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Seasonal characteristics of CO_2 fluxes in a rain-fed wheat field ecosystem at the Loess Plateau

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Abstract

This study investigated the dynamics of CO_2 flux in a rain-fed wheat field ecosystem using an eddy covariance technique during the 2011 to 2012 wheat-growing season at the Loess Plateau, China. Results showed that the daily CO_2 flux was closely related to photosynthetically active radiation (PAR), growth stage, soil temperature and rainfall. The average CO_2 flux at different growth stages followed the order jointing and booting > erecting > reviving > heading > wintering > seeding and tillering > grain filling > ripening. The first four stages were carbon sinks, whereas the last four stages were carbon sources. The relationship between nighttime CO_2 flux and air temperature was significant and fitted the index model ($y = ae^{bt}$). The relationship between daytime CO_2 flux and PAR was also significant and fitted the quadratic model ($y = ax^2 + bx + c$). Moreover, daytime CO_2 flux was significantly correlated with air temperature and PAR at the erecting, jointing and booting, and heading stages. Nighttime CO_2 flux was also significantly correlated with soil temperature at 5 cm depth at the heading as well as jointing and booting stages. The carbon budget in the rain-fed wheat ecosystem was –401 g C m^{-2} yr^{-1}, which was higher than those in other wheat ecosystems. This study implies that the ability of carbon-sequestration in different wheat field ecosystems may respond differently to climate and environment change.

Additional key words: CO_2 flux; dynamic change; eddy covariance; rain-fed wheat field ecosystem; *Triticum aestivum* L.

Introduction

Global warming is an environmental problem primarily caused by increasing greenhouse gas concentrations (Shvaleva *et al.,* 2011). The atmospheric CO_2 concentration before the industrial revolution was 280 μmol mol^{-1} but is currently 370 μmol mol^{-1} and increases at a rate of 1 to 2 μmol mol^{-1} every year (Genthon *et al.*, 1987). In the past 20 years, land use has changed through human activities, thereby producing CO_2 emissions accounting for 10%-30% (Zhan *et al.*, 2012). Thus, changes in the carbon cycle in terrestrial ecosystems are receiving increased attention from scientists and policymakers (IPCC, 2001). Many studies have focused on the net ecosystem CO_2 exchange in forest ecosystems possibly because forests can sequester high carbon levels (Pacala *et al.*, 2001). However, less attention is paid to the net ecosystem CO_2 exchange in wheat (*Triticum aestivum* L.) field ecosystems even though these ecosystems comprise approximately 33% of the grain crops worldwide (Gu & Zha, 2013).

Long-term disruptive human activities have degraded 78% of cultivated soil productivity and soil carbon pool in China. If 50% of soil organic carbon loss in Chinese farmlands can be recovered in 20 years, farmland soil would absorb $3.5 \cdot 10^{12}$ kg of atmospheric organic carbon. Accurate assessment of the status of carbon sequestration in farmland under conventional tillage can provide a theoretical basis for measures of reducing carbon emission.

Farmland ecosystem is the important component of the terrestrial ecosystem, and it is extremely related to mankind. Lal & Bruce (1999) found that 20% of CO_2 in the atmosphere came from agricultural activities and related processes. Lal (1997) also found that total carbon sequestration potential of farmland globally was 0.75-1.00 Pg C yr^{-1}, which implies that farmland ecosystems occupy a significant carbon sink on the earth.

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Abbreviations used: PAR (photosynthetically active radiation).

Although winter wheat is one of the main crops worldwide, 58% of this crop is produced under rain-fed conditions (Wang *et al.*, 2010). With the serious problem caused by climate warming and subsequent decreasing precipitation globally, the production area of rain-fed wheat will be increasing (Bai & Lin, 2003). It is then essential to evaluate the carbon budget of rain-fed wheat in agricultural ecosystems.

