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RESEARCH ARTICLE

Effect of experimental warming on soil respiration under conventional tillage and no-tillage farmland in the North China Plain

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Abstract

Understanding the response of soil respiration to global warming in agro-ecosystem is crucial for simulating terrestrial carbon (C) cycle. We conducted an infrared warming experiment under conventional tillage (CT) and no-tillage (NT) farmland for winter wheat and summer maize rotation system in North China Plain (NCP). Treatments include CT with and without warming (CTW and CTN), NT with and without warming (NTW and NTN). The results indicated that warming had no significant effect on soil moisture in irrigated farmland of NCP (P>0.05). The elevated average soil temperature of 1.1–1.6°C in crop growing periods could increase annual soil CO_2 emission by 10.3% in CT filed (P>0.05), but significantly increase it by 12.7% in NT field (P<0.05), respectively. The disturbances such as plowing, irrigation and precipitation resulted in the obvious soil CO_2 emission peaks, which contributed 36.6–40.8% of annual soil cumulative CO_2 emission. Warming would enhance these soil CO_2 emission peaks; it might be associated with the warming-induced increase of autotrophic respiration and heterotrophic respiration. Compared with un-warming treatments, dissolved organic carbon (DOC) and soil microbial biomass carbon (MBC) in warming treatments were significantly increased by 11.6–23.4 and 12.9–23.6%, respectively, indicating that the positive responses of DOC and MBC to warming in both of two tillage systems. Our study highlights that climate warming may have positive effects on soil C release in NCP in association with response of labile C substrate to warming.

Keywords: global warming, conventional tillage, no-tillage, soil respiration, dissolved organic carbon, soil microbial biomass carbon

1. Introduction

The CO_2 concentration in atmosphere has been increasing rapidly over the last 50 years and is predicted to cause global warming (Denmead 1991). The globally averaged temperature increased about 0.85°C (0.65–1.06°C) over the period 1880 to 2012 and this trend of increasing global temperature is likely to exceed at least 1.5°C for the end of the 21st century relative to 1850 to 1900 (IPCC 2013). Warmer soil temperature due to global warming will be

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likely to enhance the mineralization of soil organic matter (SOM) in terrestrial ecosystem and subsequently increases the efflux of carbon (C) from the soil to atmosphere. This will provide a positive feedback between climate change and soil C release (Rustad and Fernandez 1998).

The efflux of C from soil to the atmosphere occurs primarily in the form of CO_2, and is the result of soil respiration (Rs) (Rustad and Fernandez 1998). With increasing concern of global warming, soil C sequestration strategy, such as no-tillage (NT) with residual cover on surface soil, is recognized as one of the important management practice to mitigate CO_2 emission (Qin *et al.* 2010; Zhang *et al.* 2013; Mangalassery *et al.* 2015; Sheehy *et al.* 2015). Adoption of NT generally increases soil organic carbon (SOC) sequestration coupled with the increased macro-aggregates due to less mechanical and artificial disruption (Mangalassery *et al.* 2015; Sheehy *et al.* 2015). On the contrary, conventional tillage (CT) causes the breakdown of the soil aggregates, increases soil aerobic condition and hastens the oxidation of SOC and soil CO_2 emission (Qin *et al.* 2010; Zhang *et al.* 2013). However, whether warming stimulates decomposition of SOC and CO_2 emission or not in these two tillage systems was little understood. A few studies reported by Hou *et al.* (2014) and Liu *et al.* (2015) who argued that warming had no significant effect on cumulative Rs in arable field, while the positive response of decomposition of SOC on the surface soil (0–5 cm) might be attributed to the CO_2 release in NT field. However, uncertainties of estimates of annual cumulative CO_2 emission based on the less frequency of sampling in their studies were still high, because CO_2 emission peaks from soil after plowing, irrigation and strong precipitation contribute main proportion to total annual soil CO_2 emission in agricultural ecosystem (Reicosky *et al.* 1999; Morell *et al.* 2010). Soil CO_2 pulse deprived from tillage operation occurs as an initial burst of CO_2 emission which lasts for several hours (Morell *et al.* 2010). This CO_2 pulse is due to soil aggregate disruption and exposition of protected SOC to decomposition (Lascalajr *et al.* 2008; Morell *et al.* 2010). The rapid changes of Rs during irrigation or precipitation events may have been caused by several possible mechanisms (Kuzyakov *et al.* 2000; Huxman *et al.* 2004; Chen *et al.* 2008). Water displaces soil pore space gas with high CO_2 concentration. Irrigation or precipitation can activate microbial metabolism and root activity, resulting in a priming effect on soil CO_2 efflux (Steenwerth *et al.* 2005). Furthermore, addition of water to an extremely dry soil could increase access to labile substrate (Huxman *et al.* 2004). Some previous studies have reported that the rapid soil CO_2 flux responses to irrigation and precipitation events lasted for 2–4 days, but accounts for larger proportion of Rs to total cumulative CO_2 emission (Reicosky *et al.* 1999; Fierer 2003; Wang *et al.* 2015). Therefore, warming effect on soil CO_2 emission peaks deprived from the disturbance of management practices and precipitation may be complex in CT and NT fields.

As a direct reservoir of readily available nutrients, the labile C pool is particularly important and exerts considerable control on ecosystem functioning. CO_2 emission is largely dominated by the small but highly bio-reactive labile carbon, such as dissolved organic carbon (DOC) and soil microbial biomass carbon (MBC). Through its impacts on microbial activity and on the turnover and supply of nutrients to plant, the labile C can alter Rs components (Ra, autotrophic respiration; Rh, heterotrophic respiration). Previous studies have reported that the labile C was sensitive to alteration in soil temperature and moisture resulting from climate change, with the positive (Belay-Tedla *et al.* 2009), neutral (Xu Z *et al.* 2010; Fu *et al.* 2012) and negative response (Dou *et al.* 2010) to warming. However, DOC and MBC have not been widely used to evaluate Rs and its source components responses to experimental warming in farmland, especially in North China Plain (NCP) where is one of the most important intensive agricultural region providing approximately one fourth of China's total grain yield in China (Liu *et al.* 2011). Hence, analyzing the DOC and MBC may provide insights into indication of global warming on soil CO_2 emission in farmland of NCP. In this study, our objectives were to investigate effects of warming on Rs, DOC and MBC based on artificial infrared warming in winter wheat and summer maize season under CT and NT systems; to quantify the contributions of CO_2 emission peaks due to management practices and precipitation to annual soil CO_2 efflux and assess the effects of warming on these CO_2 peaks in these two tillage systems; and to quantify the influences of DOC and MBC on Rs in warming condition.

