT systems. The time lag had a consistent pattern during the three wheat seasons.

Estimating the Annual Soil Carbon Dioxide Emission

Effects of warming on cumulative soil CO_2 emission were different for the two tillage systems (Table 4). In the three wheat and two maize growing seasons, cumulative soil CO_2 emissions were generally ranked: CN > CW > NW > NN. The exception was the maize season of 2011 in which NW had the greatest cumulative CO_2 emission. Warming decreased annual soil CO_2 emission by 2.7% on average for CT, and increased 3.9% for NT system on average. The warming effect on both wheat and maize growing seasons were similar to the annual total CO_2 emissions in that CT had reduced emissions while NT emissions were stimulated by warming.

Between the two tillage systems, CT tended to have more soil CO_2 emission than NT during the wheat and maize seasons for both warmed and control treatments with the exception for the warmed maize plots in 2011. No-till reduced CO_2 by 11.7% without warming relative to CN, but only by 4.7% with warming for NW and CW (Table 4).

DISCUSSION

Microclimate Change under Warming

Previous reports (Dendooven et al., 2012; Shinners et al., 1994) observed higher soil temperature and lower soil moisture under CT than NT due to differences in residue retention on the soil surface. Dendooven et al. (2012) studied a long-term (since 1991) tillage experiment and found soil temperature was 1.8°C higher under CT without residue cover than NT with residue cover. Crop residue left on the soil surface insolates the soil from increased atmosphere temperatures and reflects solar radiation (Shinners et al., 1994). This study found a similar trend between NN and CN treatments with the CN soil being 0.5°C warmer on average than the NN (Table 1). For warmed plots, warming induced significantly ($P < 0.001$) greater temperature increases in CT (CW) than NT (NW) (Fig. 3).

Warming tends to reduce the soil water content. Wall et al. (2011) reported that a 3°C temperature increase by infrared warming decreased the volumetric soil-water content by 14%

Table 3. Results (P values) of three-way ANOVA on the effects of warming (W), tillage system (T), year (Y) and their interactions on soil respiration (SR), soil temperature (ST), and soil moisture (θ) in wheat and maize growing seasons.

Source of variance	Wheat			Maize		
	SR	ST	θ	SR	ST	θ
W	0.498	<0.001	0.005	0.757	<0.001	0.069
T	0.008	0.064	0.656	0.808	0.072	0.412
Y	0.009	<0.001	<0.001	0.048	0.019	0.082
W×T	0.441	0.240	0.548	0.637	0.262	0.993
W×Y	0.994	0.129	0.979	0.862	0.302	0.860
T×Y	0.614	0.133	0.656	0.563	0.210	0.913
W×T×Y	0.993	0.522	0.974	0.998	0.156	0.971

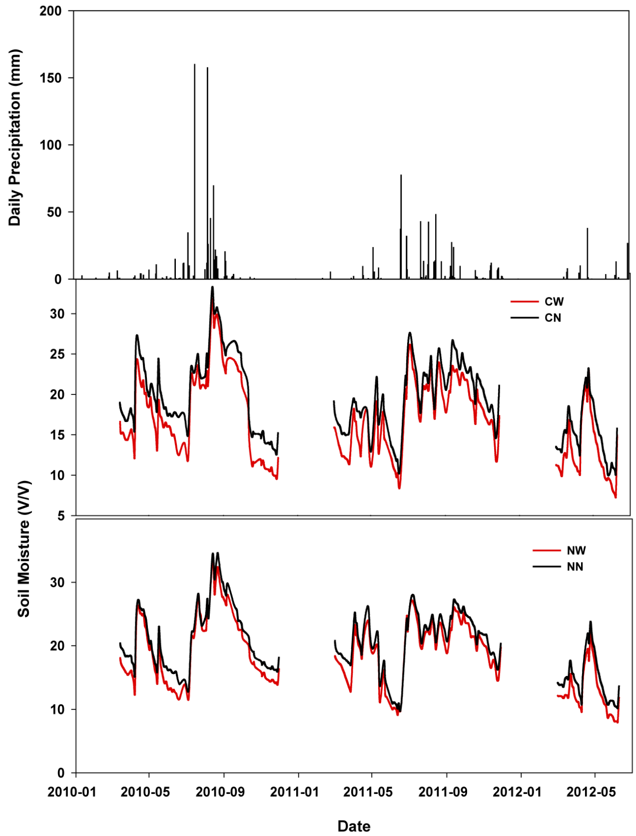

Fig. 3. Daily precipitation which was recorded by a weather station about 100 m from the study site, soil volumetric water content for the four treatments (CW and CN stand for conventional tillage with warming and without warming, respectively; NW and NN stand for no-tillage with or without warming, respectively). Warmed plots (CW and NW) are in red lines, and control plots in black lines. Soil water was frozen from December to February in the studied region and therefore not recorded. The arrows with W and M indicate the wheat season (W) and maize season (M) in the control plots for no-till and conventional tillage treatments from March 2010 to June 2012.

