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Influences of drip and flood irrigation on soil carbon dioxide emission and soil carbon sequestration of maize cropland in the North China Plain

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Abstract: The need is pressing to investigate soil CO_2 (carbon dioxide) emissions and soil organic carbon dynamics under water-saving irrigation practices in agricultural systems for exploring the potentials of soil carbon sequestration. A field experiment was conducted to compare the influences of drip irrigation (DI) and flood irrigation (FI) on soil organic carbon dynamics and the spatial and temporal variations in CO_2 emissions during the summer maize growing season in the North China Plain using the static closed chamber method. The mean CO_2 efflux over the growing season was larger under DI than that under FI. The cumulative CO_2 emissions at the field scale were 1959.10 and 1759.12 g/m² under DI and FI, respectively. The cumulative CO_2 emission on plant rows (OR) was larger than that between plant rows (BR) under FI, and the cumulative CO_2 emission on the irrigation pipes (OP) was larger than that between irrigation pipes (BP) under DI. The cumulative CO_2 emissions of OP, BP and bare area (BA) under DI were larger than those of OR, BR and BA under FI, respectively. Additionally, DI promoted root respiration more effectively than FI did. The average proportion of root respiration contributing to the soil CO_2 emissions of OP under DI was larger than that of OR under FI. A general conclusion drawn from this study is that soil CO_2 emission was significantly influenced by the soil water content, soil temperature and air temperature under both DI and FI. Larger concentrations of dissolved organic carbon (DOC), microbial biomass carbon (MBC) and total organic carbon (TOC) were observed under FI than those under DI. The observed high concentrations (DOC, MBC, and TOC) under FI might be resulted from the irrigation-associated soil saturation that in turn inhibited microbial activity and lowered decomposition rate of soil organic matter. However, DI increased the soil organic matter quality (the ratio of MBC to TOC) at the depth of 10–20 cm compared with FI. Our results suggest that the transformation from conventional FI to integrated DI can increase the CO_2 emissions and DI needs to be combined with other management practices to reduce the CO_2 emissions from summer maize fields in the North China Plain.

Keywords: drip irrigation; flood irrigation; spatio-temporal variation; carbon dioxide; soil organic carbon; North China Plain

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1 Introduction

Anthropogenic CO_2 emission is estimated to account for 60% of the undergoing global warming effect (Rastogi et al., 2002). Agricultural practices are reported to have contributed approximately

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25% of the total anthropogenic CO_2 emission (Duxbury, 1995), and soil CO_2 emission is a major component of agricultural practices-associated CO_2 emission. Agricultural practices could change soil CO_2 emission through a variety of ways, such as fertilization (Shao et al., 2014), tillage (Jabro et al., 2008), land use (Han et al., 2013), crop conversion (Alberti et al., 2010) and irrigation (Li et al., 2012). Specifically, these agricultural practices could affect soil organic matter (SOM) contents and soil CO_2 emission rates through altering soil temperatures and water contents (Bajracharya et al., 2000; Curtin et al., 2000; Parkin and Kaspar, 2003; Kirschbaum, 2004; Al-Kaisi and Yin, 2005; Amos et al., 2005). China is one of major agriculture-dominating countries in the world. The North China Plain accounts for 18.6% of China's total agricultural area (Wu et al., 2006) and contributes more than 33.0% of China's maize grain production (Kendy et al., 2003). The shortage of water resources has become a major limiting factor of food production in the North China Plain and irrigation has thus become increasingly important (Zhang et al., 2004). Although flood irrigation (FI) is still most commonly practiced, water-saving irrigation techniques have recently been extensively adopted (Gao et al., 2014).

