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Mechanism and bio-environmental controls of ecosystem respiration in a cropland in the North China Plains

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Abstract CO_2 flux was measured continuously using the eddy covariance technique in a wheat-maize rotation system in the North China Plains from October 2002 to October 2006. The annual and seasonal variation of ecosystem respiration and the bio-environmental controls on them were investigated. The results show that ecosystem respiration (R_{ec}) in the cropland increased exponentially with soil temperature at 5 cm depth. The temperature sensitivity coefficient (Q_{10}) for ecosystem respiration varied from 3.5 to 5.4 for wheat and from 2.4 to 4.5 for maize. In the wheat growing season, monthly average R_0 (ecosystem respiration at 0°C) increased linearly with soil temperature and logarithmically with leaf area index (LAI). Monthly average Q_{10} decreased logarithmically with R_0. Residual R_{ec} was significantly correlated with LAI. After considering LAI, the modified Q_{10} model could estimate R_{ec} better than before. The simulation results show that annual ecosystem respiration in the wheat-maize rotation system in the North China Plains was 1327, 1348, 1040 and 1171 gC m^{-2} yr^{-1} for the 4 years of the study. As a 4-year average, seasonal mean ecosystem respiration in wheat (2.60 gC m^{-2} day^{-1}) was much lower than in maize (6.09 gC m^{-2} day^{-1}). However, integrated ecosystem respiration for the wheat growing season (566 gC m^{-2}) was slightly higher than that for maize (520 gC m^{-2}). These account for 46.4 and 42.6% of the annual values, respectively.

Keywords ecosystem respiration; Q_{10}; eddy covariance; LAI; soil temperature; wheat-maize rotation system

INTRODUCTION

Ecosystem respiration (R_{ec}), including heterotrophic respiration (root, shoot and leaf respiration) and autotrophic respiration (organic matter decomposition), is one of the largest carbon fluxes and second to gross primary production (GPP) in the terrestrial ecosystem (Davidson et al. 2006). In the 1990s, the CO_2 emission from terrestrial ecosystems to the atmosphere was about 18 times higher than that from fossil fuel (Prentice et al. 2001). Eddy covariance measurements show that 80% of GPP in the terrestrial ecosystem returns to the atmosphere through respiration (Law et al. 2002; Verma et al. 2005; Li et al. 2006). Small imbalances between photosynthesis and respiration can lead to significant inter-annual variation in atmospheric CO_2 concentration (Trumbore 2006). CO_2 loss by ecosystem respiration has the potential to create positive feedback under global climate change (Houghton et al. 1998; Cox et al. 2000; Prentice et al. 2001). So, it is necessary to understand the

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mechanisms of ecosystem respiration to predict carbon exchange correctly between the terrestrial ecosystem and the atmosphere, and to evaluate the long-term trends of carbon sequestration in terrestrial ecosystems.

Ecosystem respiration is controlled by the complex interactions among many environmental and biotic factors. Temperature is a dominant factor controlling ecosystem respiration (Raich & Schlesinger 1992; Lloyd & Taylor 1994). The relationship between respiration and temperature is used in many physiobiochemical models to simulate ecosystem respiration. Temperature sensitivity coefficient (Q_{10}) of ecosystem respiration decreases with increasing temperature and declining soil moisture (Lloyd & Taylor 1994; Xu & Qi 2001; Reichstein et al. 2002; Flanagan & Johnson 2005). Plant growth has great effects on ecosystem respiration (Xu & Baldocchi 2004). Although many studies on the factors controlling ecosystem respiration have been conducted in recent years, the mechanisms by which temperature and the other environmental factors affect it are still poorly understood (Davidson et al. 2006).

Ecosystem respiration is mainly measured by chamber methods (Norman et al. 1992; Dugas et al. 1997; Angell et al. 2001; Franzluebbers et al. 2002; Lohila et al. 2003; Sun et al. 2004; Byrne et al. 2005; Risch & Frank 2006; Qi et al. 2007) and the eddy covariance technique (Law et al 2001; Xu & Baldocchi 2004; Griffis et al. 2004; Wen et al. 2006). Chamber methods are suitable for studying ecosystem respiration on low plants such as grasses (Norman et al. 1992; Dugas et al. 1997; Angell et al. 2001; Franzluebbers et al. 2002; Byrne et al. 2005; Risch & Frank 2005) and crops (Lohila et al. 2003; Sun et al. 2004; Qi et al. 2007) but not for taller plants (e.g., forests). Moreover, chambers can change the soil-plant environment (air temperature and humidity) and affect the measurement results. For high precision and the ability to measure plant carbon flux at different heights, the eddy covariance technique is the main tool used to measure carbon flux in many FLUXNET sites (Valentini et al. 2000; Baldocchi 2003; Giasson et al. 2006). In eddy covariance research, daytime ecosystem respiration is obtained from the empirical function of night time CO_2 exchange versus soil temperature (the Q_{10} model) (Shibistova et al. 2002; Zamolodchikov et al. 2003; Zha et al. 2004; Xu & Baldocchi 2004; Van Dijk & Dolman 2004). This method is suitable for simulating ecosystem respiration of forest, grassland and single cropping systems. However, for double cropping systems, the Q_{10} model will overestimate ecosystem respiration during the period between the two growing seasons when the ground is bare, but while solar radiation and temperature are still high.

