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Research paper

Biophysical controls of soil respiration in a wheat-maize rotation system in the North China Plain

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ABSTRACT

Croplands play a vital role in regional carbon budgets. We hypothesized that biophysical factors would be important for soil respiration in a wheat-maize rotation cropping system. Soil CO_2 efflux was measured using the closed chamber method, and net CO_2 exchange between the cropland and the atmosphere obtained by the eddy covariance technique in a winter wheat-summer maize double cropping system over four years (Oct 2002–Oct 2006). In addition to soil temperature, soil respiration was controlled by leaf area index and soil moisture in the wheat field and soil moisture in the maize field. Temperature sensitivity (Q_{10}) of soil respiration was 2.2 in the wheat and maize growing seasons. In the wheat field, the Q_{10} value during the sowing–returning green period (4.9) was more than that during the returning green–ripening period (2.0). On a monthly time scale, soil respiration was controlled by gross primary productivity in the wheat field, indicating that soil respiration was coupled with ecosystem photosynthesis. Annual soil respiration was 825 ± 73g C m^{-2} in the wheat–maize rotation system in 2003–2006. Over a 4–year average, soil respiration was 355 ± 50 g C m^{-2} in the wheat growing season and 470 ± 67 g C m^{-2} in the maize growing season, which accounted for 43% and 57% of the annual value respectively. At an annual time scale, soil respiration contributed to 72% of ecosystem respiration in the winter wheat–summer maize double cropping system.

1. Introduction

Soil is the largest source of CO_2 in terrestrial ecosystems (Bahn et al., 2009). Soil respiration accounts for 40–93% of ecosystem respiration and up to 90% of gross primary productivity (Janssens et al., 2001; Davidson et al., 2006; Payeur-Poirier et al., 2012). It is estimated that soil respiration releases about 78 Pg C annually to the atmosphere (Le Quéré et al., 2009). Thus, soil respiration is an important component of atmospheric carbon dynamics.

Soil respiration is mainly controlled by soil temperature and moisture (Knohl et al., 2008; Jassal et al., 2012; Chang et al., 2016). When soil moisture is not limiting, soil respiration increases with soil temperature (Rustad and Fernandez, 1998; Jassal et al., 2008). The Q_{10} value is defined as the change in soil respiration rate caused by a change in temperature of 10 °C (Lloyd and Taylor, 1994). Raich and Schlesinger (1992) found the Q_{10} value varied from 1.3 to 3.3, with an average of 2.4 in temperate regions. The Q_{10} value can change seasonally, decreasing with increasing soil temperature (Xu and Qi, 2001; Janssens and Pilegaard, 2003). The response of soil respiration to soil moisture is the result of several processes involving osmotic stress, diffusion and oxygen limitations (Moyano et al., 2012). Soil respiration can be inhibited under high or low soil moisture conditions (Borken et al., 1999; Rey et al., 2002; Inglima et al., 2009; Ding et al., 2010; Yan et al., 2014; López-Ballesteros et al., 2015). Low soil moisture limits microbial activity, but high soil moisture reduces air filled porosity and limits the diffusion of soil gases (Davidson et al., 1998, 2000).

However, soil temperature and moisture are not the only factors controlling soil respiration. Respiration is also correlated with gross primary productivity, indicating that the supply of photosynthates to the roots may be important in regulating respiration (Bahn et al., 2009; Jassal et al., 2012; Payeur-Poirier et al., 2012; Han et al., 2014; Jing et al., 2016). In addition, gross primary productivity is coupled with the production of fine organic matter, such as leaves and roots (Janssens et al., 2001). The decomposition of this fine organic matter can

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comprise a large fraction of heterotrophic respiration (Janssens et al., 2001). If these biotic factors (e.g. root and foliage production) exert more influence on soil respiration than soil temperature and soil moisture, estimates of soil respiration using only temperature and water content variables will result in large errors (Janssens and Pilegaard, 2003). Thus, taking into account biotic factors (e.g. leaf area index, LAI), in addition to soil temperature and moisture, will improve the accuracy of soil CO_2 efflux estimates.

The potential of C sequestration in arable soils of China is estimated to be 200–300 kg C ha^{-1} yr^{-1} (Lal, 2004). Any change in the soil carbon budget of croplands will have an important impact on the carbon cycle in China (Zhang et al., 2013). The area of croplands in the North China Plain (NCP) is approximately 1.8×10^6 ha, which is 18.3% of the land area of China. These croplands in the NCP account for 51% and 32% of national wheat and maize yields respectively. Croplands of the NCP are highly influenced by agricultural management (e.g. tillage, irrigation and fertilization), which will have an effect on the magnitude of soil respiration and the regional carbon budget. Soil temperature is a good predictor of temporal variation in soil respiration. However, temperature alone is inadequate to explain reductions in soil respiration at the milking stage of wheat and changes in soil respiration in a maize cropland in the NCP. To date, much attention has been paid to soil respiration in single cropping or intercropping systems (Eshel et al., 2014; Hu et al., 2015). However, knowledge on soil carbon fluxes of the double cropping system, and the influence of biophysical factors on soil respiration have been lacking. Therefore, the objectives of this study are to (i) investigate biophysical factors controlling soil respiration in the winter wheat and summer maize fields; (ii) examine the relationship between soil respiration and ecosystem productivity; and (iii) explore the contribution of soil respiration to ecosystem respiration. This study will provide important insights into the influence of biophysical drivers on soil respiration in croplands.

2. Materials and methods

2.1. Site description

The study was carried out at Yucheng Comprehensive Experiment Station, Chinese Academy of Sciences (36°57′N, 116°36′E, 20 m elev.). The station is located in the North China Plain, with a semiarid and warm temperate climate. Mean annual air temperature, precipitation and solar radiation in the past three decades at this site are 13.1 °C, 528 mm and 5225 MJ m^{-2}, respectively. Summer precipitation accounts for approximately 70% of annual values. Soil parent materials are alluviums by the Yellow River. Soil texture in the root zone is sandy loam. Soil organic matter and total N content is 1.2% and 0.14%, respectively. Soil bulk density is 1.28 g cm^{-3} and pH is 7.9.