Drip irrigation (DI) is one of popular water-saving irrigation techniques and has been widely employed in arid and semi-arid agro-systems. Compared with FI, DI is performed at more regular intervals in much smaller amounts with less intense water supply and slower water movement. Consequently, DI could result in heterogeneous distributions of soil water content (SWC) and soil temperature. SWC and soil temperature were demonstrated to have a great effect on soil respiration and therefore on soil CO_2 emission rates (Lloyd and Taylor, 1994). Improved understanding of the spatial and temporal variations in soil CO_2 emissions is thus crucial for accurately quantifying annual CO_2 effluxes from a given ecosystem (Fang et al., 1998; Xu and Qi, 2001). Previous studies in China on drip irrigation-related CO_2 emission appeared to be equivocal. For example, comparative studies showed that CO_2 emission was lower under DI treatment than under FI treatment (Li et al., 2011; Li et al., 2012). On the contrary, soil CO_2 emission was reported to be higher under DI treatment than under FI treatment (Zhang et al., 2014). In addition, a study in a tomato field of California did not find any significant differences in soil CO_2 emissions between DI and FI treatments (Kallenbach et al., 2010). The aforementioned discrepancies regarding drip irrigation-related CO_2 emission and the existing gap in our knowledge regarding the effects of DI on CO_2 emissions from summer maize fields well justify our attempt to investigate the temporal and spatial distribution of CO_2 emission in maize fields with DI treatment in the North China Plain.

Dissolved organic carbon (DOC) and microbial biomass carbon (MBC) are indicators of the labile total organic carbon (TOC) pool (Lützow et al., 2007) and could respond sensitively to changes in soil management practices (Haynes, 2000; Song et al., 2012; Xie and Wu, 2016). DI could change the distributions of SWC and soil temperature, further influencing the SOM decomposition and carbon loss (Kirschbaum, 2004; Sánchez-Martín et al., 2008). The changes in SWC and soil temperature could consequently influence the concentrations of soil MBC and DOC (Sparling and West, 1989; Nelson et al., 1996). Many of previous studies have focused on the changes in TOC, DOC and MBC concentrations under different land uses and tillage systems (Iqbal et al., 2010; Li et al., 2012) and compared the differences between irrigation and non-irrigation systems and the differences between fertilization and no fertilization situations (Samuelson et al., 2009). However, no data regarding the TOC, DOC and MBC concentrations under DI and FI during the maize growing season in the North China Plain were reported.

The objectives of this study were: (1) to depict the temporal and spatial distributions of soil CO_2 emission under DI and FI treatments during the maize growing season; (2) to compare the effects of DI and FI on the TOC, DOC and MBC concentrations; and (3) to examine the relationships of SWC and soil temperature with the TOC, DOC and MBC concentrations and soil CO_2 effluxes under DI and FI.

2 Materials and methods

2.1 Study area

The study was conducted in a summer maize field in Zhangfatai village of Hebei Province (38°02′02″N, 115°49′12″E) from 28 June to 14 October 2014. The site is relatively flat with an elevation of 19 m a.s.l. Winter wheat and summer maize rotation is the most commonly practiced cropping system. The region is characterized by a temperate monsoon climate with the annual mean temperature of approximately 12.8°C and the mean annual precipitation of approximately 554 mm. The top soil (0–20 cm) has a pH of 8.49, electric conductivity of 360.75 µs/cm, bulk density of 1.42 g/cm^3, and organic matter content of 22.1 g/kg.

2.2 Field experiment

In this experiment, two irrigation practices were established: flood irrigation (FI) and drip irrigation (DI). FI field was fertilized twice with urea containing N (46%): 187.5 kg/hm^2 on 19 July and 150.0 kg/hm^2 on 11 August 2014, and each followed by FI. A total of 155.2 kg N/hm^2 was applied via fertigation before each irrigation event. DI field used different irrigation frequencies and water amounts during different growing stages (Table 1). Again, compared with FI, DI was performed at more regular intervals in much smaller amounts with less intense water supply and slower water movement. As shown in Table 1, different water-soluble fertilizers were applied during different growing stages and the fertilizer types were differentiated by the ratio of nitrogen/phosphorus/potassium. Specifically, fertilizer I (the ratio, 33/6/11) was applied during the elongation and bell stages and fertilizer II (the ratio, 27/12/14) was applied during the tasseling and filling stages.

The fields were cultivated with wheat crop before maize crop. The planting spacing arrangement of maize was 60 cm×25 cm (row spacing×plant spacing). The DI pipes with 30-cm-spaced emitters were placed near maize rows along the row direction. The distances between pipes were more or less the same with row spacing.

Table 1 Amounts of irrigation water and fertilizers under DI (drip irrigation) used in different growing stages

Growing stage	Irrigation date	Irrigation amount (m^3/hm^2)	Fertilization amount (kg N/hm^2)	Fertilizer type
Elongation stage	9 Jul 2014	180	24.7	I
Bell stage	30 Jul 2014	420	99.0	I
Tasseling stage	20 Aug 2014	225	60.7	II
Filling stage	10 Sep 2014	225	20.2	II

Note: Fertilizer types are differentiated by the ratio of nitrogen/phosphorus/potassium. The ratio is 33/6/11 in fertilizer I and 27/12/14 in fertilizer II.