2. Materials and methods

2.1. Study site

Our study was performed on a long-term conservation tillage trial at Yucheng Comprehensive Experiment Station of the China Academy of Sciences (36°50´N, 116°34´E). This site is representative of the intensive agricultural areas of the NCP, with an annual mean temperature of approximately 13.4°C and precipitation of 567 mm (Hou *et al.* 2014). A winter wheat/summer maize system is the typical cropping system; the irrigation using local groundwater was applied according to the soil moisture condition in crop growing seasons.

2.2. Field treatment

The experimental field used a blocked split-plot design with warming as the main factor and CT and NT as the secondary factor. The treatments included CT with warming (CTW), CT without warming (CTN), NT with warming (NTW) and NT without warming (NTN). The tillage practice was only conducted in wheat season, but not applied in summer maize season according to the local crop management practice. Four replicates of the four treatments were arranged randomly as described by Hou *et al*. (2014). There were 16 plots by 2 m×2 m and the distance between adjacent plots was approximately 5 m. Tillage treatments were initiated in 2003. Prior to these tillage treatments the sites were under CT for 5 years. Warming treatments were distributed within tillage treatments, which were established on 4th February, 2010. Each warming treatment was continuously heated to simulate global warming using an MSR-2420 infrared heater (2 000W, Kalglo Electronics Inc., Bethlehem, PA, USA). The infrared heaters were suspended 3 m above the ground. Dummy infrared heaters of the same shape and size were suspended similarly in the un-warming control treatments to simulate the shading effect of the infrared heater. Winter wheat and summer maize were seeded on 16th October, 2013 and 10th June, 2014, and harvested on 8th June, and 10th October, 2014, respectively. Before sowing, the remaining residues from the previous crop were manually removed from all plots. For CT field, artificial plowing with a shovel was conducted to till to a soil depth of approximately 15–20 cm. Plowing was not applied in NT field. The total amount of N applied was 285 kg N ha^{-1} for wheat season and 207 kg N ha^{-1} for maize season in both of CT and NT fields, respectively. For wheat season, the basal fertilizer was applied in sowing period at a rate of 112.5 kg N ha^{-1} for CT and 64.5 kg N ha^{-1} for NT, respectively, as compound fertilizer. This granular fertilizer was sown and ploughed into the soil by the tiller in CT but was sown to the manual furrows in NT field. In addition, maize straw including approximately 0.6% N from the previous crop was chopped into pieces (approximately 5 cm in length) and scattered manually across the soil surface after wheat sowing in NT field. The topdressing fertilizer was applied at a rate of 172.5 kg N ha^{-1} in each of plot after wheat returning green stage. For summer maize, tillage was not applied according to the local crop management practice in both CT and NT fields. The urea fertilizer was used in topdressing period in each of plot and wheat straw (including approximately 1.0% N) instead of partial fertilizer was applied after maize sowing in NT fields. The winter wheat and summer maize were irrigated with local groundwater. The details of management practices are shown in Table 1.

2.3. CO_2 samplings and measurements

CO_2 flux was measured using a Static Chamber System. The system consisted of a circular stainless steel base (0.19-m inner diameter and 0.22-m external diameter) surrounded by a trough

Table 1 Agricultural management practices for the experimental fields

Crop	Treatment[1)]	Plowing		Base fertilizer application[2)]		Straw application[3)]		Top dressing fertilizer application[4)]		Irrigation application	
		Date (yr/mon/d)	Depth (cm)	Date (yr/mon/d)	Rate (kg N ha^{-1})	Date (yr/mon/d)	Rate (kg N ha^{-1})	Date (yr/mon/d)	Rate (kg N ha^{-1})	Date (yr/mon/d)	Rate (mm)
Winter wheat	CTW	2013/10/16	15–20	2013/10/16	112.5	–	–	2014/3/20	172.5	2014/7/22	70–80
	CTN	2013/10/16	15–20	2013/10/16	112.5	–	–	2014/3/20	172.5	2014/7/22	70–80
	NTW	–	–	2013/10/16	64.5	2013/10/17	48	2014/3/20	172.5	2014/7/22	70–80
	NTN	–	–	2013/10/16	64.5	2013/10/17	48	2014/3/20	172.5	2014/7/22	70–80
Summer maize	CTW	–	–	–	–	–	–	2014/7/22	207	2014/7/22	40–50
	CTN	–	–	–	–	–	–	2014/7/22	207	2014/7/22	40–50
	NTW	–	–	–	–	15/06/2014	32	2014/7/22	175	2014/7/22	40–50
	NTN	–	–	–	–	15/06/2014	32	2014/7/22	175	2014/7/22	40–50

[1)] CTW, conventional tillage with warming treatment; CTN, conventional tillage without warming treatment; NTW, no tillage with warming treatment.
[2)] Base fertilizer was applied as compound fertilizer (N:P:K ratio is 12:19:13) in sowing period of wheat season.
[3)] Straw was scattered manually across the soil surface after wheat and maize sowing in NT field. In wheat season, maize straw including approximately 0.6% N was applied. In maize season, wheat straw of approximate 1.0% N was applied.
[4)] Urea including 46.3% nitrogen content was applied as top dressing fertilizer.
– means no data.

(0.03-m width and 0.05-m height) and a cylindrical chamber made of polyvinyl chloride (0.20 m inner diameter×0.15 m height). Each chamber was fitted on the stainless steel base that was permanently inserted up to 5 cm into the soil below the infrared or "dummy" heater and was only removed for plowing. Moreover, the stainless steel base was installed between two rows of plants and small living plants were removed inside the base at least 1 day before measurements to avoid the effect of plants on sampling gas (Xue *et al.* 2015). In addition, we used root exclusion method to measure Rh (Li *et al.* 2013). The steel base was inserted inside a collar (0.50 m height and 0.23 cm diameter) which was established in August, 2014 and prevented the root growth. Samplings of Rs were conducted from 16th October, 2013 to 10th October, 2014 and Rh from 6th August, 2014 to 7th October, 2014, respectively. Four gas samples (10 mL per sample) in each plot were collected 0, 10, 20 and 30 min after chamber closure, respectively. Rs and Rh fluxes were then calculated from four measured points as the slope of the linear regression. These gas samples representing the daily CO_2 fluxes were collected between 9:00 and 11:00 a.m. (Hu *et al.* 2013). According to the previous studies, gas sampling was collected for 7 days after tillage operation or irrigation (Fierer 2003; Morell *et al.* 2010) and for 3 days after precipitation (Reicosky *et al.* 1999; Fierer 2003; Morell *et al.* 2010), respectively, except for an approximately 4–7 days interval during the crop growing season. All samples were analyzed within 24 h for CO_2 concentrations using a gas chromatograph (Agilent 7890A, Agilent Technologies, Palo Alto, California, USA) equipped with an electron capture detector (ECD, at 330°C) and a flame ionization detector (FID, at 250°C). The temperature of the column was set at 60°C.