2.2. Field management

The main cropping system is a winter wheat and summer maize rotation. The growing season of winter wheat is from early October to mid-June, and mid-June to late September/early October for summer maize. In the wheat growing season, the land was tilled, irrigated four times (at the overwintering, returning green, jointing and flowing stages, respectively), and fertilized twice (before sowing and at stem elongation stage). In the maize growing season, N fertilizer was applied at the stem elongation stage. The row spacing was 25 cm for wheat and 60 cm for maize. Further details of field management can be found in Tong et al. (2007).

2.3. Soil respiration observations

Soil respiration was measured by a closed static chamber/gas chromatograph method for four years (Oct 2002–Oct 2006). The closed opaque chamber was made of stainless steel, with a size of 50 cm × 20 cm × 30 cm for the wheat field and 50 cm × 50 cm × 50 cm for the maize field. The opaque chamber was covered with a cotton quilt to isolate heat. The chamber was fitted with two micro-fans (diameter: 10 cm; power: 12 W), a sampling tube and a thermometer. The stainless steel frames were inserted into inter-row soil at depths of 10 cm in the wheat field and 20 cm in the maize field, both with three replications. There were many holes (diameter: 2.5 cm) in the underground part of the frame to allow for roots to enter. At the beginning of the measurements, the chambers were mounted on the frame by a watertight seal. Gas inside the chambers was sampled using 100 ml injectors at 0, 10, 20 and 30 min after the chambers were closed. Air temperature inside the chamber, soil temperature and soil water content were measured simultaneously. Gas sampling was conducted twice a week from April to September, weekly in March, October and November, and every two weeks from December to February. Measurement of soil CO_2 efflux was carried out in the morning (9:00–10:00). Diurnal observations were conducted monthly from April to September. Gas samples were collected every two hours in the daytime and every three hours at night.

2.4. Gas chromatograph analysis and flux calculation

Gas samples were sent to the laboratory and analyzed by gas chromatography (GC). The gas chromatography (Angilent 4890D) was equipped with a ^{63}Ni electron capture detector (ECD) and a stainless steel separation cylinder (diameter: 3 mm, length: 2 m) with Porapak Q (80/100 mesh) inside. High purity N_2 (99.999%) was used as the carrier gas. The working temperatures of the cylinder and the detector were 55 and 330 °C, respectively. Standard gas, with a concentration of 350 ppm for CO_2, was supplied from the State Standard Material Center of China, Beijing.

Soil respiration was calculated as:

$$R_s = h_c \frac{MP}{RT} \frac{dC}{dt} \tag{1}$$

where R_s is soil respiration (μg m^{-2} h^{-1}), h_c is the height of the chamber (m) (0.3 m in the wheat field and 0.5 m in the maize field), M is the molar mass of CO_2 (g mol^{-1}), R is the gas constant (8.3144 Pa m^3 mol^{-1} K^{-1}), P is air pressure (Pa), T is air temperature inside the chamber (K), t is the time after the chamber is closed (h) and C is CO_2 concentration (μL L^{-1}).

The relationship between soil respiration and soil temperature was modeled by an exponential function:

$$R_s = R_0 e^{bT_s} \tag{2}$$

where R_0 is the base soil respiration rate when soil temperature is 0 °C, b is an experimental coefficient, T_s is soil temperature at a 5 cm depth. Q_{10} is the increase in soil respiration for a 10 °C increase in temperature, and can be expressed as (Lloyd and Taylor, 1994):

$$Q_{10} = e^{10b} \tag{3}$$

In the returning green–harvest period of wheat, the influence of soil temperature, soil moisture and LAI on soil respiration was expressed as:

$$\ln R_s = a_1 \ln LAI + a_2 T_s + a_3 \ln W_s + a_0 \tag{4}$$

where W_s is soil water content at a 20 cm depth, LAI is leaf area index, a_0, a_1, a_2 and a_3 are the fitted parameters.

The effect of soil temperature and moisture on soil respiration in the maize cropland was expressed as:

$$\ln R_s = b_1 T_s + b_2 \ln W_s + b_0 \tag{5}$$

where b_0, b_1 and b_2 are constants fitted by the regression.

2.5. Ecosystem CO_2 fluxes, micrometeorological variables and leaf area observations

CO_2 fluxes were measured by the eddy covariance system with a 3-D sonic anemometer (model CSAT3, Campbell Sci. Inc., USA) and an infrared open-path CO_2/H_2O gas analyzer (model LI-7500, Li-Cor Inc., USA). The eddy covariance system was mounted at a height of 2.1 m in the winter wheat growing season and 3.1 m in the summer maize growing season. Raw data were collected at 10 Hz and recorded by a CR5000 datalogger (model CR5000, Campbell Scientific Inc., USA). Soil temperature was measured at 0, 5, 10, 30 and 50 cm depths. Soil water content was measured with time domain reflectometers (TDR) (model CS616, Campbell Sci. Inc., USA) at depths of 20 and 30 cm. Precipitation was measured with a rain gauge (Model 52203, RM Young Inc., Michigan, USA). All meteorological data were recorded with a data logger (model CR23x, Campbell Sci. Inc., USA) and stored at half-hour intervals. During wheat and maize growing seasons, leaf areas were measured weekly with a leaf area meter (Li-3100, Li-Cor Inc, USA), with three replicates.

2.6. Data proceeding of ecosystem CO_2 fluxes

Raw carbon flux data obtained by the eddy covariance system were processed by two dimension coordinate rotations (McMillen, 1988) and Webb-Pearman-Leuning (WPL) correction (Webb et al., 1980) before the 30-min mean flux was calculated. CO_2 flux data affected by rain and dew were eliminated following the strategies summarized by Falge et al. (2001). At night, CO_2 flux would be underestimated owing to weak turbulence, and thus the data were deleted when friction velocity (u^*) was lower than 0.15 m s^{-1} (Li et al., 2006).