Based on 4-year continuous measurements of carbon flux in a wheat-maize rotation system using the eddy covariance technique, the aims of this paper are to discuss the main environmental and biotic factors controlling ecosystem respiration, to improve the Q_{10} model to evaluate the magnitude of ecosystem respiration and to analyse the seasonal and annual characteristics of ecosystem respiration in the cropland of the North China Plains.

MATERIALS AND METHODS

Site description

This experiment was conducted at Yucheng Comprehensive Experimental Station, Chinese Academy of Sciences (36°57′N, 116°38′E, 22.0 m). The station is located in the North China Plains, in the East Asia monsoon region, with a semi-humid and warm-temperate climate. Over the last 40 years, annual average temperature is 13.2°C. The warmest month is July (26.9°C) and the coldest is January (–2.4°C). The mean annual precipitation is 585 mm and the seasonal pattern of precipitation is uneven, with the precipitation in summer (June–August) accounting for 70% of that for the full year. The parent material of the soil are the alluviums of the Yellow River. Soil texture in the tillage layer is sandy loam. The soil organic matter content in the tillage layer is about 1.2%. Total nitrogen content varies from 0.06% to 0.14% and the pH from 7.1 to 8.5. The typical cropping system is winter wheat and summer maize rotation within each year. Field management details are described in Table 1.

Eddy covariance and micrometeorological measurements

The eddy covariance and micrometeorological instrumentations were located in the centre of an area of uniform cropland. The eddy covariance systems consist of a three-dimensional sonic anemometer (model CSAT3, Campbell Sci. Inc., USA) and an open-path and a fast response infrared gas analyser (model LI-7500, Li-Cor Inc., USA) at an average height of 2.8 m above the ground which can be used to measure three-dimensional wind speed, air temperature, air humidity and CO_2 concentration above the canopy. All the above raw data were continuously collected at 10 Hz with a data logger (model CR5000, Campbell Sci. Inc., USA), and 30 min means were recorded.

Micrometeorological gradient measurement systems included anemometers (model AR-100, Vector Instruments, UK) and psychrometers (model HMP-45C, Vaisala, Finland) at two heights (2.2 and 3.4 m) above the ground. All the heights of sensors were changed with crop growth and the lowest sensors were maintained at 0.5–1 m above the crop canopy. During the measurement period, the fetch was greater than 200 m, which satisfied the requirement of micrometeorological gradient measurement. Soil temperature was measured using a temperature sensor (model TCAV, Campbell Sci. Inc., USA). Soil moisture contents were monitored using two time domain reflectometers (TDR) (model CS615-L, Campbell Sci. Inc., USA) at 20 and 40 cm depths. The instruments were connected to a data logger (CR23x, Campbell Sci. Inc., USA) and the data were logged at 30-min intervals. Leaf area was measured every 5 days for winter wheat and every 7 days for summer maize using a leaf area instrument (model Li-3100, Li-Cor Inc., USA).

Data processing

The 30-min mean CO_2 fluxes were calculated from the raw data using three-dimensional coordinate rotations (Wilczak et al. 2001) and WPL-correction (Webb et al. 1980). Sensor malfunction and extreme weather conditions can lead to anomalous data, which were first eliminated. Then, the daytime and night time monthly average fluxes were calculated using the screened 30-min data. The flux was rejected if its deviation from the monthly average was more than three times the squared difference. The data were eliminated on rainy days and on mornings having significant dew (Falge et al. 2001). CO_2 flux was often underestimated due to insufficient turbulent mixing during a still night (Goulden et al. 1996; Aubinet et al. 2000; Baldocchi 2003). A mean threshold wind-speed (u*) was obtained based on the relationship between friction wind speed and carbon flux (Falge et al. 2001; Anthoni et al. 2004) and any data lower than threshold value were rejected. In this study, the u* threshold of 0.15 m s^{-1} was chosen during the periods from March to May, 0.18 m s^{-1} from June to September, and 0.12 m s^{-1} from October to February of the next year. Interpolated values were used to fill gaps within any 2-h period. When the data gaps were more than 2 h, the daily mean variance method (MDV) was employed to replace the missing data (Falge et al. 2001).