Rs and Rh were calculated from several parameters, including the measured slope of the linear increase from the change in the CO_2 concentration within the chamber over time after chamber closure, the chamber headspace height, the air pressure and air temperature within the chamber. (Liu *et al.* 2014). Ra was calculated by subtracting Rh from Rs. The cumulative soil CO_2 emission for each treatment was estimated by summing the daily mean Rs rate of two neighboring observations multiplying the number of days between samples (Chen *et al.* 2008).

2.4. Auxiliary measurements

For each plot, the soil temperature and soil volumetric water content at 10 cm soil depth were manually measured with hand-held probes at the same time as gas sampling. Air temperature and precipitation data were supplied by the local meteorological station in the experimental site. In addition, soil at 0–10 cm was collected in different growing periods to determine DOC and MBC. Soil samples were extracted by 50 mL of 0.5 mol L^{-1} K_2SO_4. DOC in the extraction solution was determined by dichromate digestion (Vance *et al.* 1987). MBC was determined using the fumigation extraction method (24 h fumigation), which was calculated as the differences of DOC between the fumigated and non-fumigated soils (Vance *et al.* 1987; Belay-Tedla *et al.* 2009).

2.5. Data analysis

All data were analyzed with SPSS 16.0 to examine differences in Rs, Ra, Rh, soil temperature, soil moisture, DOC and MBC among treatments. Statistically significant differences (P<0.05) were identified using analysis of variance (ANOVA) and least significant difference (LSD) calculations. Repeated measures of ANOVA, with warming and tillage systems as the main factors (between-subject factors) and sampling dates as within-subject factors, were used to determine the temporal variation and effects of warming and tillage systems on Rs, soil temperature, soil moisture, DOC and MBC. In addition, the linear regression relationship between Rs, soil temperature and soil moisture, exponential regression relationship between Rs, DOC and MBC were used to conduct the effects of abiotic and biotic factors on Rs.

3. Results

3.1. Temperature and moisture

Air temperature and precipitation are shown in Fig. 1. The mean values of air temperature and total precipitation in winter and maize seasons were 10.3, 23.0°C and 171.0, 196.8 mm, respectively. Air temperature in crop growing seasons was similar to the perennial average value. But precipitation was 50.1% lower than that of perennial average (394 mm) in summer maize season.

Warming, tillage systems and different sampling dates significantly affected soil temperature at 10 cm depth (Fig. 2). The average values were significantly increased by 1.1–1.6°C in warming treatments compared with un-warming treatments in crop growing seasons (P<0.05). In wheat season, soil temperature was significantly increased by 1.8°C in CTW relative to CTN and by 1.4°C in NTW relative to NTN, respectively (P<0.05). In winter season (from December to February), the elevated soil temperature was reached to 2.2°C in CT fields and 1.8°C in NT fields, respectively (P<0.01). As ambient air temperature rising, increases in soil temperature in two tillage systems were slight. In maize season, we found that warming only increased soil temperature by 1.2°C in CT fields and 0.8°C in NT fields,

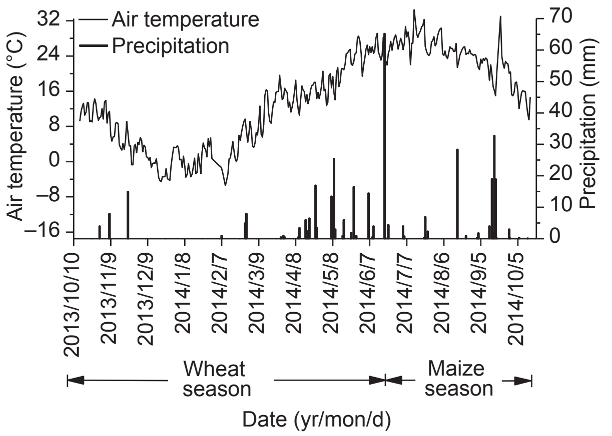

Fig. 1 Daily average air temperature, precipitation from 2013 to 2014 at study site.

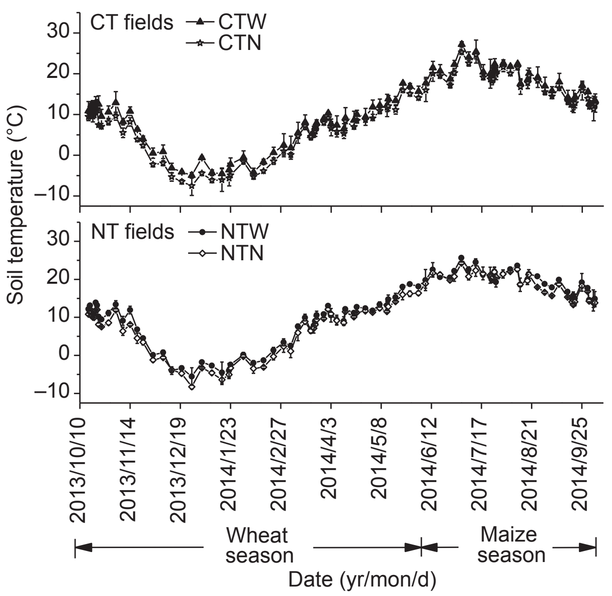

Fig. 2 The dynamic of soil temperature (10 cm) in wheat and maize seasons of 2013–2014. CT, conventional tillage; NT, no-tillage; CTW, CT with warming treatment; CTN, CT without warming treatment; NTW, NT with warming treatment; NTN, NT without warming treatment. Vertical bars indicate the standard deviations of soil temperature.

respectively (P>0.05). Due to the effects of straw cover, soil temperature was significantly increased by 1.0°C (NTW *vs*. CTW) and 1.4°C (NTN *vs*. CTN) in NT fields compared with in CT fields in crop growing seasons (P<0.05).

