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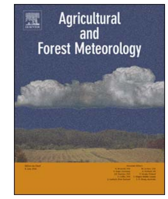

Research paper

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.