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Dynamics of CO_2 fluxes and environmental responses in the rain-fed winter wheat ecosystem of the Loess Plateau, China☆

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HIGHLIGHTS

- The winter wheat ecosystem acted as a strong carbon sink.
- Environmental responses of CO2 fluxes varied with different ranges of factors.
- Response of CO2 fluxes to environmental factors varied with soil water conditions.
- Strong fluctuations of CO2 fluxes usually appeared after effective rainfall events.
- Strong fluctuations of CO2 fluxes also occurred within 5days after sowing.

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ABSTRACT

Chinese Loess Plateau plays an important role in carbon balance of terrestrial ecosystems. Continuous measurement of CO_2 fluxes in cropland ecosystem is of great significance to accurately evaluate the carbon sequestration potential and to better explain the carbon cycle process in this region. By using the eddy covariance system we conducted a long-term (from Sep 2009 to Jun 2010) CO_2 fluxes measurement in the rain-fed winter wheat field of the Chinese Loess Plateau and elaborated the responses of CO_2 fluxes to environmental factors. The results show that the winter wheat ecosystem has distinct seasonal dynamics of CO_2 fluxes. The total net ecosystem CO_2 exchange (NEE) of -218.9 ± 11.5 gC m^{-2} in the growing season, however, after considering the harvested grain, the agro-ecosystem turned into a weak carbon sink (-36.2 gC m^{-2}). On the other hand, the responses of CO_2 fluxes to environmental factors depended on different growth stages of winter wheat and different ranges of environmental variables, suggesting that the variations in CO_2 exchange were sensitive to the changes in controlling factors. Particularly, we found the pulse response of ecosystem respiration (R_{eco}) to a large rainfall event, and the strong fluctuations of CO_2 fluxes usually appeared after effective rainfall events (daily precipitation > 5 mm) during middle growing season. Such phenomenon also occurred in the case of the drastic changes in air temperature and within 5 days after field management (e.g. tillage and plough).

1. Introduction

In recent years, sustainable development across the globe has been severely restricted by the negative impacts of global climate change. Considering the fact that carbon cycling in terrestrial ecosystems plays an important role in global carbon balance and that carbon exchange at regional scale exerts direct influence on regional climate change, monitoring and understanding carbon cycling processes have become a major focus of regional sustainable development as well as global climate change. Cropland ecosystem is a critical component of the terrestrial ecosystems and its carbon pool is of vital importance to maintain the global carbon balance. Thus long-term measurement of CO_2 exchange and evaluation of carbon budget may provide theoretical guidance for laying down measures to reduce carbon emissions and improve carbon sequestration.

Since the 1980s, based on eddy covariance (EC) technique, many researchers have endeavored to measure and analyze the potential of carbon sequestration in terrestrial ecosystems. Although previous studies mainly focused on forest and grassland ecosystems (Hernandez-Ramirez et al., 2011), the study on the characteristics of the CO_2 exchange in cropland ecosystem is gradually increasing in academic field. Scientists have carried out detailed study on inter- and intra-annual variations of CO_2 fluxes (Aubinet et al., 2009; Moors et al., 2010; Glenn et al., 2010). Some of them have conducted research on the methods of data quality assessment and data processing

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(Soegaard et al., 2003; Anthoni et al., 2004; Saito et al., 2005). Others have reported the responses of CO_2 fluxes to environmental factors. For instance, the relationships between physiological characteristics of crops and CO_2 fluxes at different crop growth stages (Moureaux et al., 2008; Hoyaux et al., 2008), the variations in CO_2 fluxes under different meteorological conditions (Béziat et al., 2009; Dufranne et al., 2011), the relationship between daytime net ecosystem CO_2 exchange (NEE) and photosynthetically active radiation (PAR) under different water conditions (Pingintha et al., 2010), the effects of temperatures on ecosystem respiration (R_{eco}) in different periods (Moureaux et al., 2006; Hernandez-Ramirez et al., 2011) and different crop sites (Suyker et al., 2004), and the impact of agricultural management practices on carbon balance (Ceschia et al., 2010; Eugster et al., 2010; Glenn et al., 2010). Winter wheat with exclusive worldwide distribution, at present, there are a small number of Chinese scholars who have conducted research on estimating the carbon budget (Li et al., 2006; Li et al., 2007; Lei and Yang, 2010) and analyzing the environmental responses of CO_2 fluxes in winter wheat ecosystem (Li et al., 2006; Yan et al., 2009), whereas most of them are mainly located in Huang-Huai-Hai plain, China.

The Loess Plateau covers an area of 64×10^4 km^2 in Northwest China, including 14.5×10^4 km^2 of arable land. More than 70% of crop plant in rain-fed land, which is much more susceptible to climate change impacts. Thus, measurement of CO_2 exchange in the rain-fed field is of great significance to better understand the relationship between the carbon cycling and climatic change in the region. Based on the eddy covariance (EC) system, we performed continuous observation (from Sep 2009 to Jun 2010) in the rain-fed winter wheat field of the Chinese Loess Plateau. The main objectives of this study were to: (1) elaborate the dynamics of CO_2 fluxes and estimate the carbon budget in growing season; (2) analyze the response mechanisms of CO_2 fluxes to environmental factors.