Soil volumetric water content exhibited fluctuating change in crop growing seasons (Fig. 3). The mean values ranged from 19.8 to 23.5% among treatments. Due to irrigation application and precipitation events, we found that no significant differences between warming and un-warming treatments (P>0.05). However, the effect of tillage system showed that soil moisture was increased by 2.1% (NTW *vs*. CTW) and 2.0% (NTN *vs*. CTN) in NT fields relative to in CT fields, respectively, in the whole year.

3.2. Rs

Rs rates among treatments were shown in Fig. 4 in wheat and maize seasons. We found the marked fluctuating changes in Rs rate after March and the relative stable change in December–February. The mean Rs values during the winter wheat season were 386.3, 363.9, 335.8 and 300.4 mg CO_2 m^{-2} h^{-1} for CTW, CTN, NTW and NTN, respectively. We found that no significant differences between CTW and CTN. However, experimental warming significantly increased Rs rate by 11.8% in NTW relative to NTN (P<0.01). Although the elevated soil temperature due to warming was observed in winter season, we did not detect the significant differences in Rs between warming and un-warming treatments, which ranged from 123.3 to 147.1 mg CO_2 m^{-2} h^{-1}. In maize season, measured Rs from CTW, CTN, NTW and NTN were 428.7, 360.6, 478.0 and 400.8 mg CO_2 m^{-2} h^{-1}, respectively. Experimental warming significant increased Rs by 18.9% in CT fields (CTW *vs*. CTN) and by 19.3% in NT fields (NTW *vs*. NTN), respectively (P<0.05). In addition, the ANOVA analysis also indicated that tillage systems significantly affected Rs. In crop growing seasons, Rs rate in NT fields was decreased by 15.1% (NTW *vs*. CTW) and 21.1% (NTN *vs*. CTN) compared with that in CT fields, respectively (P<0.05).

3.3. The influences of warming on Rs peaks and annual cumulative CO_2 emission

During the wheat and maize seasons, Rs peaks were observed after plowing, irrigation and rainfall events (Table 2). Measured mean values of Rs after plowing (from 16th October to 17th October, 2013) were 528.2, 432.5, 377.7 and 288.4 mg CO_2 m^{-2} h^{-1} for CTW, CTN, NTW and NTN, respectively. Warming could significantly increase Rs rate by 22.1% in CT fields and by 31.0% in NT fields, respectively (P<0.01). In addition, we also found that Rs in CT fields was significantly enhanced by 39.8% (CTW *vs*. NTW) and by 50.0% (CTN *vs*. NTN) compared with in NT fields, respectively (P<0.01).

Irrigation application triggered Rs peak, which ranged from 375.8 to 1 222.0 mg CO_2 m^{-2} h^{-1}. However, neither warming nor tillage systems affected Rs in this period. In contrast to it, we found the relative slight change ranged from 252.0 to 301.0 mg CO_2 m^{-2} h^{-1} in precipitation periods when warming significantly increased by 10.4% in CT fields and 19.4% NT fields, respectively (P<0.05).

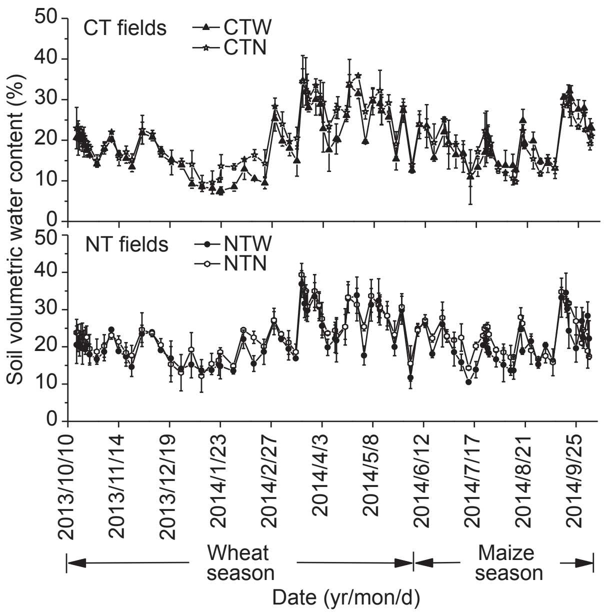

Fig. 3 The dynamic of soil volumetric water content (0–10 cm) in wheat and maize seasons of 2013–2014. CT, conventional tillage; NT, no-tillage; CTW, CT with warming treatment; CTN, CT without warming treatment; NTW, NT with warming treatment; NTN, NT without warming treatment. Vertical bars indicate the standard deviations of soil temperature.

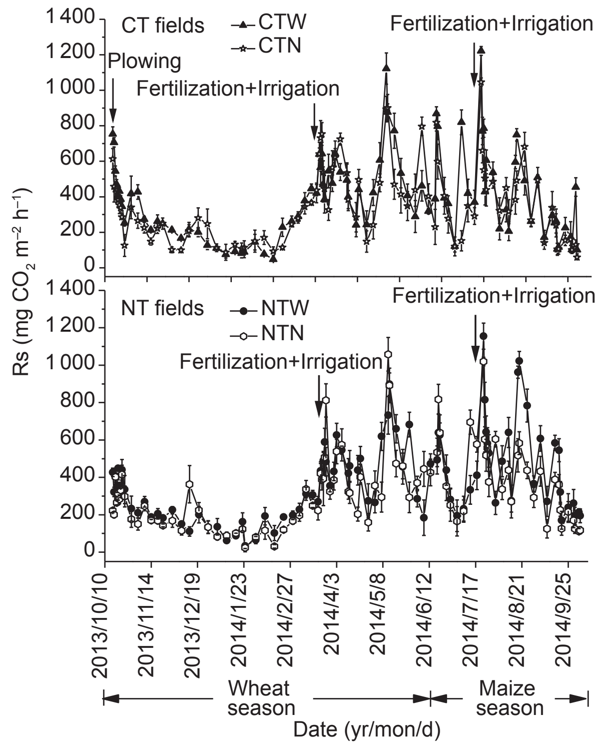

Fig. 4 Temporal pattern of daily soil respiration (Rs) rate during wheat and maize seasons of 2013–2014. CT, conventional tillage; NT, no-tillage; CTW, CT with warming treatment; CTN, CT without warming treatment; NTW, NT with warming treatment; NTN, NT without warming treatment. Vertical bars indicate the standard deviations of soil temperature.