2.3 Gas measurements

Gases were collected using a static opaque chamber with a dimension of 30 cm (length)×30 cm (width)×40 cm (height). The chamber was made of 8-mm-thick black acrylic material with a tinfoil reflecting film attached to the external surface. The opaque chamber could eliminate the influence of plant photosynthesis and also prevent the temperature inside the chamber from rising during measurement. In FI plot (Fig. 1), chambers were placed on plant rows (OR) and between plant rows (BR). In DI plot, chambers were placed on irrigation pipes (OP) and between irrigation pipes (BP). Bare areas (BAs) were purposely reserved under both FI and DI treatments. Plants in the bare area (BA) were removed after sprouting and BAs under FI and DI situations were irrigated and fertilized in the same ways as in FI treatment and in DI treatment, respectively. Each of the two treatments (FI and DI) had three replicates or experimental plots and the size of each irrigation plot was 6 m×50 m.

The aboveground standing parts of maize within the experimental plots (40 cm×40 cm) were cut to ground level, and plant litter was removed before the measurements. Then, stainless steel frames sharpened at the bottom were inserted into the soil to a depth of 5 cm 24 h prior to the measurements to reduce perturbation of the soil structure resulted from steel frame insertion. During the course of measurements, the chambers were temporarily mounted on frames and maintained gas-tight by filling the groove with water. The lid of each chamber was installed with a mini fan inside the chamber driven by a 12 V lead-acid battery to ensure a uniform gas concentration within the chamber and also with a thermometer to measure temperature inside the chamber as well as silica gel guide tube connecting with a 100-mL syringe and a three-way stopcock for gathering gas.

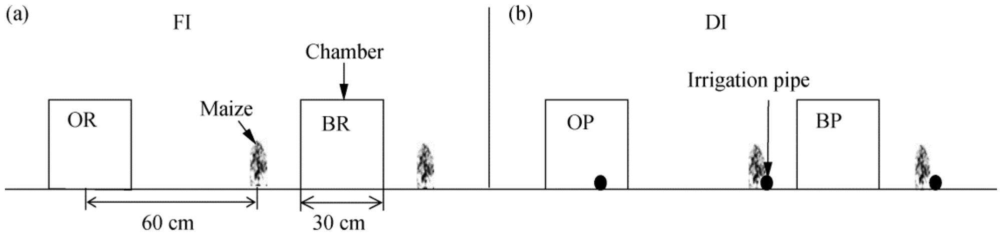

Fig. 1 Locations of the chambers under FI (a) and DI (b) treatments. FI, flood irrigation; DI, drip irrigation; OR, on plant rows; BR, between plant rows; OP, on irrigation pipes; BP, between irrigation pipes.

Gas sampling lasted for 30 min each time. On each sampling day, gas samples were taken immediately after chamber closure and collected into polyethylene-coated aluminum gas bags at 10-min intervals (at 0, 10, 20, and 30 min) for CO_2 gas concentration analysis. Meanwhile, when gas sampling is done each time, air temperature (T-air) was simultaneously measured by a DHM2 mechanical ventilated thermometer. The soil temperatures at the depths of 0 (T-0), 5 (T-5) and 10 cm (T-10) around the chamber were measured using a SN2202 digital thermos detector immediately before the closure of chamber and after the removal of chamber. Temperature in the interior of the chamber was measured immediately after each gas sampling with a thermometer installed on the chamber lid.

Following the advices by Xu and Qi (2001), samplings were conducted between 09:00 and 11:00 (Beijing time) when the measured efflux is advocated to be representative for the daily mean efflux. Flux measurements were made in 10-day intervals during the growing season. The CO_2 concentrations were analyzed using a LI-6252 infrared CO_2 analyzer (LICOR Inc., Lincoln, NE, USA) in the laboratory within 7 days after gas sampling. The CO_2 flux rates were calculated from the rate of change in the CO_2 concentration in the air inside the chambers with time.

The Q_{10} value, namely temperature sensitivity of soil respiration, indicated the temperature dependence of soil respiration. The Q_{10} values were calculated from the b coefficient (Q_{10}=e^{10b}) of exponential regression functions between the soil CO_2 effluxes and temperature factors.