in wheat season over control plots. In this study, the average reduction in volumetric soil-water content by warming was 14 and 10% for CT and NT systems, respectively (Table 1). Retaining crop residue on the surface can form a barrier against evaporation and prevent runoff (Shaver et al., 2002). The soil moisture response to warming for CT and NT in this study was consistent with literature in that residue retention on the soil surface under NT (NW) reduced the warming-induced decrease in soil moisture compared to CT (CW). The average difference between CN and NN in soil moisture over the whole study period was 0.005 $m^3 m^{-3}$ and 0.014 $m^3 m^{-3}$, respectively for warmed treatments (CW and NW) (Table 1). This result indicated that warming-induced loss of moisture would be greater in CT system in a future warmer world. Maintaining crop residue on the soil surface could partly offset the warming-induced negative effects on soil moisture and temperature.

The Effects of Warming on Soil Respiration under Two Tillage Systems

This study has, for the first time to our knowledge, quantified the effect of warming-induced changes on soil respiration and CO_2 emissions under contrasting tillage/residue management systems. Different from most previous field-scale studies that show warming significantly increased soil respiration (Rustad et al., 2001), warming-induced changes on soil respiration under this wheat–maize irrigated cropland was not significant for either CT or NT system. Zhou et al. (2006) also found the effect of warming on grassland soil respiration was not significant in some years.

In this study, two factors might limit the response of soil respiration to warming. For one, there was a stable water supply from irrigation relative to other ecosystems. Wan et al. (2007) considered that reduction in soil moisture by warming caused a change in the energy balance. Higher soil moisture leads to more energy dissipation as latent heat (for evapotranspiration) and less soil heat flux (for soil warming) (Liu et al., 2008). A significant negative relationship was observed in this study between the increase in soil temperature and warming-induced decrease in soil moisture. The relatively ample soil water supply by irrigation could lessen soil temperature increases and thereby lessen warming-stimulated soil respiration changes. The other reason could be the lower SOC content at the surface of CT plots which could result in lower soil respiration response to warming (Luo et al., 2001). Zhou et al. (2006) attributed the lower response in soil respiration to warming to lower SOC content in grassland than forest. In this study, the high SOC content in the NT surface layer was still $<1.5\%$ (Hou et al., 2012a) which was lower than grassland and forest ecosystems studied by Zhou et al. (2006). This study revealed a time lag in soil respiration increase for control plots compared to warmed plots during wheat seasons from March to June. Given the relation between changes in soil respiration and changes in soil moisture, this time lag could simply be a response of soil moisture decreasing sooner under warmed plots than control plots which would have been greater if plots had not been irrigated. Luo et al., (2001) observed a similar short-term pattern in soil respiration in a grassland warming experiment in the United States. These authors explained it as the acclimation of decomposer organisms to the warmed soil. In this study, advanced phenology (Hou et al., 2012b) could be the main reason for the time lag. It is clear that soil respiration is strongly affected by root-derived CO_2 efflux especially during the growing season (Kuzyakov, 2006). Generally, the root-derived soil respiration account for 30 to 40% of the total soil CO_2 efflux (Li et al., 2013; Subke et al., 2006; Zhou et al., 2007). In wheat season, the pattern of root-derived CO_2 efflux changed following wheat root development and root-derived CO_2 efflux began to decrease when wheat turned to the reproductive period (Huang et al., 2012). The anthesis periods for warmed and control plots in this study are shown in Fig. 4, which generally correspond with the peaks in soil respiration during the wheat seasons. Hou et al. (2012b) reported that warming advanced the wheat flowering period 6 and 11 d in 2010 and 2011, respectively. In 2012, the advanced days of warmed plots were 9 on average relative to control plots (unpublished data, 2012). This shift in phenological periods could result in the root-derived CO_2

efflux peaking earlier in warmed plots relative to control plots.