The annual cumulative CO_2 emission was not affected by warming in CT fields, but it was significantly increased by 12.7% in NTW treatment compared with NTN treatment (P<0.05, Table 2). The disturbances due to agricultural management practices and precipitation resulted in the obvious soil CO_2 emission in crop growing seasons. The contributions of annual cumulative CO_2 emissions accounted for 36.6–40.8% among treatments during these periods. This indicated that soil CO_2 emission resulted from the disturbances had an important contribution to annual CO_2 emission. Moreover, warming would enhance soil cumulative CO_2 emission by 13.1–19.7% in these periods for CT and NT fields.

3.4. DOC and MBC

The ranges of DOC in 0–10 cm soil depth were lower than that of MBC content (Fig. 5). They were affected by warming and tillage systems. However, these effects on DOC and MBC varied with sampling date. In wheat season, warming significantly increased DOC by 23.4% in CT fields (CTW *vs*. CTN) and by 12.8% in NT fields (NTW *vs*. NTN), respectively (P<0.05). MBC was also significantly increased by 12.9% in CTW and 16.9% in NTW, respectively (P<0.05). However, in maize season, warming did not alter DOC and MBC contents in CT fields but it significantly increased DOC by 11.6% and MBC by 12.4% in NTW compared with that in NTN treatment (P<0.05). In addition, the effects of tillage systems on DOC and MBC showed that NTW and NTN treatments significantly enhanced DOC by 11.4–21.8% and MBC by 18.0–23.6% relative to CTW and CTN treatments, respectively (P<0.05). These increases in DOC and MBC in NT fields would enlarge to 14.1–34.7 and 23.0–30.1% in maize season, respectively (P<0.01). This indicated that the effects of tillage systems on DOC and MBC varied with different crop growing seasons and subsequently modified the response of them to experimental warming.

3.5. Relationships between Rs and soil temperature, soil moisture, DOC and MBC

To examine the degree to which soil temperature and soil moisture can predict Rs, we evaluated the linear relationships between Rs, soil temperature and soil volumetric water content at 10 cm. The weaker moisture factors relative to temperature controlling the seasonal Rs variation, of which 0.6–0.8% were explained by changes with linear regression (Fig. 6), showing that the seasonal dynamics of soil moisture could slightly affect Rs in irrigated farmland of NCP. But we

Table 2 Effects of warming and tillage systems and their interactions based on ANOVA on cumulative soil CO_2 emission (g CO_2 m^{-2}) in different periods of wheat and maize seasons

Treatment[1)]	Wheat season[2)]				Maize season			Annual cumulative CO_2 emission
	PLO	IFF	PRE	Total CO_2 emission in wheat season	IFF	PRE	Total CO_2 emission in maize season	
CTW	87.2±7.6 a	90.1±9.7 a	608.0±29.2 a	1 807.5±66.3 a	55.8±8.9 b	160.8±21.5 b	649.3±93.9 a	2 456.8±121.8 a
CTN	71.9±3.2 b	95.9±4.5 a	535.5±35.0 b	1 688.7±45.6 b	49.5±10.9 b	133.0±25.7 b	558.6±115.2 a	2 227.3±160.5 ab
NTW	62.7±3.7 c	75.0±5.7 b	544.4±22.7 b	1 623.5±78.8 b	55.2±5.7 a	171.5±38.3 a	712.5±126.1 a	2 336.0±204.1 a
NTN	48.9±6.7 d	69.9±7.9 b	457.5±43.1 c	1 436.4±30.2 c	41.6±8.2 c	140.6±13.2 b	635.8±165.7 a	2 072.2±195.1 b
Warming effects								
Warmed	74.9±14.2 a	82.5±12.9 a	576.2±41.7 a	1 715.5±126.8 a	55.5±9.7 a	166.1±29.3 a	680.9±10.8 a	2 396.4±172.1 a
Un-warmed	60.4±13.2 b	82.9±15.1 a	496.5±55.3 b	1 562.6±154.8 b	45.6±9.9 a	136.8±19.3 b	597.1±13.8 a	2 159.8±198.3 b
Tillage systems effects								
CT	79.5±9.8 a	93.0±7.7 a	571.7±39.0 a	1 748.1±86.1 a	52.6±9.9 a	146.9±26.5 a	603.9±10.9 a	2 352.0±176.1 a
NT	55.8±8.9 b	72.4±9.7 b	500.9±32.3 b	1 530.0±124.4 b	48.4±12.0 a	156.0±31.3 a	674.1±14.2 a	2 204.1±239.7 a
P-value of two-way ANOVA								
Warming	<0.01	0.93	<0.01	<0.01	0.07	0.04	0.22	0.01
Tillage	<0.01	<0.01	<0.01	<0.01	0.42	0.50	0.29	0.07
Warming×Tillage	0.80	0.23	0.68	0.19	0.48	0.91	0.92	0.71

[1)] CTW, conventional tillage with warming treatment; CTN, conventional tillage without warming treatment; NTW, no tillage with warming treatment.

[2)] PLO, IFF and PRE denote that soil cumulative CO_2 emission after plowing (PLO, 7 days), irrigation followed by fertilization (IFF, 14 days) and precipitation (PRE, 30 days) events, respectively.

Different letters within a column are significantly different at P<0.05.

found the higher R^2 coefficients among Rs, DOC and MBC (Fig. 7). These indicated that the labile C content could better modulate the soil CO_2 emission variation.

4. Discussion

4.1. The effect of experimental warming on Rs under CT and NT fields

Our study showed the positive response of Rs to experimental warming in CT and NT farmlands in NCP, which was consistent with other study in cropland of South China (Yaohong *et al.* 2013), but differed with the studies of semi-arid farmland reported by Hou *et al*. (2014) and Liu *et al*. (2015) who reported no significant effect of warming on Rs. The annual cumulative soil CO_2 emissions ranged from 2 336.0 to 2 456.8 g CO_2 m^{-2} in our study were lower than the results from Hou *et al.* (2014) (equivalent 2 599.7 to 3 391.7 g CO_2 m^{-2}) but higher than that from Liu *et al.* (2015) (equivalent 1 450.0 to 1 625.0 g CO_2 m^{-2}). Temporal and spatial variability of soil CO_2 emission was regulated by various factors including temperature, soil moisture, C substrate quality and its quantity, etc. (Parkin and Kaspar 2004), while some studies argued that sample number might result in coefficients of variation of annual cumulative CO_2 emission in the range of 25–85% (Reicosky *et al.* 1999; Davidson *et al.* 2002). In our study, there were 91 sampling events during crop growing seasons compared with 16–46 sampling events in other studies (Hou *et al.* 2014; Liu *et al.* 2015). Therefore, a higher sampling frequency with regard to the precision of estimate plays an important role in assessing Rs response to warming.