Numerous uncertainties exist regarding the role of wheat ecosystems in the global carbon budget, and the factors affecting CO_2 flux dynamics vary among wheat ecosystems under different climatic conditions and management practices (Wang *et al.*, 2003). Studies have shown that some wheat ecosystems are significant CO_2 sinks or sources (Li *et al.*, 2007; Lin *et al.*, 2008; Wang *et al.*, 2010). However, many wheat ecosystems show a high inter-annual change in annual CO_2 flux (Li *et al.*, 2005). Studies have shown that the time and the amount of annual precipitation are the dominant factors affecting CO_2 exchange in semi-arid wheat fields (Peter *et al.*, 2004). Temperate wheat ecosystems also exhibit different responses to inter-annual variations in precipitation because these ecosystems are drier and more water stressed than many other ecosystems and are also ecologically fragile and sensitive to climate change (Li *et al.*, 2004; Niu *et al.*, 2008). However, studies regarding CO_2 flux in rain-fed wheat field ecosystems are mainly focused on particular crop growth stages (Mo *et al.*, 2003; Duan *et al.*, 2005) rather than on whole crop growth stage. By introducing an eddy covariance system, we analysed the dynamic change of CO_2 flux and its mainly related factors during the winter wheat growth stage in a rain-fed ecosystem. Present study can provide information and theory basis to understand carbon budget situation and how to improve the carbon accumulation ability of farmland ecosystem in similar environments in the world. Thus, present study aims to determine the variations of CO_2 flux during the winter wheat growth stage and its key factors in a rain-fed wheat ecosystem.

Material and methods

Site description

The experiment was conducted between 2011 and 2012 over the wheat field ecosystem at the Changwu Agriculture Research Centre in Shaanxi Province, China. The site is located at 107° 40’ E 35° 12’ N at an altitude of 1,200 m above sea level. The annual rainfall at the site is 586 mm, with a minimum of 296 mm and a maximum of 594 mm, approximately 60% of the total annual rainfall occurs between July and October. The annual mean temperature is 9.9°C, with an annual total of 2,230 h of sunshine duration and an annual no-frost period lasting 171 days. The soil in the top 1.0 m is Eum-Orthrosols (Chinese soil taxonomy), with a mean bulk density of 1.30 g cm^{-3}. The available nitrogen (N), phosphorus (P), and potassium (K) are 37.90, 10.12, and 129.64 mg kg^{-1}, respectively. The organic matter content and pH of the 0 to 20 cm soil layer are 9.19 g kg^{-1} and 7.30, respectively. The study area that is 1 km around the flux tower is fairly open and flat with < 1% slope, characteristic required for the experiment.

Experimental design

The experiment, which was conducted from September 2011 to June 2012, used a stubble cultivation system and winter wheat as the crop (Chang Wu 131). Weeds were artificially removed during crop growth, and crops were harvested once mature. All aboveground parts were removed. During the fallow period, the soil was loosened by tractor ploughing (20 cm) to conserve water. The soil was tractor ploughed (20 cm) again before sowing. A seedbed was prepared for the next stubble. Before sowing, 150 kg N ha^{-1} was applied as urea and 120 kg P_2O_5 ha^{-1} was applied as superphosphate. Wheat was harvested on June 23, 2011. The first tractor ploughing was conducted on July 18, 2011. Fertilisation and sowing were then performed on September 16 and 17, 2011. The crops were harvested on June 30, 2012. The wheat growth stage division and start-stop time are shown in Table 1.

Table 1. Division of winter wheat growth stages in Changwu from 2011 to 2012

Growth stage	Date (month.day)	Time (days)
Seeding and tillering	9.17-11.10	55
Wintering	11.11-3.16	126
Reviving	3.17-4.8	22
Erecting	4.9-4.28	20
Jointing	4.29-5.12	14
Booting	5.13-5.26	14
Heading	5.27-6.9	14
Grain filling	6.10-6.26	17
Ripening	6.27-6.30	4

Measurements

The eddy covariance system was used to measure CO_2 flux over the wheat field ecosystem at the height of 2 m using a three-dimensional sonic anemometer (Model CSAT-3, Campbell Sci., Logan, UT, USA) and a CO_2 analyser (Model Li-7500, Li-Cor Inc., NE, USA). The data of CO_2 flux were recorded with a datalogger (CR5000, Campbell Sci.) at 30 min intervals.