2.4 Soil sampling and analyses

After gas sampling, soil samples were also collected using a soil drill at the depths of 0–10 and 10–20 cm from each one of chamber locations. The soil microbial biomass carbon (MBC) was analyzed with the chloroform fumigation-extraction method using 0.5 M K_2SO_4 as an extractant (Wu et al., 2006). The soil dissolved organic carbon (DOC) was extracted by deionized distilled water. For MBC analyses, the sub-samples were stored at 4°C; and for DOC analyses, the sub-samples were stored at –20°C. The air-dried samples were hand-ground through a 100-mesh sieve for total organic carbon (TOC) analysis. The concentrations of MBC, DOC and TOC were all analyzed by a TOC analyzer (Vario TOC Cube, Elementar, Germany). The soil water contents (SWCs) at the depths of 0–10 and 10–20 cm were determined at 105°C for 24 h using the oven-drying method.

2.5 Data analysis

According to the relative area of each location per irrigation treatment, the total emission was the averaged total emissions of OP and BP under DI and of OR and BR under FI. The cumulative emissions for each irrigation type and each location were calculated by successive linear interpolation of all measurement times per day using Matlab 7.0. Graphs were prepared using Origin 8.5. Pearson correlation coefficients between the soil environmental factors and the CO_2 effluxes were calculated, and one-way ANOVA and paired sample tests were used for statistical comparisons across locations and between irrigation practices (FI and DI) using SPSS 17.0.

3 Results

3.1 Temporal variations of CO_2 effluxes

The soil CO_2 effluxes under FI and DI showed similar temporal patterns (Fig. 2). The fluxes decreased before the elongation stage, rapidly increased and reached the peak at the bell stage, and then declined until harvest. The daily CO_2 effluxes changed in the range of 233.86 to 1026.85 and 257.72 to 992.73 mg/(m^2•h) under DI and FI, respectively. Over the entire growing season, the mean CO_2 effluxes were 694.66 mg/(m^2•h) under DI and 609.54 mg/(m^2•h) under FI, and no significant diurnal difference was detected between the two irrigation practices. In all, the cumulative CO_2 emissions at the field scale were 1959.10 and 1759.12 g/m^2 under DI and FI, respectively.

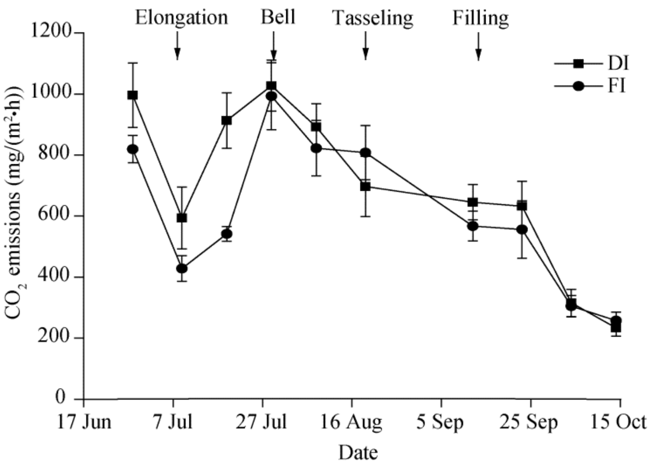

Fig. 2 Temporal dynamics of soil CO_2 effluxes under drip irrigation (DI) and flood irrigation (FI) during the maize growing season in 2014. Vertical bars indicate standard errors (n=6).

3.2 Spatial variations of CO_2 effluxes

In the FI treatment, the CO_2 effluxes in the reserved bare area (BA) were larger than those in other locations (i.e., maize plots) before the elongation stage, and then the CO_2 effluxes on plant rows (OR) were larger than those in the BA and also than those between plant rows (BR) (Fig. 3). The average CO_2 effluxes under FI for OR, BR and BA were 699.72, 549.89 and 601.86 mg/(m^2•h), respectively. The difference between OR and BR is significant according to the paired-sample t-test (P<0.05). In the DI treatment, the CO_2 effluxes on irrigation pipes (OP) were significantly larger than those between irrigation pipes (BP) and in the BA (P<0.01). The average CO_2 effluxes for OP, BA and BP under DI were 774.33, 622.52 and 617.86 mg/(m^2•h), respectively. The proportion of root respiration contributing to the soil CO_2 emissions on OR under FI ranged from 17.49% to 46.66%, and the proportion on irrigation pipe (OP) under DI ranged from 3.45% to 46.55%.