Elevated temperature increased Rs because warming might increase soil biological activity, decompositions of SOC and litter (Yaohong *et al.* 2013; Hou *et al.* 2014). However, this positive response of Rs to warming will be declined over time because warming accelerates labile soil C decay. For example, Melillo *et al.* (2002) documented that Rs increased significantly under warming in a 10-year experiment from mid-latitude forest. But this stimulatory effect on CO_2 was lasted for 6 years and then markedly decreased over the last 4 years. Lin *et al.* (2001) also reported that warming positively affected Rs while the enhancement was much less in the second years. However, for agro-ecosystem, the supplied C input into soil deprived from plant production and straw cover was not appeared to limit the SOC substrate supply for Rs, because we did not find the significant differences of SOC between warming and un-warming treatments (Appendix A). In addition, previous studies documented that Rs response to warming was mediated

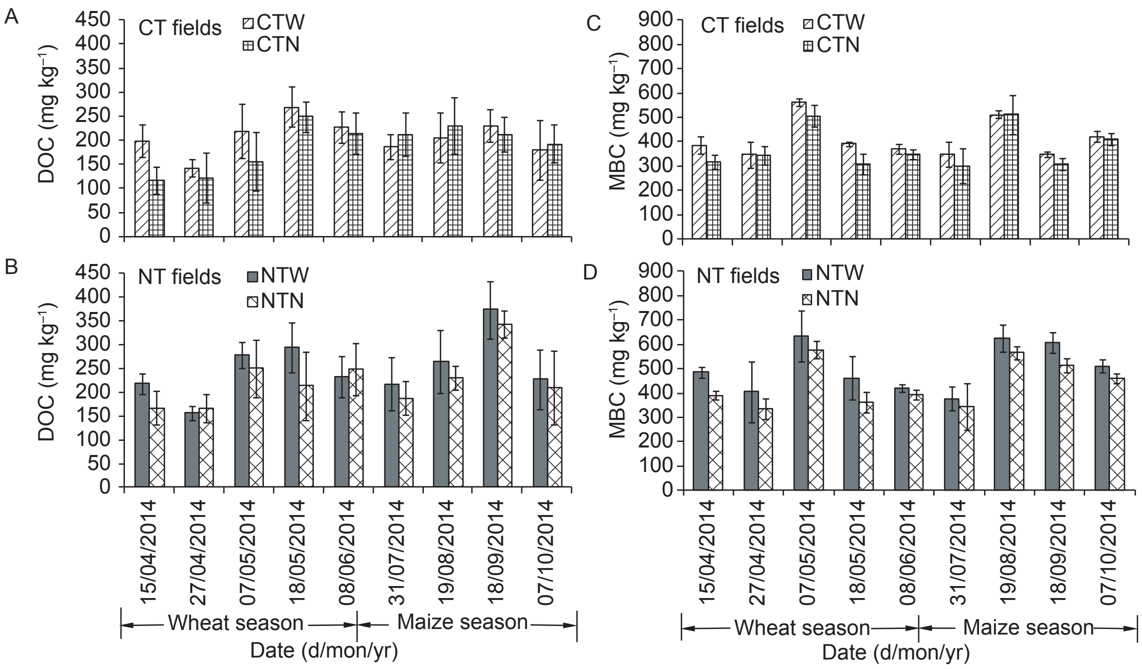

Fig. 5 Variations of dissolved organic carbon (DOC, A and B) and microbial biomass carbon (MBC, C and D) in wheat and maize seasons of 2014. CT, conventional tillage; NT, no-tillage; CTW, CT with warming treatment; CTN, CT without warming treatment; NTW, NT with warming treatment; NTN, NT without warming treatment. Vertical bars indicate the standard deviations of soil temperature.

by soil moisture. The effect of warming on decreasing soil moisture can induce reductions in plant root respiration and microbial activity, both of which contribute to bulk Rs (Xu Z *et al.* 2010; Liu *et al.* 2015). However, we observed no significant effect of warming on soil moisture in warming treatments where soil volumetric water still remained at a relatively high level (19.8–21.7%) over the growing season due to frequent rainfall and irrigation. Thus, if soil moisture becomes favorable for root and microbes activities, warming effect on Rs can be much stronger. The linear relationship between Rs and soil temperature in present study provided evidence that increase in soil temperature of 1.4–1.8°C in irrigated farmland was likely to enhance root and soil microbial activity and subsequently increase Rs (Fig. 6).

We found that the stimulatory effect of warming on Rs in CT was stronger than that in NT in wheat season. But it was opposite for this stimulation under these two tillage systems in maize season. This was because that warming might affect Ra and Rh. As two main Rs source components, Ra and Rh could be responsible for variability of Rs. Ra mainly originates from root respiration. Rh involves microbial respiration deprived from decomposition of SOC. Tillage practices affected soil physical and chemical condition. Ussiri and Lal (2009) documented that plowing aerated the soil and caused the breakdown of the macro-aggregates preventing from the decomposition of labile organic C, this would hasten the oxidation of SOC and Rh. In contrast to this, NT reduced soil disturbance and increased soil impaction which weaken the CO_2 gas diffusion from soil to atmosphere. Moreover, lower soil temperature due to the retaining of straw on soil surface would reduce the decomposition of SOC. This was possible to reduce Rh and result in the lower Rs in NT farmland. As the rising of ambient air temperature and increase in precipitation in maize season, higher SOC from straw cover in upper soil in NT would be decomposed rapidly by soil microbes. Soil CO_2 emission originating from Rh would be higher in NT relative to CT fields. We used root exclusion method to distinguish Ra and Rh, this method was widely used to partition Rs (Li *et al.* 2013). Although we didn't measure these two Rs components in wheat season, warming significantly enhanced Ra and Rh in NT fields in maize season (Appendixes B and C). This verified that warming might stimulate root growth and microbe activity.