The meteorological conditions, including photosynthetically active radiation (PAR), were measured by a quantum sensor (PAR-LITE, Kipp and Zone, the Netherlands). Air temperature and relative humidity were measured using shielded and aspirated probes (Model HMP45C, Campbell Sci.) at 2.5 m height. Precipitation was measured with a rain gauge (Model 107-L, Campbell Sci.) installed on top of the tower 2 m above the ground. Soil temperature was measured at a depth of 5cm below the ground using thermometers (Model 107-L, Campbell Sci.). All aforementioned meteorological conditions were recorded with a CR23X (Model CR23XTD, Campbell Sci.) at 30 min intervals.

Data processing

Flux data were analysed based on 30 min mean values of CO_2 concentration collected from September 2011 to June 2012. The relevant meteorological conditions were also measured within the same period. CO_2 flux was counted by the covariance ($\overline{w'c'}$) of vertical wind speed (w) and the fluctuating value of CO_2 concentration (c). Through three times of coordinate rotation (Wilczak *et al.*, 2001) and the WPL method was applied to adjust density changes resulting from fluctuations in heat and water vapor (Webb *et al.*, 1980), we obtained the average CO_2 flux every 30 min. According to the eddy correlation principle and the limitation of instruments, data were eliminated according based on the following situations: (1) during rainfall, (2) insufficient turbulence (friction velocity $u^* < 0.15$ m s^{-1}) (Falge *et al.*, 2001), (3) higher than the instrumental range and reasonable range of data (the effective range of CO_2 flux is –1.0 to 1.0 mg m^{-2} s^{-1}, and the effective range of CO_2 concentration is 500 to 800 mg m^{-3}) (Massman & Lee, 2002), (4) effective < 1,500 sample size every 30 min, and (5) prominent data (the absolute value of CO_2 flux minus the average of its five adjacent data more than three times the five data variance).

To obtain complete information on the annual sum of CO_2, we filled the small gaps (< 2 h) with linear interpolations. For large nighttime gaps (> 2 h), we used a soil temperature-dependent exponential equation (Falge *et al.*, 2001):

$$F_n = a \cdot \exp(b \cdot T_s)$$

where F_n is the CO_2 flux at PAR ≤ 1.0 µmol, T_s is soil temperature at 5 cm depth, and a and b are the fitting constants obtained by the nonlinear least-squares method.

For large gaps (> 2 h), we filled the data at daytime using a PAR-dependent equation (Falge *et al.*, 2001):

$$F_d = \frac{a_1 \times PAR}{a_2 + PAR} + a_0$$

where F_d is CO_2 flux at PAR > 1.0 µmol; a_0, a_1, and a_2 are fitting constants obtained by the nonlinear least-squares method.

All statistical analyses were performed with SPSS 17.0 software (SPSS Inc., Chicago, IL, USA). ANOVA was conducted, and significant differences for all statistical tests were calculated at a least significant difference of 0.05. SigmaPlot 12.0 (Aspire Software International, Ashburn, VA, USA) was used for map drawing.