The cumulative CO_2 emissions for OR, BR and BA under FI were 2034.17, 1575.92 and 1712.42 g/m^2, respectively. The cumulative emissions for OP, BP and BA under DI were 2205.56, 1720.55 and 1704.41 g/m^2, respectively. It means that the difference between DI and FI is not significant. The soil CO_2 emissions in the BA were larger than those between BR under FI, whereas the soil CO_2 emissions in the BA were smaller than those between BP under DI.

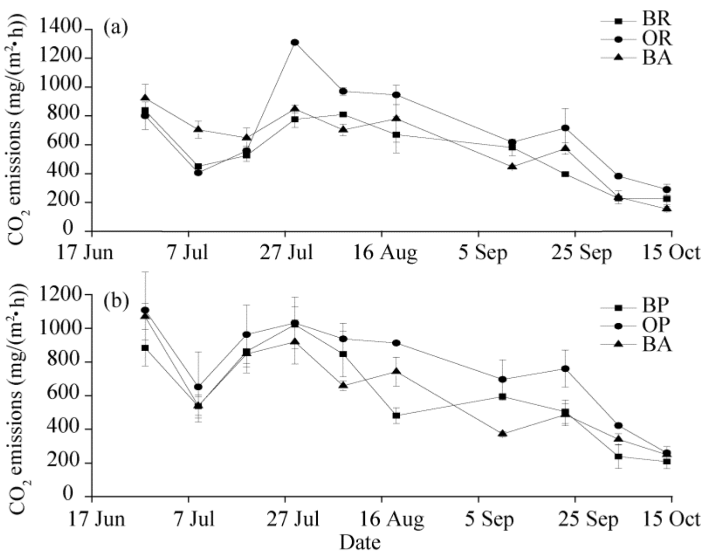

Fig. 3 Spatial variations in soil CO_2 effluxes in the maize field under flood irrigation (a) and drip irrigation (b) during the maize growing season in 2014. BR, between plant rows; OR, on plant rows; BA, bare area; BP, between irrigation pipes; OP, on irrigation pipes. Vertical bars indicate standard errors (*n*=3).

3.3 Soil water content and temperature

3.3.1 Soil water content (SWC)

SWC at the depth of 0–10 cm varied between 14.14% and 29.51% under FI and between 14.54% and 27.92% under DI (Fig. 4). SWC at the depth of 10–20 cm varied between 17.89% and 32.76% under FI and between 13.73% and 28.22% under DI. SWC exhibited a decreasing order of BA>BP>OP under DI and a decreasing order of BA>BR>OR under FI at each one of the measured soil depths. Generally speaking, SWC under FI was larger than that under DI at the same depth and SWC at shallow depth (0–10 cm) was larger than that at deeper depth (10–20 cm). Correlation analysis indicated that the soil CO_2 effluxes were highly and positively correlated with SWC during the growing season. The stepwise regression analysis suggested that the main factor affecting CO_2 emissions was SWC at the depth of 0–10 cm under FI, whereas the main factor was SWC at the depth of 10–20 cm under DI.

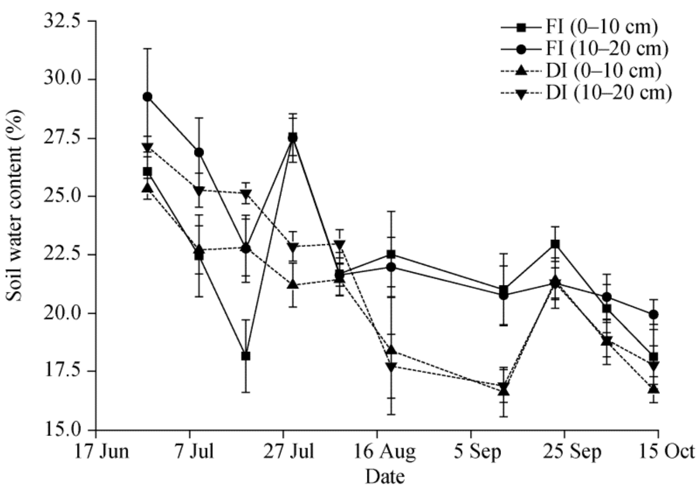

Fig. 4 Soil water content at the depths of 0–10 and 10–20 cm under flood irrigation (FI) and drip irrigation (DI) in 2014. Vertical bars indicate standard errors (*n*=3).