RESULTS AND DISCUSSION

Response of ecosystem to temperature

Temperature is one of the most important factors controlling ecosystem respiration. Many observations show that ecosystem respiration increases exponentially with increasing temperature (Wang et al. 2004; Xu & Baldocchi 2004; Suyker et al. 2005; Moureaux et al. 2006; Powell et al. 2006). Similar results were found in our experiments. The night time ecosystem respiration (R_{ec}) in the wheat-maize rotation system increased exponentially with soil temperature at 5 cm depth (T_s, °C) (Fig. 1) and can be described as:

$$R_{ec} = R_0 e^{bT_s} \tag{1}$$

where R_0 is ecosystem respiration at 0°C ($gCO_2\ m^{-2}\ day^{-1}$) and b the exponential coefficient.

The relationship between night time ecosystem respiration and soil temperature explains 65–80% of the variability in R_{ec} for wheat and 31–79% for

Table 1 Field management details of winter wheat and summer maize.

Year	Crop	Variety	Sowing date	Applied N before sowing (kg N ha^{-1})	Applied N after sowing (kg N ha^{-1})	Irrigation (mm)	Harvest date
2003	Winter wheat	'Keyu 13'	15 Oct 2002	84.4	66.5	165.0	8 Jun 2003
	Summer maize	'Ludan 981'	14 Jun 2003		112.5	60.0	27 Sep 2003
2004	Winter wheat	'Keyu 13'	23 Oct 2003	90.0	189.0	228.8	13 Jun 2004
	Summer maize	'Ludan 981'	20 Jun 2004		165.0		25 Sep 2004
2005	Winter wheat	'Keyu 13'	18 Oct 2004	90.0	132.0	225.0	10 Jun 2005
	Summer maize	'Danyu 86'	18 Jun 2005		90.0		15 Oct 2005
2006	Winter wheat	'Weimai 8'	28 Oct 2005	225.0		225.0	8 Jun 2006
	Summer maize	'Ludan 9002'	18 Jun 2006		97.5	60.0	19 Sep 2006

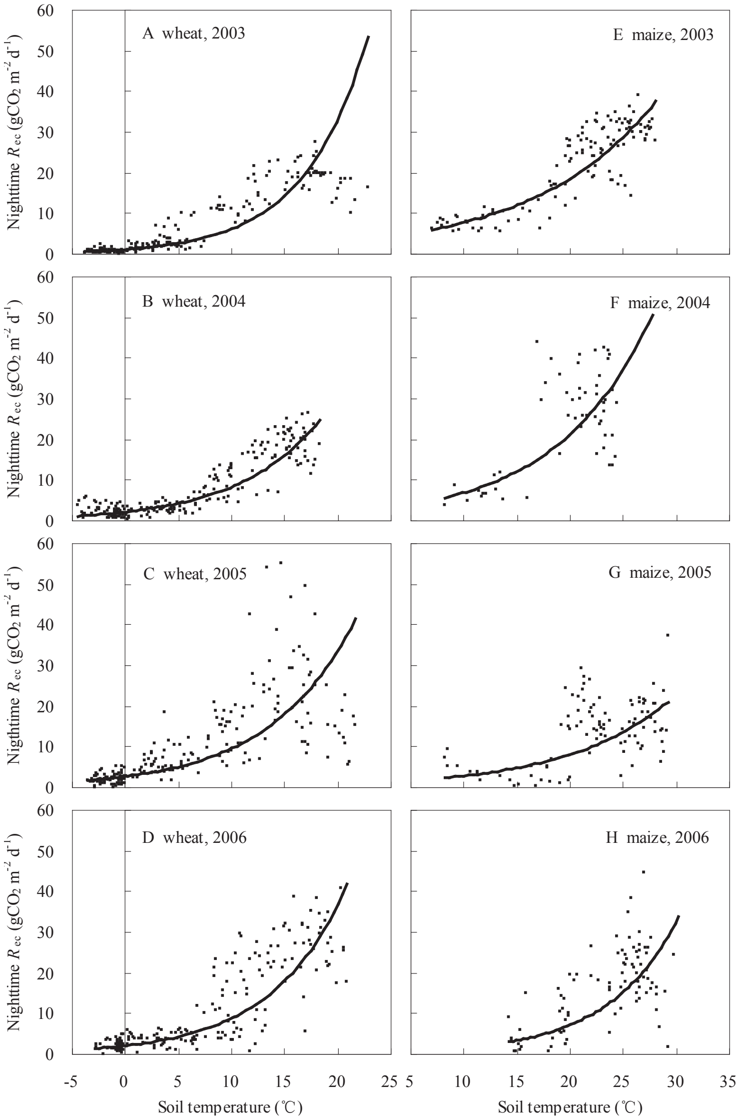


Fig. 1 Relationship between night time daily average ecosystem respiration (R_{ec}) and soil temperature at 5 cm depth in wheat and maize. The parameters (R_0, Q_{10}, r^2) of the regression line displayed in the figure are described in Table 2.