Results

Seasonal environmental variables

Variations in the daily mean of environmental conditions at the experimental site from September 2011 to June 2012 are plotted in Fig. 1, including air relative humidity, soil temperature at 5 cm depth, air temperature, PAR, and precipitation. The climate conditions showed distinct seasonal variations because of the temperate continental monsoon climate. The total PAR throughout the entire wheat-growing season was 6,818.51 mol m^{-2}. The maximum PAR was 57.8 mol m^{-2} d^{-1} in summer, whereas the average PAR was 16.3 mol m^{-2} d^{-1} in winter. The illumination conditions were sufficient. Rainfall was mainly concentrated in October. Throughout the entire wheat-growing season, the rainfall was 269.43 mm, the average air temperature was 7.59°C, and the average soil temperature at 5 cm depth was 8.98°C. Compared with air temperature, the changes in soil temperature showed hysteresis.

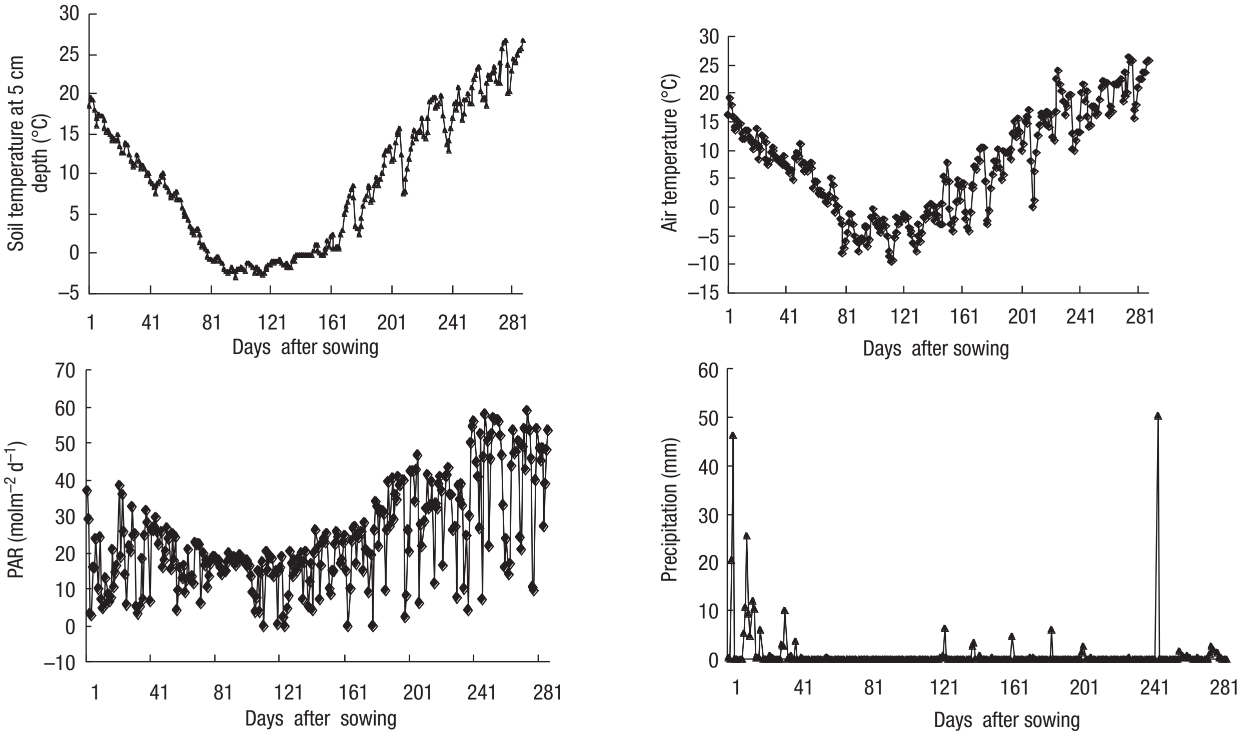

Figure 1. Daily meteorological factors.

Diurnal course of CO_2 flux variable

The CO_2 flux per day was calculated. Diurnal variations in CO_2 flux (shown as the arithmetic mean) per growth stage are shown in Fig. 2. According to the diurnal variations in CO_2 flux in each growth stage, in the seeding and tillering as well as wintering stages, the value of CO_2 flux was very small, with an order of magnitude of 10^{-3}. In subsequent growth stages, CO_2 flux increased in daytime, reaching the maximum value until the jointing and booting stage. In the heading, grain-filling, and ripening stages, CO_2 flux subsequently decreased.