3.3.2 Air temperature and soil temperature

The mean values of T-air (air temperature), T-0 (soil temperature at depth of 0 cm), T-5 (soil temperature at depth of 5 cm) and T-10 (soil temperature at depth of 10 cm) during the growing season exhibited a decreasing order of T-air>T-0>T-5>T-10 under both DI and FI (Fig. 5). Correlation analysis indicated that the soil CO_2 effluxes were highly and positively correlated with air temperature (T-air) and also with soil temperatures of different depths. The Q_{10} values (i.e., temperature sensitivity of soil respiration) increased with soil depths under the same irrigation treatment (Table 2), indicating that the soil respiration in the deeper soil horizons was more sensitive to the temperature change than that in the shallow soil horizons. T-0 under FI and T-5 under DI were found to be the best-fitting factors for explaining the change in CO_2 emissions, and they could explain approximately 41.3% (FI) and 45.9% (DI) of the variations in soil CO_2 emissions, respectively.

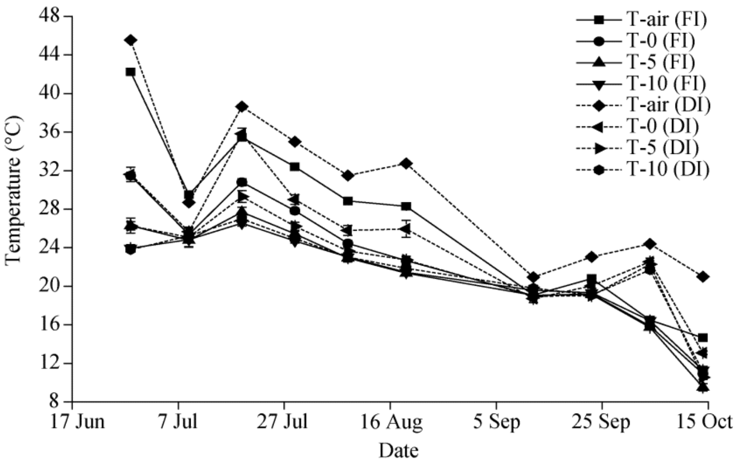

Fig. 5 Air temperature (T-air) and soil temperatures at the depths of 0 cm (T-0), 5 cm (T-5) and 10 cm (T-10) under DI and FI in 2014. Vertical bars indicate standard errors (*n*=3).

Table 2 Exponential regression functions between soil CO_2 emissions and temperature under FI and DI

Irrigation treatment	Parameter	Equation	R^2	Q_{10}
FI	T-air	y=207.4e$^{0.036x}$	0.382	1.43
	T-0	y=173.2e$^{0.050x}$	0.413	1.65
	T-5	y=157.7e$^{0.058x}$	0.400	1.79
	T-10	y=128.7e$^{0.068x}$	0.379	1.97
DI	T-air	y=164.6e$^{0.043x}$	0.396	1.54
	T-0	y=149.9e$^{0.057x}$	0.450	1.77
	T-5	y=123.6e$^{0.071x}$	0.459	2.03
	T-10	y=100.6e$^{0.083x}$	0.442	2.29

Note: T-air, air temperature; T-0, soil temperature at depth of 0 cm; T-5, soil temperature at depth of 5 cm; T-10, soil temperature at depth of 10 cm.

3.4 Soil DOC, MBC and TOC

The concentrations of soil dissolved organic carbon (DOC), microbial biomass carbon (MBC) and total organic carbon (TOC) of BR (i.e., between plant rows) and OR (i.e., on plant rows) situations under FI (i.e., flooding irrigation), OP (i.e., on irrigation pipes) and BP (i.e., between irrigation pipes) situations under DI (i.e., drip irrigation) during the growing season were averaged at each of the two measured soil depths (Table 3). The DOC, MBC and TOC concentrations decreased with increasing soil depths, and the average concentrations under FI were larger than those under DI at all the measured soil depths. No significant differences were found between FI and DI in the soil TOC, DOC, and MBC concentrations for the same soil depth (either 0–10 or 10–20 cm). However, significant differences were found between shallow soil (0–10 cm) and deeper soil (10–20 cm) under the same irrigation treatment (either FI or DI).