Warming and Soil Emission under Two Tillage Systems

Relative to CT system, NT has been reported to reduce soil CO_2 emissions (Fuentes et al., 2012). Ussiri and Lal (2009) suggested that mechanical tillage aerates the soil, breaks up aggregates, and incorporates crop residue into the soil. The enhanced contact between microorganisms and crop residue accelerates the decomposition of SOC thereby increasing soil CO_2 emissions. Since NT maintains residue on the surface, the reduced contact with soil and lower soil temperatures would reduce the decomposition of SOC relative to CT. In this study, a similar trend was observed in that the cumulative CO_2 emissions over the three observation years was 11.7% lower for NT than CT in control plots, and the differences between them were 104 and 72 g CO_2–C m^{-2} yr^{-1} in 2010 and 2011, respectively (Table 4).

However, in this study, NT and CT systems showed contrasting responses to the effects of warming on soil CO_2 emissions. Carbon dioxide emissions under NT were increased by warming during the three wheat seasons and two maize seasons (Fig. 5) while there were negative effects of warming on the CO_2 emission on CT systems. This resulted in the cumulative CO_2 emissions being only 4.7% lower for NW than CW on average during the 3 yr, and the differences decreased to 54 and 18 g CO_2–C m^{-2} yr^{-1} in 2010 and 2011, respectively (Table 4).

The response of soil CO_2 emissions to warming could be affected by soil moisture (Poll et al., 2013; Shaver et al., 2002).