Seasonal changes in daily CO_2 budget

Daily CO_2 budget changed markedly at different growth stages due to the differences in temperature, radiation, rainfall and other environmental factors in the wheat field ecosystem (Fig. 3). The daily CO_2 budget ranged from –16.32 to 2.11 g m^{-2} d^{-1} throughout the entire growth period. The seeding and tillering, wintering, grain-filling, and ripening stages were carbon sources, whereas the other growth stages were carbon sinks. Wintering was the weakest carbon source with 0.12 g m^{-2} d^{-1}. Jointing and booting reached the maximum with –16.32 g m^{-2} d^{-1}.

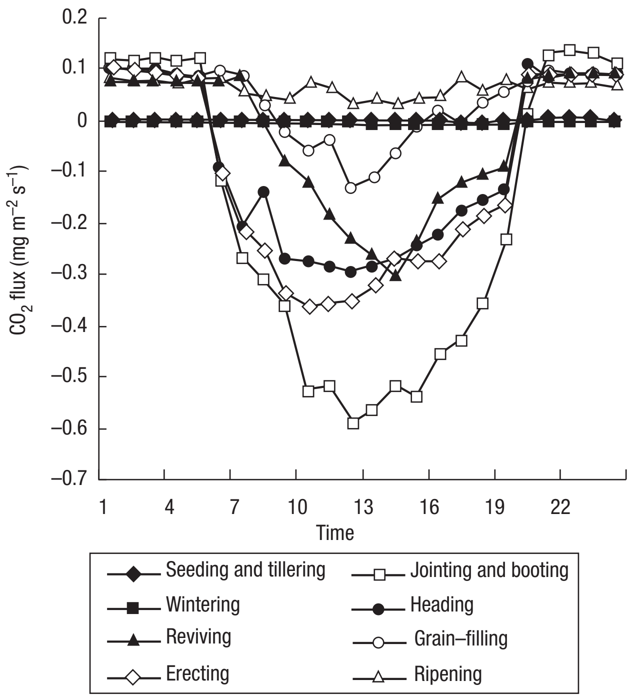

Figure 2. Daily CO_2 flux in a wheat field at each growth stage.

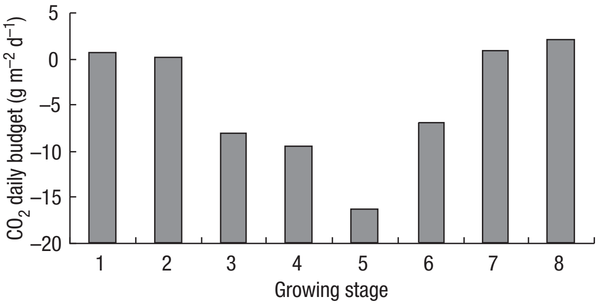

Figure 3. Daily CO_2 budget at each growth stage: 1, seeding and tillering; 2, wintering; 3, reviving; 4, erecting; 5, jointing and booting; 6, heading; 7, grain-filling; 8, ripening.

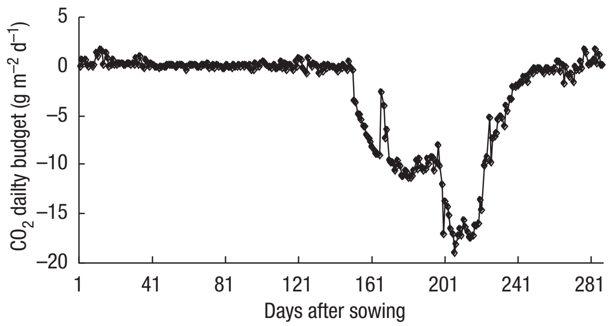

Figure 4. Daily CO_2 budget throughout the entire winter wheat growth period.