4.2. The effect of warming on soil CO_2 emission peak in CT and NT fields

We increased sampling frequencies after plowing, irrigation and precipitation events and observed the obvious soil CO_2 emission peaks, which contributed 36.6–40.8% of annual soil cumulative CO_2 emission (Table 2). This was consistent with Reicosky *et al.* (1999) who reported that tillage

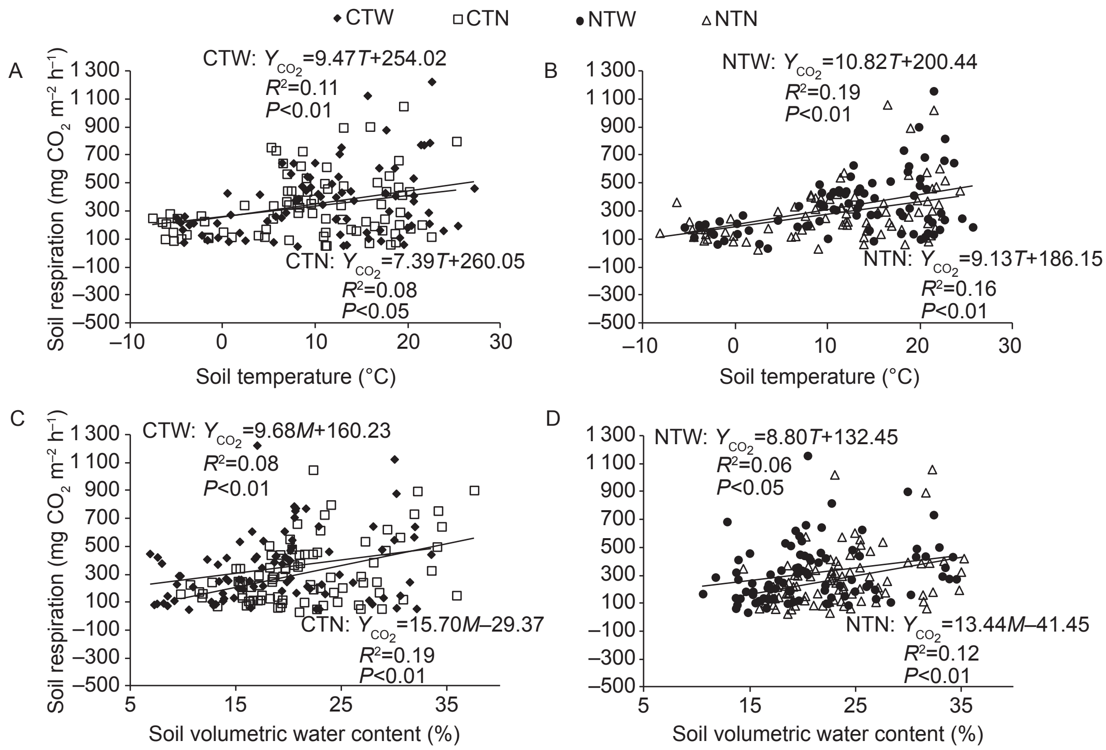

Fig. 6 The linear regression relationships for soil temperature (T, A and B) and soil volumetric water content (M, C and D) against daily average soil respiration (Y_{CO_2}) in wheat and maize seasons. CT, conventional tillage; NT, no-tillage; CTW, CT with warming treatment; CTN, CT without warming treatment; NTW, NT with warming treatment; NTN, NT without warming treatment. Vertical bars indicate the standard deviations of soil temperature.

and irrigation resulted in 30% increase in cumulative CO_2 emission. We found that warming enhanced these peaks in both of two tillage systems, especially in NT fields, warming significantly stimulated it in wheat and maize seasons. Generally, infrared warming caused greater evapotranspiration rates and increased consumptive water to dry the surface soil layer (Steenwerth *et al.* 2005). Following an irrigation or rainfall events, Rs might have been more responsive to addition of water and created more Rs pulse in warming treatments. In the days following an irrigation or precipitation event, warming would stimulate plant growth and soil microbe activity producing more root respiration and microbial respiration (Wall *et al.* 2013). In addition, as the increase in soil moisture, more DOC was solute and utilized by soil microbe. Xu Z *et al.* (2010) demonstrated that warming increased DOC content in relative higher soil moisture condition, indicating higher labile C might partly favor the microbial respiration. Majdi and Öhrvik (2004) also reported that soil warming significantly increased the fine root of Norway spruce forest, implying that more labile C could be added in humid soil condition. This could also contribute partly to the increase in microbial respiration (Majdi and Öhrvik 2004). Our study showed that Rh was positively correlated with DOC (R^2=0.35, P<0.05) and MBC (R^2=0.36, P<0.05) across all treatments data, respectively, which provided evidence that increase in labile C deprived from straw cover in NT fields would modify the effect of warming on microbial respiration. However, removing residual in CT filed would reduce the new C input when water addition after irrigation or precipitation events. This would limit the stimulatory effect of warming on Rh. The higher Ra in present study in NTW compared with NTN treatment was not accorded with aboveground biomass that exhibited the no significant differences among treatments (Appendix D). Previous study in same study site showed the early plant growth stages in warming treatments (Hou *et al.* 2012), indicating that the positive effect of warming on Ra might be as a result of the rapid plant growth.

4.3. Effects of DOC and MBC on Rs in warming condition

DOC and MBC could improve detection and prediction of changes in soil C emission that may not be readily evident with the traditional monitoring of SOC. Specifically, analysis of SOC does not normally permit detection effect of small change on Rs because of the relative high and stable soil C background level (Wei *et al.* 2014). Some studies report-