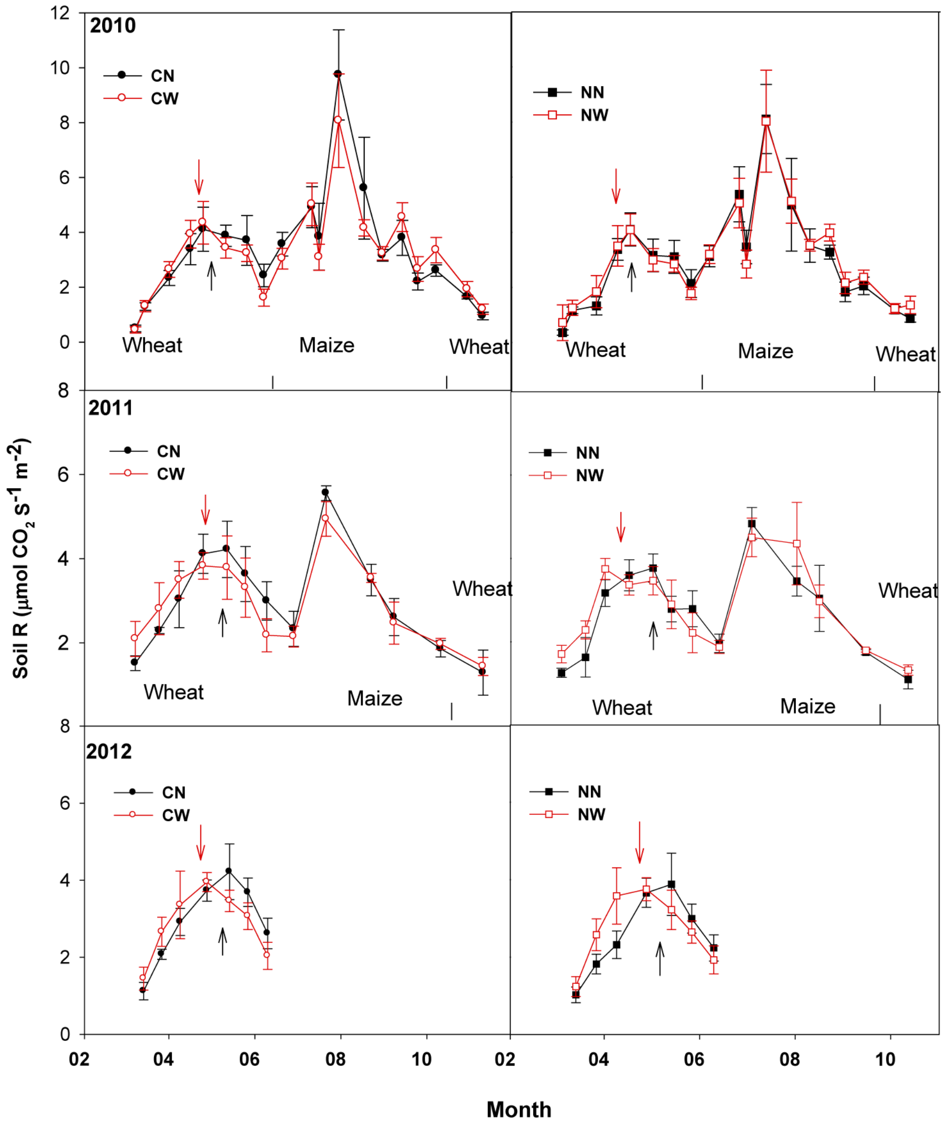

Fig. 4. Seasonal variations in overall means of soil respiration during three growing seasons under the four treatments: CW (conventional tillage with warming, red open circles), CN (conventional tillage without warming, black solid circles), NW (no-tillage with warming, red open squares) and NN (no-tillage without warming, black solid squares). There is only wheat season data in 2012. Arrows indicate the anthesis dates of wheat for warmed (in red) and control plots (in black), respectively.

According to Suseela et al. (2012), soil respiration is sensitive to soil moisture, higher soil water contents result in greater CO_2 fluxes. These two critical factors interact in that warming decreases soil moisture by increasing evapotranspiration. Previous studies considered that low soil moisture would slow the diffusion of labile substrate and reduce the activity of exo-enzymes needed for the decomposition of organic matter (Stark

Table 4. Cumulative soil CO_2 emissions (g CO_2–C m^{-2} yr^{-1}) for wheat and maize growing seasons under conventional tillage without warming (CN), conventional tillage with warming (CW), no-tillage without warming (NN) and no-tillage with warming (NW) treatments (trt). Different letters on means indicate significant differences between treatments within each column ($P < 0.05$).†

Trt	2010		2011		2012	Annual		
	Wheat	Maize	Wheat	Maize	Wheat	2010	2011	2012
CN	394 ± 31a	531 ± 47	425 ± 28a	355 ± 35	313 ± 21	925 ± 75	781 ± 62	313 ± 21
CW	390 ± 26a	505 ± 33	417 ± 24ab	344 ± 23	307 ± 27	895 ± 57	761 ± 48	307 ± 27
NN	332 ± 29b	489 ± 44	369 ± 27b	340 ± 30	279 ± 38	821 ± 58	709 ± 56	279 ± 38
NW	343 ± 20b	499 ± 37	381 ± 25ab	362 ± 45	291 ± 27	841 ± 52	743 ± 68	291 ± 27

† Data shown as mean ± SE.

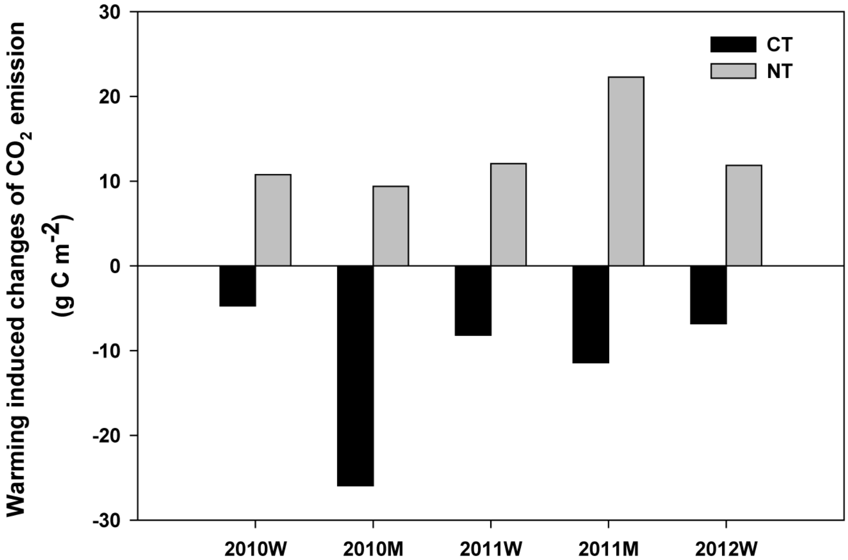

Fig. 5. Warming induced changes in CO_2 emissions during three wheat seasons (W) and two maize seasons (M) under CT and NT systems from 2010 to 2012. Wheat season and maize season indicated by W and M, respectively.