In the nighttime net ecosystem carbon exchange (NEE) is often used to represent ecosystem respiration (R_n). The relationship between nighttime NEE and corresponding soil temperature at a 5 cm depth (T_s) and LAI was expressed by:

$$R_n = ae^{bT_s}e^{(mLAI+n)} \tag{6}$$

where a, b, m and n are the fitted parameters. Daytime ecosystem respiration (R_d) can be estimated by extrapolation from the parameterization derived from Eq. (6).

Daily ecosystem respiration (R_{ec}) was given by:

$$R_{ec} = R_d + R_n \tag{7}$$

Gross primary productivity (GPP) was calculated as:

$$GPP = R_{ec} - NEE \tag{8}$$

where NEE is net ecosystem carbon exchange obtained by eddy covariance.

3. Results

3.1. Seasonal variation of soil respiration

Fig. 1 shows the seasonal pattern of daily soil respiration and biophysical factors. In autumn, soil respiration was not low (> 2 g C m^{-2} d^{-1}). Tillage and fertilization changed soil physical properties before winter wheat was sowed. Respiration was small in winter when soil biological activity was minimal owing to low soil temperature. In spring, soil respiration increased as wheat growth progressed, peaking in May when soil temperature was high and LAI was large. The maximum soil respiration in the wheat growing seasons of 2003–2006 was 3.6, 4.2, 3.2 and 4.4 g C m^{-2} d^{-1}, respectively. After late June, soil respiration rose, coinciding with increasing soil temperature and soil moisture and the growth of maize. Annual maximum soil respiration occurred in July, before decreasing after August with declining LAI.

During the wheat growing season there was low precipitation in spring. Irrigation and fertilization on April 5, 2005 resulted in soil moisture increasing from 10% to 20%, and consequently soil respiration increased on April 6, 2005 (Fig. 1). Similarly, enhanced soil respiration occurred on June 27, 2005 following heavy rainfall events on June 24–26, 2005. In contrast to these results, soil respiration declined steeply on August 12 and 18, 2004 following an intense precipitation event (Fig. 1).

3.2. Diurnal course of soil respiration

The diurnal pattern of soil respiration and soil temperature in the wheat and maize croplands is shown in Fig. 2. Maximum and minimum soil respiration occurred at 13:00 and 4:00, respectively. Soil respiration generally tracked changes in soil temperature, with a notable exception during high temperatures (> 30 °C) which were associated with declines in respiration (Fig. 2d). Nighttime and morning soil respiration were generally lower than afternoon soil respiration under the same soil temperature conditions.

3.3. Effects of soil temperature, soil moisture and LAI on soil respiration

Soil respiration increased exponentially with soil temperature at a 5 cm depth in the wheat and maize growing seasons (Fig. 3). Over the 4–year period, soil temperature explained 54% and 43% of the variation of soil respiration in wheat and maize croplands respectively. The mean Q_{10} value was 2.2 in the wheat–maize rotation system during the 4–year period (Fig. 3). The Q_{10} value varied largely among years, but not between crop types (Table 1). In the wheat field there were large differences in Q_{10} values over 2003–2006 (1.6–3.2; Table 1). Q_{10} values of 2003–2006 ranged from 1.9 to 3.1 in the maize field (Table 1). The Q_{10} value of the wheat field was highest in 2005, which had the lowest soil temperature. Similarly, Q_{10} was highest in the maize field in 2003 which also had the lowest temperature.

We also examined changes in the Q_{10} value in the wheat field during 2004 to assess intra-annual variation in Q_{10}. The Q_{10} value during the sowing–returning green period of winter wheat (4.9) was larger than that during the returning green–ripening period (2.0; Fig. 4). The larger Q_{10} value was associated with lower soil temperatures before the returning green stage of wheat.

Fig. 5 shows the effect of soil water content on soil respiration in the wheat and maize croplands. Soil respiration increased with an increase of soil water content in the wheat and maize fields, which is not regularly irrigated and relies on precipitation. Soil water content explained 22% and 29% of the variation in soil respiration in the wheat and maize fields respectively (Fig. 5).

Soil respiration had a significant relation with LAI in the wheat field ($P < 0.001$; Fig. 6a). During the returning green–flowering period of wheat, LAI may be correlated with soil temperature and soil moisture over time. During wheat milking–harvest period, soil temperature increased continuously but soil respiration decreased due to the decline of LAI (Fig. 1). There was no evident relationship between soil respiration and LAI in the maize field (Fig. 6b) because in this case soil temperature and soil moisture might be hiding the effect of LAI.

Table 2 shows a stepwise line regression of soil respiration against soil temperature, moisture and LAI. Soil temperature was the dominating factor controlling soil respiration during the period of wheat sowing–returning green. However, soil respiration was primarily determined by LAI, with 48% of the variation in soil respiration explained by LAI at the returning green–harvest stage of wheat. Additionally, LAI, soil temperature and moisture together explained 67% of the variability of soil respiration in the same period. Soil respiration was mainly controlled by soil temperature in the maize field, and less of the variation in soil respiration was attributed to soil moisture.