Daily and annual CO_2 balance

Changes in daily CO_2 balance throughout the entire wheat growth period are shown in Fig. 4. At the seeding and tillering as well as wintering stages, the absolute value of CO_2 flux was very small and fluctuated around zero. One hundred and sixty days after sowing, the carbon budget sharply changed, resulting in a more remarkable CO_2 flux. At the jointing and booting stage, the wheat field ecosystem absorbed the daily maximum amount of carbon. After this stage, carbon absorption decreased until about 265 days after sowing (the mid- and late-grain-filling stages), and the stage became a carbon source. Throughout the entire growth period, the carbon budget significantly fluctuated after rainfall. The degree of fluctuations differed among the various growth stages. The late seeding and tillering, late heading, and early grain-filling stages showed the most intense fluctuations, but in the wintering stage were not obvious.

The CO_2 balance in this paper was lower and higher, respectively, than that in maize and other wheat ecosystems (Table 2). Table 2 shows that the changes in CO_2 flux in the winter wheat ecological system were quite large, ranging from –215 to –401 g C m^{-2} yr^{-1}. Compared with wheat, maize plants were taller and showed stronger carbon-sequestering abilities.

The effect of PAR on daytime CO_2 flux

The relationship between daytime CO_2 flux and PAR fitted the quadratic function ($p < 0.01$) during the period from the seeding to ripening stage as suggested by Fig. 5. When PAR was low, the rate of net carbon sink increased. When PAR exceeded a certain value, the rate of net carbon sink decreased with increased PAR.

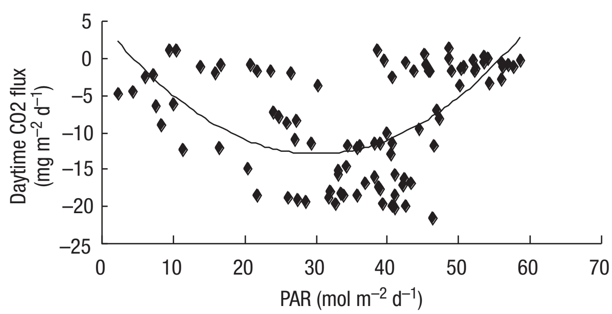

Figure 5. Effects of photosynthetically active radiation (PAR) on daytime CO_2 flux.

Table 2. Comparison of carbon uptake in different farmland ecosystems

Test period	Test location	Crop type	NEE[a] (g C m^{-2} yr^{-1})	Reference
1997	IL, USA	Maize	–532	Hollinger *et al.* (2005)
2001	Thuringia, Germany	Winter wheat	–215	Anthoni *et al.* (2004)
2001	NE, USA	Maize	–474	Verma *et al.* (2005)
2007-2009	Anhui, China	Winter wheat	–273	Ye *et al.* (2012)
2008	Jinzhou, China	Maize	–653	Liang *et al.* (2012)
2011-2012	Changwu, China	Winter wheat	–401	This study

[a] NEE: net ecosystem exchange of CO_2.

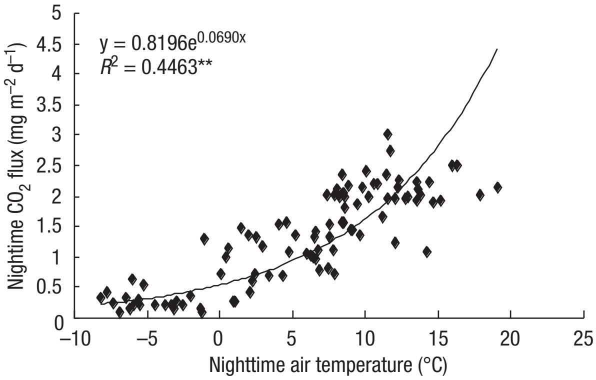

Figure 6. Effects of air temperature on nighttime CO_2 flux. **: significance at $p \leq 0.01$, *t*-test.