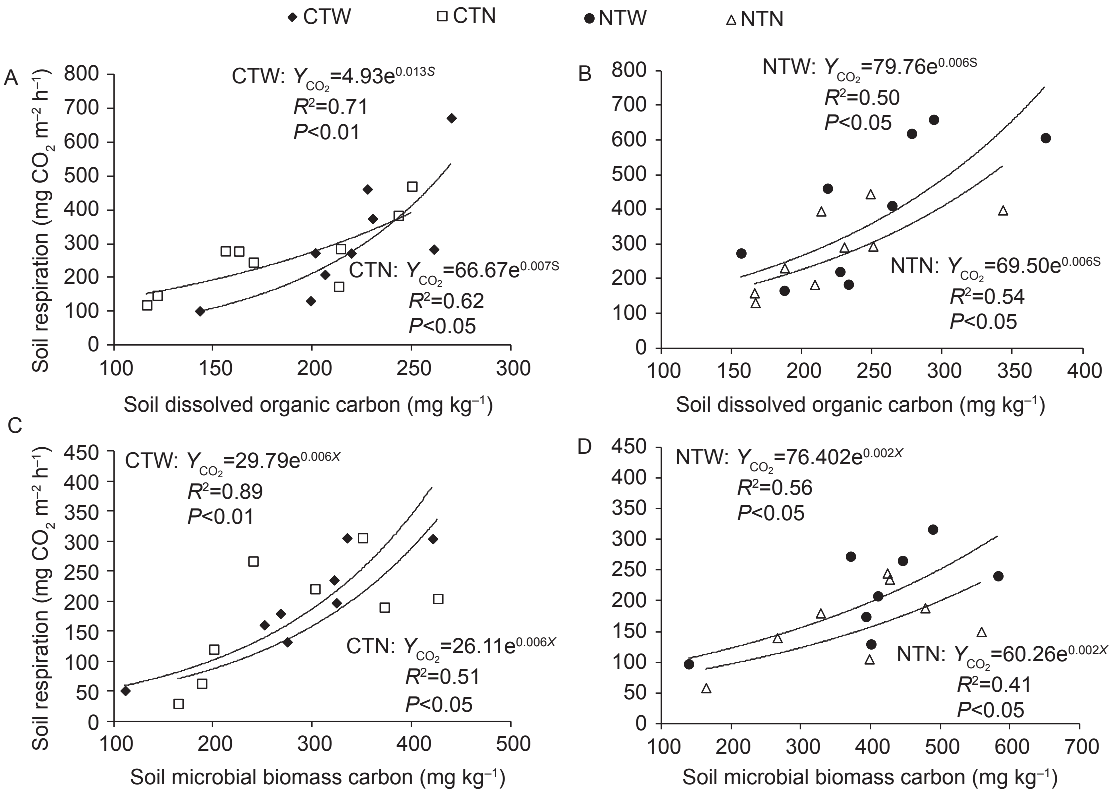

Fig. 7 The exponential regression relationships for soil dissolved organic carbon (S, A and B) and soil microbial biomass carbon (X, C and D) against daily average soil respiration rate (Y_{CO_2}) in wheat and maize seasons. CT, conventional tillage; NT, no-tillage; CTW, CT with warming treatment; CTN, CT without warming treatment; NTW, NT with warming treatment; NTN, NT without warming treatment. Vertical bars indicate the standard deviations of soil temperature.

ed that DOC in soil comes mainly from litter and recently generated organic sources through plant production (Møller *et al.* 1999; Cleveland *et al.* 2004). Møller *et al.* (1999) and Cleveland *et al.* (2004) documented that dissolved organic matter from soluble and biodegradable fractions of senesced litter plays an important role in the delivery of labile C and nutrients to soil surface microbial communities. In addition, root growth and root exudates are recognized to be key processes governing inputs of carbon to soil and may be a main source of the DOC released (Cleveland *et al.* 2004; Luo *et al.* 2009). In our study, DOC was significantly tended to increase with warming in two tillage systems. This provided the evidence that the change in the quantity of DOC affect the activity of soil microbes and subsequently microbial respiration in warming condition. In particular, DOC contents in NT fields were significantly higher than that in CT fields in maize season, indicating that warming effect on litter decomposition and DOC release by straw cover (Luo *et al.* 2009).

MBC is considered as the active C fraction and the precondition for Rs. Previous studies with short-term (<3 years) field experiments showed that warming had no obvious effect on microbial biomass (Zhang *et al.* 2005; Xu Z F *et al.* 2010), whereas long-term (>3 years) warming indicated that microbial biomass was increased or decreased (Frey *et al.* 2008; Liu *et al.* 2009; Rui *et al.* 2011). In our study, we observed that experimental warming had a positive effect on MBC in wheat-maize rotation under CT and NT systems, which differed with previous reports. Given the sufficient soil moisture due to irrigation in crop growing seasons, experimental warming would enhance soil microbial activity. NT fields had a higher MBC contents than that of CT fields. This was a consequence of the long-term application of straw cover on the soil surface for NT treatments, which increased organic C content in the topsoil (Tellez-Rio *et al.* 2015). It also indicated that more labile organic C can be utilized by soil microorganisms. Moreover, straws cover in NT could decrease the rate of evapotranspiration following irrigation or rain, which would enhance the positive effect of warming on soil microbial activity and microbial metabolism (Ussiri and Lal 2009).

We found the significant exponential relationships between Rs, DOC and MBC (R^2=0.50–0.89, Fig. 7), which indirectly verified that the enhancement in microbial activity and labile C substrate due to soil warming would stimulate Rs (Belay-Tedla *et al.* 2009; Dou *et al.* 2010). The significant relationship showed that CO_2 fluxes would be affected by soil active C. Experimental warming would increase the DOC and MBC contents in two tillage systems and subsequently stimulate Rs from microbial respiration. This indicates that the enhancement of soil microbe and C substrate quantities in climate warming projection is likely to trigger soil C release in farmland of NCP.

5. Conclusion

A field manipulation experimental warming was conducted to determine the response of Rs to climate warming in wheat-maize rotation farmland under CT and NT systems from NCP. The results showed that higher sampling frequency increased the precise of estimation of cumulative CO_2 emission and increase average soil temperature of 1.1–1.6°C could significantly enhance Rs in both of two tillage systems under semi-arid irrigated farmland. In crops growth periods, disturbances of management practices such as plowing, irrigation and precipitation resulted in the significant soil CO_2 emission peaks, which contributed 36.6–40.8% of annual soil cumulative CO_2 emission. In this case, warming would enhance these CO_2 emission peaks. In particular, increase in Rh and Ra might modulate the positive response of Rs to warming. DOC and MBC were affected positively by warming and tillage systems, indicating that warming significantly stimulated labile C substrate availability and soil microbial activity in NT fields with straw cover. Therefore, the enhancement in labile C content and soil microbial biomass in future climate warming is likely to increase soil C release in farmland of NCP.

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Appendix associated with this paper can be available on http://www.ChinaAgriSci.com/V2/En/appendix.htm

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