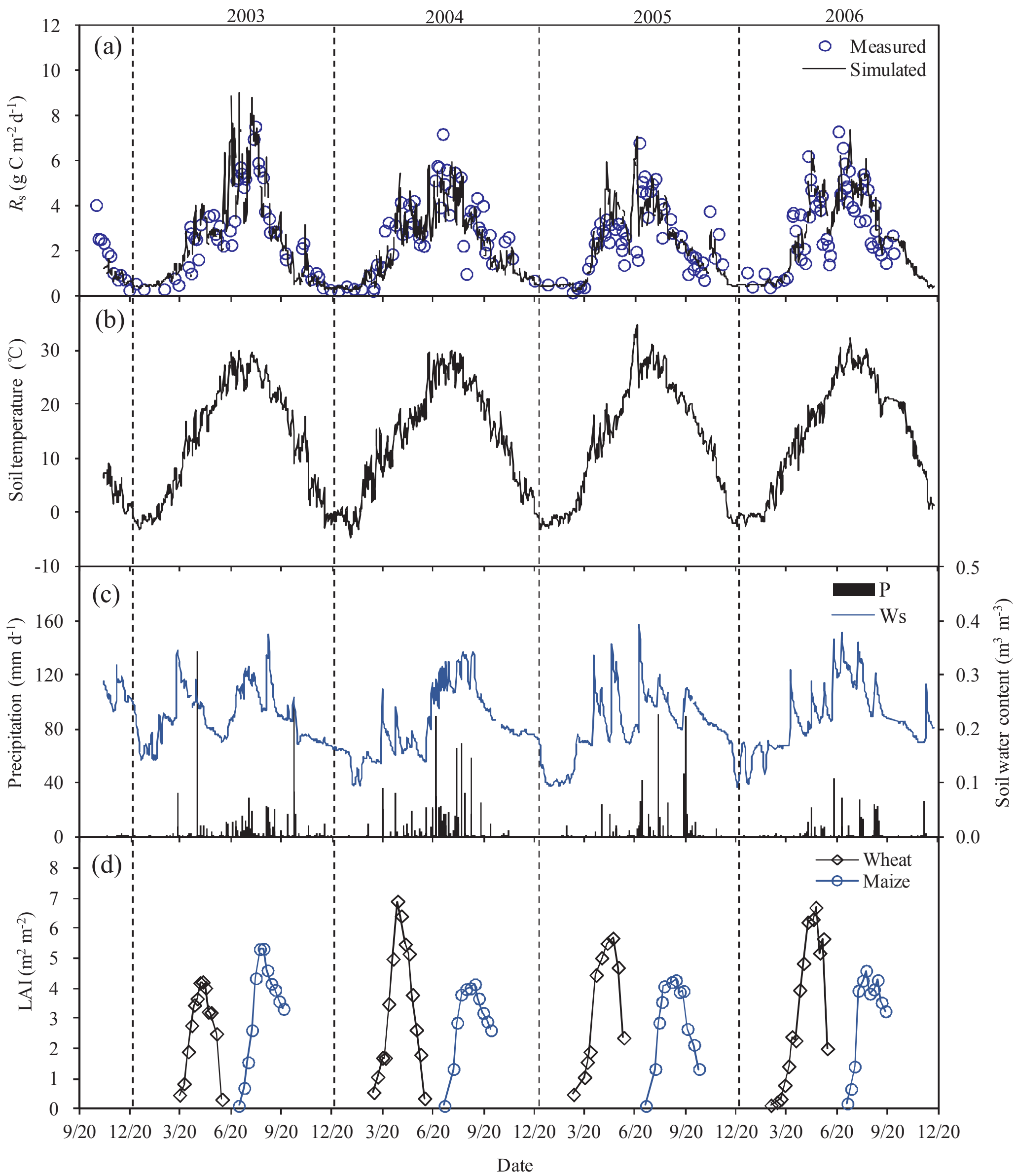

Fig. 1. Seasonal variation in daily soil respiration (R_s), daily mean soil temperature at a 5 cm depth, soil water content (W_s) at a 20 cm depth, daily precipitation (P) and leaf area index (LAI).

3.4. Effect of gross primary productivity on soil respiration

Monthly soil respiration was correlated with monthly GPP in the wheat field, but there was no relationship in the maize field (Fig. 7). At a monthly time scale, about 25% of photosynthates were consumed by soil respiration and entered into the atmosphere in the wheat field.

3.5. Annual and interannual soil respiration

Seasonal soil respiration of the wheat field was highest in 2006 and lowest in 2004 (Table 3), coinciding with a shorter period of maximum LAI compared to other years (Fig. 1d). Low soil respiration in 2004 was associated with spring drought and low soil moisture (Table 3 and Fig. 1c). In the maize field, seasonal soil respiration was highest in 2003 and lowest in 2005 (Table 3). The highest soil respiration in 2003 was due to large LAI (Table 3 and Fig. 1d).

Though the growing season of wheat was longer than that of maize, seasonal soil respiration in the maize field was higher than that in the wheat field (Table 3). In 2003–2006, soil respiration was 355 ± 50 g C m^{-2} for the wheat growing seasons and 470 ± 67 g C m^{-2} for the maize growing seasons, which accounted for 43% and 57% of the mean annual values respectively. Annual soil respiration in October 2002–October 2006 ranged between 759 and 893 g C m^{-2}, and the 4-year average was 825 ± 73 g C m^{-2} yr^{-1} (Tables 3 and 4), lower than the value of a double crop wheat-soybean rotation system but more than the result of a wheat-maize intercropping system (Table 4). Compared with single crop systems, annual soil respiration in this study was higher (Table 4). It was attributed to the less bare soil period in the double cropping system of this study.

3.6. Contribution of soil respiration to ecosystem respiration

Compared with the maize field, monthly soil respiration was more closely coupled with ecosystem respiration in the wheat field (Fig. 8). Monthly soil respiration accounted for about 47% of ecosystem respiration in the wheat cropland (Fig. 8a). The ratio of monthly soil respiration to ecosystem respiration (R_s/R_{ec}) was approximately 0.40 in the maize cropland (Fig. 8b). At an annual time scale, the R_s/R_{ec} ratio ranged from 66% to 76% in 2003–2006, and there was little difference among years (Table 3). The annual R_s/R_{ec} ratio in 2006 was highest during the 4-year period due to larger GPP than in other years. Mean annual R_s/R_{ec} ratio of winter wheat-summer maize rotation cropland was 72%.