The effect of canopy temperature on nighttime CO_2 flux

Present experiment showed a positive and exponential relationship between ecosystem respiration and temperature within canopy (Fig. 6). The result suggests that the CO_2 released from the rain-fed wheat field ecosystem increased with increasing soil temperature during nighttime.

Correlations between CO_2 flux and air temperature, PAR, soil temperature at 5 cm depth

The relationship between CO_2 flux and air temperature reached a significant level at the erecting and heading stages (Table 3). The jointing and booting stage showed highly correlated levels. The wintering, reviving, and grain-filling stages showed a low correlation. The other two stages were almost uncorrelated. Correlation analysis showed that the relationship between daytime CO_2 flux and PAR was almost not related under the seeding and tillering, wintering and ripening stages. Moreover, a low correlation was observed in the reviving and grain-filling stages, but significantly high levels were observed in the other growth stages. Nighttime CO_2 flux and soil temperature at 5 cm depth reached a significant level at the jointing and booting as well as heading stages.

Discussion

At the seeding and tillering stage, wheat plant was relatively small with loose soil and high temperature. The amount of CO_2 uptake and release was approximately the same in daytime, so the CO_2 flux was relatively low. At the wintering stage, the low temperature (–4 to 6°C) resulted in slow wheat growth and relatively low CO_2 emission through wheat respiration. However, the low temperature inhibited the activity of soil microbes and reduced soil CO_2 emissions. Therefore, the amount of CO_2 released from soil was small. Low temperature is the main factor that limits wheat photosynthesis in winter (Wang *et al.*, 2003). Thus, diurnal variations in CO_2 flux are relatively small at this stage. In subsequent growth stages, the value of daytime CO_2 flux increased, reaching the maximum until the jointing and booting stage but decreasing in the heading, grain-filling, and ripening stages. Given that the jointing and booting stage mainly occurs in May, the net photosynthetic rate of wheat reaches the maximum with increased PAR and air temperature (Qi *et al.*, 2009). However, the CO_2 consumed by photosynthesis is higher than the CO_2 released by plant and

Table 3. Coefficients of the correlation of CO_2 flux with air temperature, PAR, and soil temperature at 5 cm depth

Growth stage	R_1	P_1	R_2	P_2	R_3	P_3
Seeding and tillering	0.07	*	–0.04	*	0.13	*
Wintering	–0.14	*	–0.07	*	0.02	*
Reviving	–0.19	*	–0.12	*	0.14	*
Erecting	–0.26	**	–0.18	**	0.17	*
Jointing and booting	–0.34	**	–0.23	**	0.24	**
Heading	–0.21	**	–0.21	**	0.32	**
Grain filling	–0.14	*	–0.11	*	0.02	*
Ripening	–0.09	*	–0.07	*	–0.01	*

R_1: correlation coefficient between daytime air temperature and CO_2 flux. R_2: correlation coefficient between daytime PAR and CO_2 flux. R_3: correlation coefficient between soil temperature at 5 cm depth and CO_2 flux at nighttime. *,**: significance at $p < 0.05$ and 0.01, respectively (*t*-test).

soil (Li *et al.*, 2007). At the maturing stage, wheat leaves gradually turned yellow, plant photosynthetic ability decreased, plant and soil respiration were higher than plant photosynthesis ability, and wheat field ecosystems performed CO_2 release each day. CO_2 flux in daytime peaked at about 10:00 h. Similar phenomena have been observed in winter wheat in the Hetao irrigation region, Inner Mongolia (Duan *et al.*, 2005). At about 07:00 and 19:00 h, the flux symbol changed, which may be related to the stability of the atmosphere and condensed water. Based on diurnal CO_2 flux at different growth stages, we conclude that the developmental status of wheat directly affects CO_2 flux.