and Firestone, 1995), as well as reduced microbial respiration (Liu et al., 2008). These reports partly explain the contrasting responses of soil CO_2 emission during the five growing seasons (three wheat seasons and two maize seasons) between CT and NT systems in this study, in which significantly ($P < 0.05$) lower soil moisture and higher temperatures were observed in the CT system than NT (Tables 1 and 2). The effects of warming on soil CO_2 emission are the balance of an autotrophic component (autotrophic respiration, Ra) and a heterotrophic component (heterotrophic respiration, Rh) (Kuzyakov, 2006; Subke et al., 2006). The contrasting results in this study might come from the different responses of Ra and Rh to warming under the two tillage systems.

Li et al. (2013) found that warming did not change the soil respiration significantly on grassland during their 3-yr study, but warming significantly decreased Ra by 29% and increased Rh by 22% on average. For root-derived CO_2, field studies have found a significantly positive relationship between Ra and aboveground biomass (AGB) (Li et al., 2013; Yan et al., 2010). In this study, warming significantly stimulated wheat AGB from 10 to 20% in 2010 and 2011 (Hou et al., 2012b), which indicates that warming could stimulate the Ra in both NT and CT treatments during the wheat seasons.

For Rh, the different SOC distribution and quality between these tillage systems (Baker et al., 2007; Machado et al., 2003) could result in differences in SOM mineralization. The SOC pool was stored primarily in the surface soil layer and had greater labile organic C (Chen et al., 2009) in NT system, while CT stored more SOC in the deeper soil layers (Luo et al., 2010). Machado et al. (2003) used ^{13}C as a tracer to compare the content of recent C accumulation under NT and CT after 21 yr in Brazil, and found the recent C in NT accounted for 98% of SOC but only 60% for CT in the 0- to 5-cm soil layer. Past research reported that warming-induced increases in soil CO_2 emissions were maintained by substrates and would gradually dampen with depletion of the labile SOC in continuous soil-warming experiments (Kirschbaum, 2004; Hartley and Ineson, 2008). Frey et al. (2008) found that the microbial biomass decreased with the exhaustion of substrate after 12 yr of 5°C warming. Considering that the soil surface layer is more sensitive to environmental change than deeper soil layers, SOC stored in the surface might be decomposed faster. Thus, the warming-induced CO_2 emission could become greater under NT relative to a CT system as the SOC pool was depleted by a future warmer world if other factors such as soil moisture were maintained equal by irrigation. Future studies are needed to better understand the effects of warming on the Ra and Rh under NT and CT systems.

The stability of soil C in the soil surface layer might determine whether NT could continue to sequestrate C or not. Given that NT tends to sequester SOC in the soil surface while CT sequesters more in the deeper soil layers (Hou et al., 2012a), NT could potentially have greater CO_2 emission under warming. In such case, the advantage of NT for C sequestration relative to CT could decrease under warming. However, it should be noted that NT had 4.7% lower CO_2 emissions than CT when warmed in this study due to impacts of warming on other soil properties, for example, T and θ. Given the potential for managing these other properties and continued increase in surface SOC pool under NT, there might be a potential risk of the soil C balance changing under NT in a future warmer world. The impact of NT on the mitigation on climate change might need to consider this effect and the effect of NT CO_2 emissions on climate change.

CONCLUSIONS

This study quantified the differential effects of warming on soil properties (soil temperature and soil moisture) and soil CO_2 emission response under CT and NT systems and considered their inherent differences in soil moisture and SOC distributions. These results documented that the influence of warming on CT and NT systems are not equivalent and soil emissions under NT increased to a greater extent than under CT when temperature increased. These findings highlight the need to incorporate these contrasting responses to warming between CT and NT systems in assessments of C sequestration and CO_2 emissions.

Combining the advantages of CT on SOC sequestration in the whole soil profile (0–60 cm) (Hou et al., 2012a), the acclimation of crops to temperature increases (Hou et al., 2012b) and CO_2 emission in the present study, CT may be a better tillage system relative to NT with regards to global warming in the NCP. However, there are still further studies needed regarding responses of soil water management and nutrient use efficiency under global climate change which are important to selecting the best tillage and residue management system for the NCP and other regions of the world. In addition, future studies should address the temporal dynamics in C sequestration and CO_2 emissions for these tillage systems under different residue management systems such as alternating seasons and rates of residue retention.

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