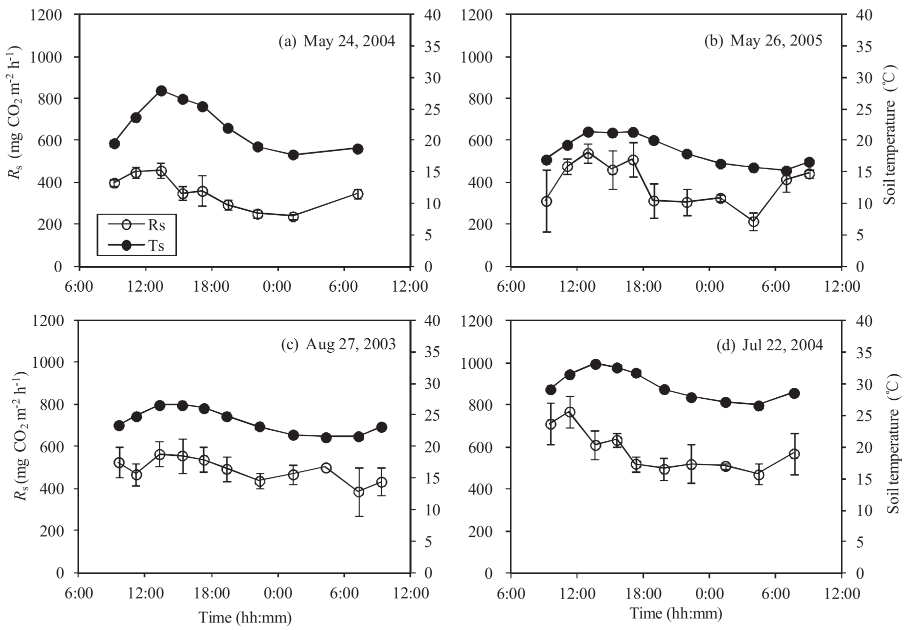

Fig. 2. Diurnal course of soil respiration (R_s) (open circle) and soil temperature (T_s) (solid circle) at a 5 cm depth in the wheat (a, b) and maize (c, d) fields.

4. Discussion

4.1. Effects of soil temperature on soil respiration

Soil temperature was the primary factor controlling soil respiration in the winter wheat and summer maize rotation in the North China Plain. However, at a daily time scale, there were differences in respiration for a given temperature throughout the day (Fig. 2). Carbon substrate supply and atmospheric CO_2 concentration can affect the relationship between soil temperature and respiration (Högberg et al., 2001; Kuzyakov and Cheng, 2001; Tang et al., 2005). Heat and CO_2 transport processes in soil can also result in soil respiration being out of phase with soil temperature (Phillips et al., 2011; Zhang et al., 2015). Substrate supply, heat transport and CO_2 diffusion are affected by soil moisture, which can affect the soil-temperature relationship at a seasonal time-scale (Phillips et al., 2011).

At a seasonal time scale, soil respiration is closely correlated with soil temperature when soil water is not limiting (Rustad and Fernandez, 1998; Curiel Yuste et al., 2003; Jassal et al., 2008). In this study, soil respiration had an exponential relationship with soil temperature in both wheat and maize fields (Fig. 3). During the period of 2002–2006, the Q_{10} value was 2.2 in wheat-maize rotation system in our study site with sandy loam soils, which is similar to the value reported by Alvarez and Alvarez (2001) for a wheat-soybean rotation field (2.18) with a thermic Typic Argiudoll (pH = 6.0). However, the Q_{10} value reported here is lower than reported for a maize field (3.04) with a sandy loam texture (pH = 8.65) (3.04, Ding et al., 2010), an Andosols of a grassland ecosystem (2.7–3.1, Yazaki et al., 2004) and a Gray Luvisol with coarse textured soils in an alfalfa cropland (5.4, Chang et al., 2016). Lower Q_{10} values have been reported for wheat fields with a Mexico silt loam soil (1.62, Buyanovsky et al., 1986) and a Stagnic Luvisols (a texture of 2.3% sand and 17.7% clay) (1.48–1.98, Demyan et al., 2016). This indicates the wide variation in Q_{10} across soil types, even under cultivation.

Table 1
Seasonal mean soil temperature at a 5 cm depth, soil water content (W_s) at a 20 cm depth, maximum leaf area index (LAI_{max}) and temperature sensitivity coefficient (Q_{10}).

Crop	Year	Soil temperature (°C)	W_s (m^3 m^{-3})	LAI_{max}(m^2 m^{-2})	Q_{10}	R^2	n
Wheat	2003	14.4	0.23	4.2	1.6	0.49	40
	2004	14.9	0.17	6.9	2.5	0.74	61
	2005	11.5	0.22	5.7	3.2	0.70	45
	2006	13.0	0.21	6.7	2.1	0.56	57
Maize	2003	24.2	0.26	5.3	3.1	0.57	47
	2004	25.7	0.28	4.1	1.9	0.45	24
	2005	24.3	0.25	4.3	2.6	0.53	53
	2006	26.1	0.29	4.6	2.6	0.54	63

The Q_{10} value decreased with an increase of soil temperature in the

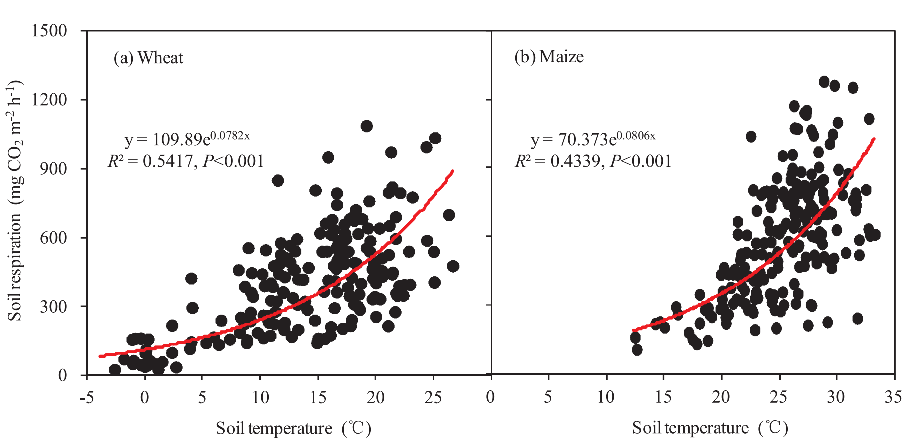

Fig. 3. Response of soil respiration to soil temperature at a 5 cm depth in the wheat (a) and maize (b) fields.