2. Materials and methods

2.1. Site description

The experimental field (latitude 35°14′ N, longitude 107°41′ E, 1220 m above mean sea level) is situated at the Changwu agro-ecological experiment site, which is located in the central-southern part of Chinese Loess Plateau, Shaanxi Province. This region belongs to warm continental monsoon climate zone. Mean annual global solar radiation and mean annual temperature at the Changwu site are 484 kJ cm^{-2} and 9.1 °C, respectively (mean values computed over 20 years from 1986 to 2005). Mean annual accumulated temperature of ≥0 °C is 3688 °C, and ≥10 °C is 3029 °C, with mean annual sunshine duration of 2226.5 h and a frost-free period of 171 days. Mean annual precipitation is 584.1 mm and mainly in July to September, which accounts for more than 55% of the total. Multiple cropping index is 116%. Groundwater depth is 50–80 m. The soil type of the field is dark loessial soil. In September 2009, the soil organic matter and soil organic carbon content in the first 0.3 m were 11.58 and 6.74 g kg^{-1}, respectively. This region is a typical rain-fed agricultural area with single cropping system and without irrigation. The soil nutrient and topographic characteristics of the experimental field are quite representative of the similar areas in the Chinese Loess Plateau.

The field has an approximate area of 100 m × 100 m and has flat terrain with eddy covariance (EC) system installed in the middle. This field has been cultivated for more than 30 years and within the range of the field all crops grown were winter wheat, which forms homogeneous underlying surface in order to satisfy the requirement of the fetch in the prevailing wind directions. The tested winter wheat cultivar was Changwu 134 with sowing rate of 150 kg ha^{-1} and row spacing of 0.2 m. The winter wheat growth stages based on the Zadoks scale (Zadoks et al., 1974) are listed in Table 1. The conventional tillage by a rotary harrow to a depth of 25 cm was performed during sowing. 120 kg ha^{-1} mineral N, 90 kg ha^{-1} phosphorus and 62 kg ha^{-1} potassium had been applied to the arable layer as base fertilizer in September 2009. Note that no farmyard manure and no irrigation were applied during the growing season.

Table 1
Winter wheat growth stages in Changwu site during the 2009–2010 growing season.

Growth stage	Date
Sowing	26-Sep-2009
Seedling stage	03-Oct-2009
Tillering stage	22-Oct-2009
Winter dormancy stage	11-Nov-2009
Stem elongation stage	11-Mar-2010
Booting stage	22-Apr-2010
Heading stage	15-May-2010
Grain filling stage	04-Jun-2010
Ripening stage	20-Jun-2010
Harvesting	25-Jun-2010

2.2. Measurements

CO_2 flux (F_c), latent heat flux (LE) and sensible heat flux (H_s) were measured by the eddy covariance (EC) system positioned 2 m above the soil surface. Three-dimensional wind velocity and virtual temperature were measured with a 3D sonic anemometer (Gill Instruments Ltd., UK). The densities of CO_2 and water vapor were measured with a LI-7500 open-path infrared CO_2/H_2O gas analyzer (LI-COR Inc., USA). The data from the sonic anemometer and the CO_2/H_2O gas analyzer were recorded at 10 Hz on a CR5000 data logger (Campbell Scientific Inc., USA).

Other relevant instruments were as follows: photosynthetically active radiation radiometer (LI-COR Inc., USA), 3-Cup Anemometer (Vaisala Inc., Finland), temperature-humidity sensors (Vaisala Inc., Finland), soil temperature–moisture sensor (Campbell Scientific Inc., USA) at depths of 0.02, 0.1, 0.2, 0.4, and 0.8 m, two soil heat flux plates (Hukseflux, Delft, Netherlands) at depth of 0.05 m and a tipping bucket rain gage (Campbell Scientific Inc., USA). All the above mentioned instruments used CR10X data logger (Campbell Scientific Inc., USA) to collect and store data.

A LI-3000 portable leaf area meter (LI-COR Inc., USA) was utilized to measure the leaf area index (LAI) bi-weekly from seedling stage to winter dormancy stage and weekly from stem elongation stage to ripening stage. LAI was expressed as one-half the total leaf area per unit ground area (m^2 m^{-2}). At harvest, grain yield was measured by gathering grains from three zones of 2 m × 50 m.

2.3. Data analysis and processing

The original data from the EC measurements were processed off-line using the software MATLAB 7.5 (Math works Inc., USA). The half-hourly CO_2 fluxes were computed by the eddy covariance method as the mean covariance between fluctuations in vertical wind velocity (w', m s^{-1}) and the CO_2 density (ρ_c', mg m^{-3}). Thereafter, the CO_2 fluxes were corrected by a 3D coordinate rotation in order to align the sensor of 3D sonic anemometer in the mean streamline direction (Wilczak et al., 2001), and then they were corrected for fluctuations of air and water vapor density according to the Webb–Pearman–Leuning (WPL) algorithm (Webb et al., 1980).

Besides, some studies have demonstrated that even for short crops (e.g. winter wheat, rice) the CO_2 storage term should be considered when calculate CO_2 fluxes (Soegaard et al., 2003; Saito et al., 2005). To measure the change of CO_2 storage below the EC sensor, a single height (at the height of EC measurement, 2 m) method according to Moureaux et al. (2008) was applied. Thus, the NEE value was