Over the growing season, the DOC concentrations varied between 24.71 and 94.18 mg/kg under FI and between 30.20 and 98.20 mg/kg under DI at the depth of 0–10 cm. The DOC concentrations varied between 8.61 and 125.06 mg/kg under FI and between 19.21 and 88.84 mg/kg under DI at the depth of 10–20 cm. The soil MBC concentrations varied between 90.94 and 369.80 mg/kg under FI and between 48.12 and 326.15 mg/kg under DI at the depth of 0–10 cm. The MBC concentrations varied between 6.85 and 252.29 mg/kg under FI and between 42.94 and 202.33 under DI at the depth of 10–20 cm. The TOC concentrations varied between 22.4 and 32.8 g/kg under FI and between 20.9 and 26.0 g/kg under DI at the depth of 0–10 cm. The concentrations varied between 20.6 and 37.2 g/kg and between 19.2 and 23.3 g/kg under DI at the depth of 10–20 cm.

Correlation analysis showed that soil CO_2 effluxes were significantly and positively correlated with soil MBC concentration at the depth of 0–10 cm under DI (r=0.505). And, soil CO_2 effluxes were significantly and negatively correlated with soil DOC concentration at the depth of 10–20 cm under DI (r= –0.672).

Table 3 Concentrations of soil DOC, MBC and TOC at the depths of 0–10 and 10–20 cm under DI and FI

	DI		FI	
	0–10 cm	10–20 cm	0–10 cm	10–20 cm
DOC (mg/kg)	58.51±4.00^{Aa}	43.86±3.65^{Ab}	62.12±3.67^{Aa}	47.21±5.68^{Ab}
MBC (mg/kg)	168.52±25.30^{Aa}	126.50±15.78^{Ab}	210.61±25.38^{Aa}	121.91±21.95^{Ab}
TOC (g/kg)	22.7±0.62^{Aa}	21.8±0.40^{Aa}	25.1±1.07^{Aa}	23.9±1.61^{Aa}

Note: DOC, dissolved organic carbon; MBC, microbial biomass carbon; TOC, total organic carbon. Different capital letters indicate significant differences in the soil DOC, MBC and TOC concentrations at the same soil depth under different irrigation treatments (i.e., FI and DI), and different lowercase letters represent significant differences in the soil DOC, MBC and TOC concentrations at different soil depths under the same irrigation treatment.

4 Discussion

4.1 Effects of irrigation on soil CO_2 emissions

Irrigation practice may affect the production and emission of CO_2 (Kallenbach et al., 2010). Again, compared with FI, DI was performed at more regular intervals in much smaller amounts with less intense water supply and slower water movement (Chai et al., 2008). Therefore, the less-disturbed soil with more air movement under DI treatment could release more CO_2 from the soil into the atmosphere. Additionally, more frequent irrigation at regular intervals in small amounts under DI treatment could enhance soil wetting-drying cycles, and thus increase the CO_2 fluxes by promoting microbial activities, carbon mineralization, and respiration (Sparling and Ross, 1988; Van Gestel et al., 1993; Calderón and Jackson, 2002). Our results indicated that soil CO_2 emission during the growing season was higher under DI than under FI, being supportive to the results obtained by Niu et al. (2014) and Zhang et al. (2014). Correlation analysis suggested that the soil CO_2 emission was highly correlated with SWC and soil temperatures, lending further support to Wiseman and Seiler (2004) who concluded that SWC and soil temperatures could affect soil CO_2 emission through modulating the decomposition rate of the soil organic matter. However, no significant differences in soil CO_2 emissions were observed between FI and DI. This may be resulted from lower SWC under both DI and FI treatments and the lowered SWC could mitigate the effect of temperature on the production and emissions of CO_2 during the maize growing season (Qi et al., 2010).