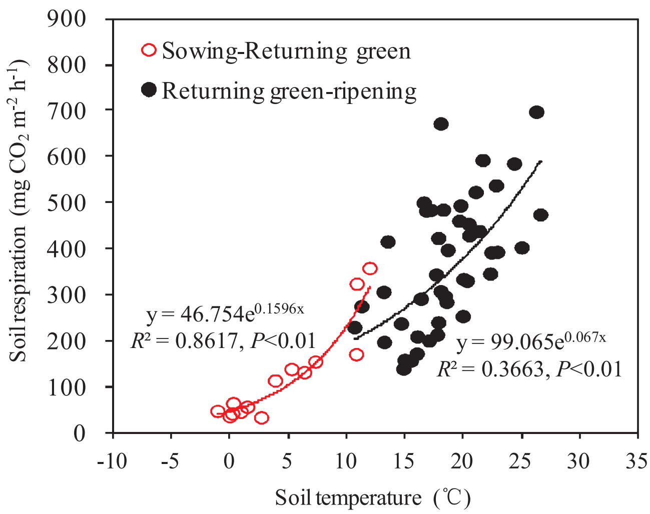

Fig. 4. Relationship between soil respiration and soil temperature at a 5 cm depth during the sowing–returning green (open circle) and returning green–ripening (solid circle) period of 2004 in a wheat field.

winter wheat field (Fig. 4), in agreement with the results obtained by Xu and Qi (2001) and Janssens and Pilegaard (2003). In forest ecosystems, larger Q_{10} values similarly occur under lower compared to higher temperatures (Peng et al., 2009; Pang et al., 2013). This difference in Q_{10} across temperatures may be due to the response of microbial populations to low temperatures and the effects of other temperature-sensitive processes such as the diffusion of organic matter through soil water films and cell metabolism (Janssens and Pilegaard, 2003).

4.2. Effect of soil water content on soil respiration

Strong inhibition of soil respiration has been reported under low soil water content (Borken et al., 1999; Harper et al., 2005; Shi et al., 2011; Liu et al., 2013; López-Ballesteros et al., 2015). Soil respiration was positively correlated with soil water content in the wheat and maize fields (Fig. 5), in agreement with previous observations (Medinski et al., 2015). When soil temperature is not restrictive, increased soil moisture enhances microbial activity and hence rhizosphere respiration, thus enhancing C mineralisation and soil CO_2 emissions (Van Gestel et al., 1993). Low soil moisture limits root respiration and microbial activity, decreases the soluble substrate diffusivity and microbial transport, and hence reduces the contact between microbes and the substrate (Rey et al., 2002).

Irrigation and precipitation events can result in a rapid burst of microbial activity and C mineralisation (Sainju et al., 2010), leading to an increase in soil respiration, consistent with our observations (Fig. 1). This increase in soil respiration following an irrigation or precipitation pulse is known as the Birch effect, where there is an activation of soil respiration and consequent mineralization of organic matter and CO_2 emission (López-Ballesteros et al., 2015). Precipitation can promote the decomposition of soil organic matter after prolonged dry periods, increasing soil microbial biomass (Rey et al., 2002). However, there is a limit to this positive relationship between pulses of soil moisture and respiration, with intense events suppressing CO_2 efflux, as we observed here (Fig. 1). This can be attributed to soil pores becoming filled with water after heavy precipitation, restricting CO_2 diffusion and the activity of microorganisms (Lee et al., 2010). Additionally, soil physical properties (e.g. soil compactness, clay content, C and N) can be degraded by heavy precipitation events (Ball et al., 1999; Borken and Matznen, 2009).

4.3. Effect of LAI on soil respiration

Apart from abiotic factors, biotic factors (e.g. LAI, net primary production) influence soil respiration (Bremer and Ham, 2002; Han et al., 2007). LAI rapidly increased over the wheat growing season (Fig. 1d). Increased LAI can increase detritus, but with a time lag of several months. Soil respiration increased with LAI in the wheat field (Fig. 6a), suggesting that the timing of photosynthetic activity and subsequent belowground allocation respond to seasonal variation in substrate availability (Hibbard et al., 2005). Similar results were found by other studies (Curiel Yuste et al., 2004; Hibbard et al., 2005; Shi et al., 2006). Therefore, in addition to soil temperature, LAI should be taken into account to improve the accuracy of soil respiration models. We did not find an evident relationship between soil respiration and LAI in the maize field (Fig. 6b). This may be due to the effects of soil temperature and moisture masking the effects of LAI on respiration.

4.4. Effect of gross primary productivity on soil respiration

Soil temperature and moisture often cannot explain more than 60% of seasonal variations in soil respiration (Sjogersten and Wookey, 2002; Ekblad et al., 2005). Thus, other factors (e.g. assimilate supply) are likely to be influencing soil respiration (Bahn et al., 2009; Jassal et al., 2012; Jing et al., 2016). At a monthly time scale, we found that soil respiration was highly correlated with GPP in the wheat field (Fig. 7a), consistent with results obtained in forests (Janssens et al., 2001; Jassal et al., 2012; Payeur-Poirier et al., 2012). Mycorrhizal and root respiration are directly affected by photosynthesis (GPP) (Moyano et al., 2008). The root and rhizosphere component of soil respiration is largely affected by allocation of photosynthates to roots and root exudates (Kuzyakov and Cheng, 2001; Wang et al., 2010). A high GPP increases substrate input to the soil and enhances soil fungi and bacteria decomposition of soil organic carbon (Kuzyakov and Cheng, 2001; Dijkstra and Cheng, 2007; Fontaine et al., 2007). Microbial activity in the rhizosphere can in turn affect heterotrophic respiration (Tang et al., 2005).