At the jointing and booting stage, the daily CO_2 budget reached the maximum of –16.32 g m^{-2} d^{-1}. In rain-fed wheat fields, soil moisture is the major factor limiting wheat growth because soil moisture affects plant root distribution and regular plant growth (Chen *et al.*, 2003; Lou *et al.*, 2003). At this stage, soil had sufficient water for regular plant growth and the leaf area index was adequately large (data not shown); thus, the carbon sequestration effect was obvious. These results were similar to those of Mo *et al.* (2003). More attention should be given to the fact that the grain-filling stage is a carbon source because the wheat photosynthesis rate decreased at daytime and temperature increased at nighttime. Consequently, CO_2 release increased (Yuan *et al.*, 2010). With increased temperature at the ripening stage, wheat leaves gradually turned yellow, the wheat leaf area index rapidly decreased, and photosynthesis weakened in the ecological system. At this stage, the ecological system was based on soil respiration.

Photosynthesis is driven by PAR. In this experiment, the net wheat ecosystem CO_2 exchange exhibited light saturation phenomenon because the assimilatory power caused by the photoreaction was more than that needed for CO_2 assimilation. Accordingly, the reactive oxygen increased. If the protection system cannot be cleared in time, the photosynthetic membrane would be damaged, the photosynthetic rate of the wheat ecosystem would decrease, and the whole wheat ecosystem would change from a carbon sink into a carbon source (Huang, 2003). Puckridge & Ratkowsky (1971) as well as Wall & Kanemasu (1990) also found that wheat canopy CO_2 exchange showed light saturation. Baldocchi *et al.* (1996) studied the wheat and maize ecosystem, and he found a positive relationship between net CO_2 uptake and PAR absorption, in which light saturation did not occur. The aforementioned results are due to the differences in climate, soil, crop varieties, and growth status at different places (Tong *et al.*, 2011). These results were similar to those of Liu & Ma (1997), who conducted a study in the suburbs of Beijing.

Ecosystem respiration is controlled by environmental and biological factors at nighttime. Temperature is the main environmental factor controlling ecosystem respiration (Li *et al.*, 2004). Many studies have shown that ecosystem respiration exponentially grew with increased temperature (Harley *et al.*, 1992; Hall *et al.*, 1995; Baldocchi *et al.*, 1996). This is because the soil temperature increased with global warming, and then enhanced soil respiration to same extent (Reth *et al.*, 2005). Meanwhile, global warming also strengthen the plant respiration at nighttime (Sun *et al.*, 2005), which also contributed to the high CO_2 concentration in the atmosphere. Influenced by soil moisture and other environmental factors, the data in Fig. 6 were scattered. Only 44% of carbon flux change can be explained by nighttime canopy temperature. Despite this result, the relationship between average CO_2 flux and canopy temperature was significant ($p < 0.01$) at nighttime. The relationship between CO_2 flux and air temperature reached a highly correlated levels at the jointing and booting stages. This result was consistent with Liu & Ma (1997) in the suburbs of Beijing. Given the influence of rainfall, the degree of correlation may be weakened at different growth stages.

Observed values of CO_2 flux in six stations, including wheat and maize ecosystems, are reported in literature. This difference shows that rain-fed wheat field ecological systems had strong carbon-sequestration abilities. The differences in climate, soil, and wheat varieties in different regions mainly caused the differences in carbon sink function among wheat ecosystems (Li, 2002).

Present study shows that temperature, precipitation and PAR have a significant influence on seasonal characteristics of CO_2 fluxes in a rain-fed wheat field ecosystem by using an eddy covariance technique. This high sensitivity of carbon-sequestration responded to wheat ecosystems implies that the vast rain-fed wheat field ecosystems may be critical to regulate future climate change. Systematic studies in this ecosystem are needed for developing and improving relevant prediction models.

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