4.2 Effects of irrigation on spatial variations in soil CO_2 emissions

Under DI treatment, SWC and soil nutrients distributions are highly heterogeneous due to vertical and lateral infiltrations (Allen et al., 1998). The spatial heterogeneities of the SWC and soil nutrients certainly have a significant impact on the spatial distribution of greenhouse gas emission from agricultural soil (Xu and Qi, 2001; Tang and Baldocchi, 2005; Kallenbach et al., 2010; Kennedy et al., 2013). Our results showed that the proportions of root respiration contributing to the soil CO_2 emissions of OP (on irrigation pipes) ranged from 3.45% to 46.55% under DI and from 17.49% to 46.66% to the soil CO_2 emissions of OR (on plant rows) under FI. Moreover, the average contribution of root respiration to the soil CO_2 emission of OP under DI was 22.72%, being significantly larger than that of OR under FI (15.82%), probably because irrigation water and fertilizers were applied along plant rows, providing more water and more nutrients under DI. The CO_2 emissions from the plant rows (OR under FI and OP under DI) were higher than those from other locations (e.g., BR under FI and BP under DI), being consistent with the measurements by Lv et al. (2014). The soil CO_2 emissions of BA under DI had no significant difference with those of BP, probably because higher SWC in the BA than in other locations (e.g., OP and BP) offset the contribution of root respiration to soil CO_2 emission of BP and the high SWC may have been resulted from lessened evapotranspiration due to shelter from maize plants. Correlation analysis showed that the soil CO_2 emissions were highly and positively correlated with the SWC and temperatures. The relatively high soil CO_2 emissions from the plant rows (OR under FI and OP under DI) mean that higher SWC and root respiration might have released more CO_2. For the same spatial locations, DI treatment with less-disturbed soil and with more air movement might have released more CO_2 and the SWC and soil temperatures might have affected soil CO_2 emission through modulating the decomposition rate of the soil organic matter.

4.3 Effect of irrigation on total organic carbon and labile carbon

Our results showed that the concentrations of soil DOC and MBC under FI were larger than those under DI, being consistent with the results obtained by Han et al. (2010) who reported that high irrigation amounts under FI could result in temporary water saturation and could consequently inhibit the microbial activity, leading to higher DOC and MBC. Our results show that DOC had a negative relationship with SWC only at the 10–20 cm depth (not at the depth of 0–10 cm), being somewhat supportive to Wang and Bettany (1993) and Han et al. (2010) who reported that FI could increase the leaching loss of soil DOC in shallow soil layers, leading to an increase in the DOC concentration in deep soil layers.

Either under FI or under DI, SWC could be tightly associated with microbial activities, thus increasing or decreasing soil organic matter accumulation and decomposition (Gillabel et al., 2007; Butenschoen et al., 2011; McDowell and Smith, 2012; Arroita et al., 2013). In other words, either too less or too much of irrigated water in crop fields could result in an increase in soil microbial activities, leading to a reduction in decomposition rate of the soil organic matter. Our results showed that the SWC and temperature conditions under DI were more favorable for organic matter decomposition. The microbial quotient (the ratio of MBC to TOC) was calculated to further assess the quality of soil TOC, and it was regarded by some authors as a good index of the changes in soil organic matter quality (Insam and Merschak, 1997). Larger ratios implied an increase in the availability of fresh substrates (Anderson and Domsch, 1986). In the present study, the ratios of MBC/TOC under FI were larger than those under DI at the depth of 0–10 cm, whereas they were smaller than those under DI at the depth of 10–20 cm. It suggested that DI was better in improving the soil quality at the depth of 10–20 cm.

5 Conclusions

Our results demonstrated that drip irrigation (DI) increased both the mean CO_2 effluxes and the cumulative CO_2 emissions compared with flood irrigation (FI) during the maize growing season. The ratio of the root respiration contribution to soil respiration was larger under DI than under FI. The soil temperature and SWC were the main factors affecting the CO_2 effluxes both under DI and FI. The Q_{10} values (i.e., temperature sensitivity of soil respiration) at different soil layers were larger under DI than under FI. Generally speaking, FI with a higher irrigation volume resulted in temporary water saturation and consequently inhibited the microbial activity, leading to higher DOC and MBC. However, DI significantly increased the quality (the ratio of MBC to TOC) of soil total organic matter (TOC) at the depth of 10–20 cm compared with the ratio at the same depth under FI. Our results suggest that the transformation from conventional FI to integrated DI can increase the CO_2 emissions and that drip irrigation practice needs to be combined with other management practices to reduce the CO_2 emissions from summer maize fields in the North China Plain. The CO_2 emissions could be compensated by the net primary productivity of maize, and the net carbon balance should be in-depth and further studied to assess the effect of different irrigation practices on the total carbon sink.

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