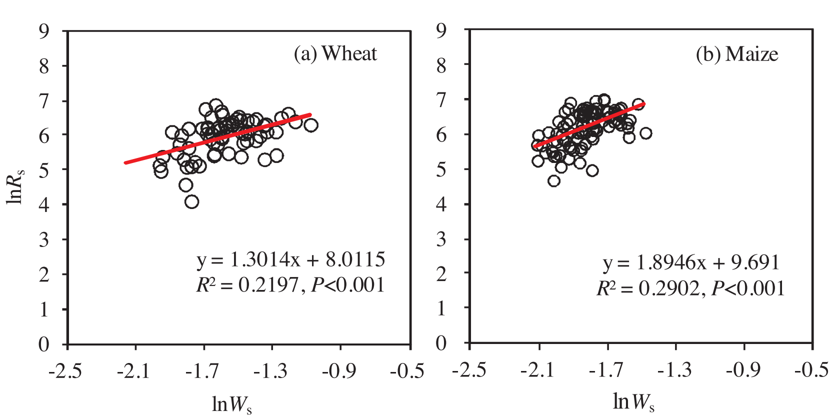

Fig. 5. Relationship between soil respiration (R_s) (mg CO_2 m^{-2} h^{-1}) vs daily mean soil water content (W_s) (m^3 m^{-3}) at a 20 cm depth in the wheat (a) and maize (b) fields.

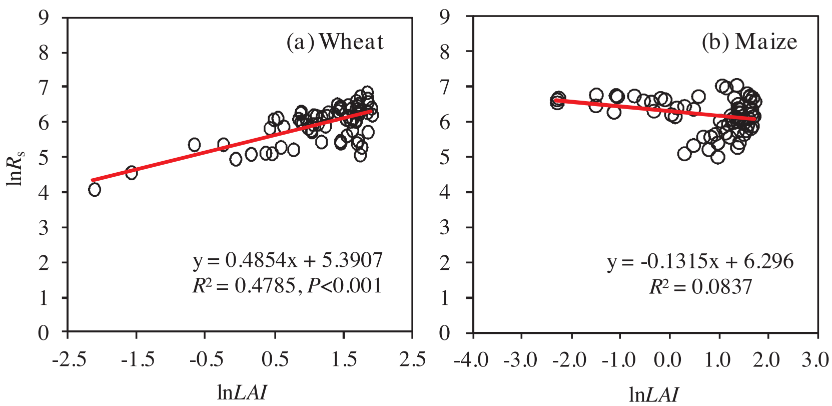

Fig. 6. Relationship between soil respiration (R_s) (mg CO_2 m^{-2} h^{-1}) vs leaf area index (LAI) (m^2 m^{-2}) in the wheat (a) and maize (b) fields.

Table 2
Stepwise multiple linear regression models for assessing the effects of soil temperature (T_s), leaf area index (LAI), soil water content (W_s) on soil respiration (R_s).

Cropland	Period	Independent variable	Model	*F*	R^2
Winter wheat	Sowing-returning green	T_s	$\ln R_s = 0.119T_s + 4.435$	40.23***	0.59
	Returning green-harvest	*LAI*	$\ln R_s = 0.486\ln LAI + 5.390$	61.67***	0.48
		LAI, T_s	$\ln R_s = 0.392\ln LAI + 0.040\ T_s + 4.912$	45.92***	0.58
		LAI, T_s, W_s	$\ln R_s = 0.324\ln LAI + 0.042\ T_s + 0.855\ln W_s + 6.323$	43.65***	0.67
Summer maize	Sowing-harvest	T_s	$\ln R_s = 0.084T_s + 4.177$	87.82***	0.56
		T_s, W_s	$\ln R_s = 0.075T_s + 0.679\ln W_s + 5.639$	48.79***	0.59

***: $P < 0.001$.

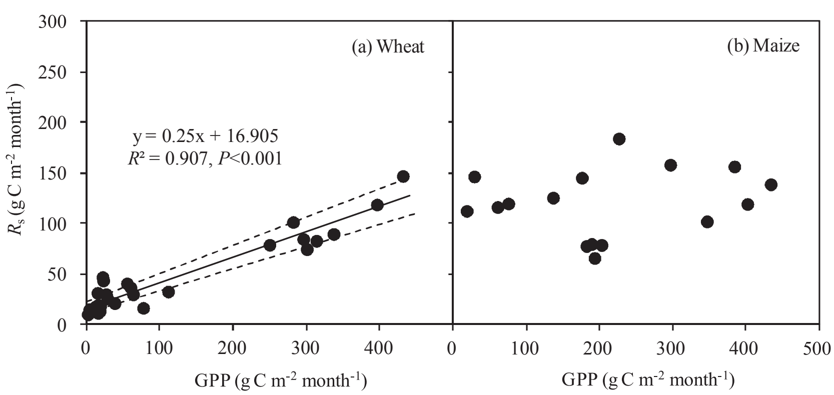

Fig. 7. Relationship between monthly soil respiration (R_s) and gross primary productivity (GPP) in the wheat (a) and maize (b) fields. The solid line is the fitted linear regression and the dotted lines are the upper and lower 95% confidence intervals.

Table 3
Seasonal, annual soil respiration (R_s), ecosystem respiration (R_{ec}), gross primary productivity (GPP) and the ratio of R_s to R_{ec} (R_s/R_{ec}).

Year	Growing season	R_s g C m^{-2}	R_{ec} g C m^{-2}	GPP g C m^{-2}	R_s/R_{ec}
2003	Wheat	325	570	714	0.57
	Maize	567	791	840	0.72
	Annual	893	1361	1554	0.66
2004	Wheat	317	531	749	0.60
	Maize	442	504	783	0.88
	Annual	759	1036	1533	0.73
2005	Wheat	351	576	922	0.61
	Maize	415	459	749	0.90
	Annual	766	1035	1671	0.74
2006	Wheat	427	645	880	0.66
	Maize	455	510	971	0.89
	Annual	883	1155	1851	0.76

4.5. Contribution of soil respiration to ecosystem respiration

Soil respiration accounted for 57–66% of ecosystem respiration in the wheat cropland (Table 3), slightly higher than values found by others (39–55%) (Moureaux et al., 2008; Suleau et al., 2011; Wang et al., 2015). The mean R_s/R_{ec} ratio of maize was about 0.85 during the 4–year period (Table 3), larger than that reported for maize crops in the Northwest of Wageningen in the Netherlands (0.41) (Jans et al., 2010) and in the North China Plain (0.49) (Wang et al., 2015). Compared with other years, the annual R_s/R_{ec} ratio of 2006 was largest owing to relatively high GPP compared to other years (Table 3). The root and rhizosphere component of soil respiration is largely coupled with aboveground photosynthesis (Kuzyakov and Cheng, 2001). High GPP increases substrate input to the soil and accelerates microbial decomposition of native soil organic carbon (Kuzyakov and Cheng, 2001; Dijkstra and Cheng, 2007). During the 4–year period, mean annual R_s/R_{ec} ratio of the winter wheat-summer maize rotation cropland was 72%, which is similar to juvenile boreal black spruce (67%), but less than mature boreal black spruce (93%, Payeur-Poirier et al., 2012) and mature aspen (86%, Gaumont-Guay et al., 2009). These differences between R_s/R_{ec} reported here and mature forests likely result from differences in GPP.

5. Conclusions

Both soil temperature and soil moisture had a strong effect on soil respiration in a winter wheat-summer maize double cropping system. Heavy precipitation or irrigation can stimulate soil respiration after a

Table 4
Annual soil respiration in the different croplands.

Crop	Experiment site	Location	Soil type	Soil pH	Soil respiration ($g\ C\ m^{-2}\ yr^{-1}$)	References
Wheat-soybean double cropping rotation	Rolling Pampa, Argentina	33°56′S, 60°34′W	Typic Argiudoll	–	1160	Alvarez et al. (1995)
Winter wheat	Columbia, MO, USA	–	Mexico silt loam	–	640	Buyanovsky et al. (1986)
Soybean	Missouri, USA	–	–	–	760	Buyanovsky and Wagner (1995)
Maize	Wisconsin, USA	43°18′N, 89°21′W	Typic Argiudoll	–	508–534	Wagai et al. (1998)
Soybean	Iowa, USA	42°11′N, 93°30′W	Fine-loamy, Cumulic Haplaquoll	–	750	Tufekcioglu et al. (2001)
Maize	Iowa, USA	42°11′N, 93°30′W	Fine-loamy, Cumulic Haplaquoll	–	740	Tufekcioglu et al. (2001)
Millet/barley rotation	Jiangxi, China	28°15′N, 116°55′E	Red soil	5.15	450	Lou et al. (2003)
Barley	Spanish plateau, Spanish	41°48′N, 4°55′W	Typic xerofluent	7.8–8.1	760	Sánchez et al. (2003)
Spring wheat/fallow	North Dakota, USA	46°46′N, 100°55′W	Silt loam	–	700	Frank et al. (2006)
Spring wheat	North Dakota, USA	46°46′N, 100°55′W	Silt loam	–	600	Frank et al. (2006)
Wheat	Tibetan plateau, China	29°40′N, 91°20′E	Sandy loam	7.0–8.5	579	Shi et al. (2006)
Wheat	Southern Israel	31°20′N, 34°41′E	Sandy loam	–	110.87	Eshel et al. (2014)
Wheat-maize intercropping	Gansu, China	37°96′N, 102°64′E	Aridisol	–	160.7	Hu et al. (2015)
Maize monoculture	Gansu, China	37°96′N, 102°64′E	Aridisol	–	172.3	Hu et al. (2015)
Winter wheat-summer maize double cropping rotation	Shandong, China	36°57′N,116°36′E	Sandy loam	7.9	825	This study

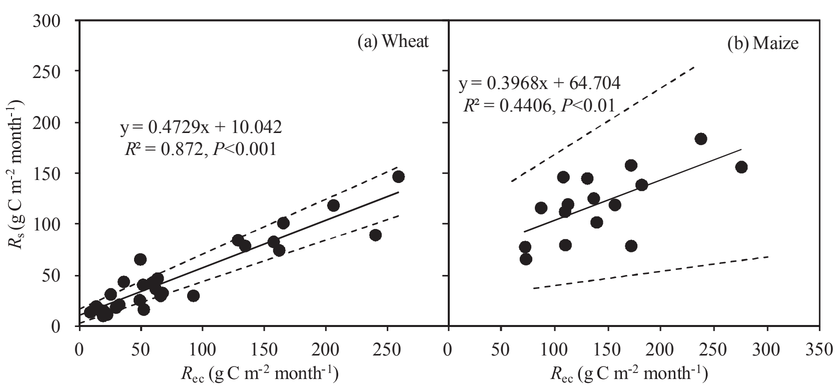

Fig. 8. Relationship between monthly soil respiration (R_s) and ecosystem respiration (R_{ec}) in the wheat (a) and maize (b) fields. The solid line is the fitted linear regression and the dotted lines are the upper and lower 95% confidence intervals.

prolonged dry period. Future climate projections indicate increasing temperature and decreasing precipitation, resulting in an increase in drought periods in semiarid regions and an increased frequency of extreme precipitation events. This may lead to increased CO_2 emissions in the North China Plain, with important consequences for atmospheric CO_2. Thus, it is vitally important to improve carbon cycle models, particularly of soil respiration. Although soil temperature and moisture are crucially important in modelling soil respiration, our results indicate that biotic factors (e.g. photosynthesis) are also important, as monthly soil respiration of the wheat field was controlled by photosynthesis. Therefore, incorporating the effect of photosynthesis on soil respiration will improve the accuracy of soil respiration models in croplands.

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