Table 2 Parameters of the Q_{10} model on daily night time ecosystem respiration and soil temperature at 5 cm depth in a wheat-maize rotation system. *n*, sampling number; r^2, correlation coefficient; **, $P < 0.01$.

Crop	Year	R_0	Q_{10}	r^2	*n*
Wheat	2003	1.161	5.349	0.804**	204
	2004	2.210	3.758	0.748**	210
	2005	2.737	3.508	0.652**	206
	2006	2.112	4.175	0.672**	196
	Average	2.055	4.198		
Maize	2003	3.258	2.389	0.792**	118
	2004	2.256	3.071	0.581**	79
	2005	1.022	2.818	0.313**	96
	2006	0.355	4.509	0.452**	86
	Average	1.723	3.197		

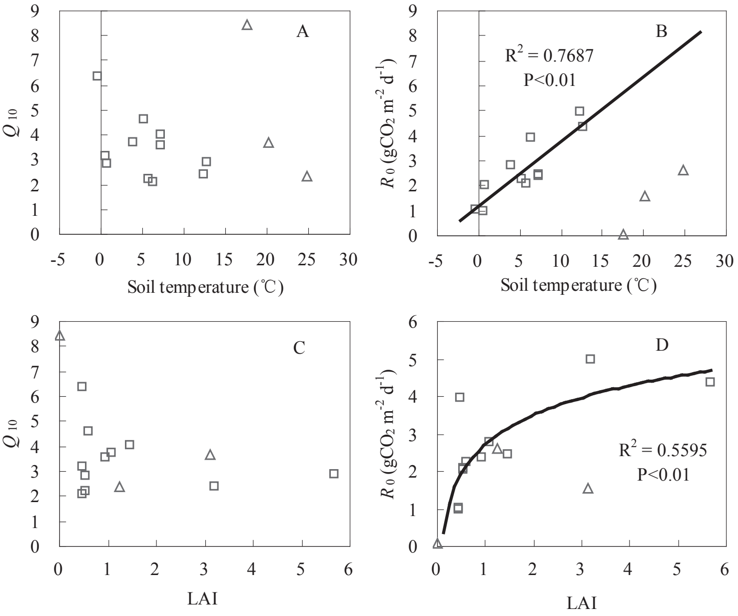


Fig. 2 Influence of leaf area index (LAI) on monthly Q_{10} and R_0. □, wheat field; △, maize field.

maize (Fig. 1 and Table 2). From 2003 to 2006, the Q_{10} values of ecosystem respiration ranged from 3.51 to 5.35 for wheat (average 4.20) and from 2.39 to 4.51 for maize (average 3.20) (see Table 2). Our Q_{10} values were higher than those reported by Suyker et al. (2005) (from 1.3 to 1.4 for maize and from 1.3 to 1.6 for soybean) and Pattey et al. (2002) (from 1.6 to 2.2 for maize). The Q_{10} of ecosystem respiration in wheat was larger than that of soil respiration reported by Chen et al. (2004) at the same site, which illustrates that ecosystem respiration in wheat was more sensitive to temperature than soil respiration. In most years, the Q_{10} of ecosystem respiration in wheat was higher than that in maize except for 2006 when many data were lost (Table 2). Temperature sensitivity of ecosystem respiration declined for high temperatures in maize. The results were similar to those reported for forest (Xu & Qi 2001). R_0 in maize dropped from year to year. It was higher than that in wheat in 2003 and 2004, but lower in 2005 and 2006. The 4-year mean Q_{10} and R_0 for wheat were higher than for maize field (Table 2). The inter-annual variances of Q_{10} and R_0 for wheat and maize were large, which made it difficult to parameterise the Q_{10} model.

Many researchers indicate that the Q_{10} of ecosystem respiration is a function of temperature and soil moisture (Fang & Moncrieff 2001; Tjoelker et al. 2001; Xu & Qi 2001; Reichstein et al. 2002). We found that not only Q_{10} but also R_0 were inconstant during the observation period (Table 2 and Fig. 2). Monthly averaged R_0 for wheat increased linearly with soil temperature, and logarithmically with LAI (Fig. 2B,D). In the wheat growing season, R_0 increased with increase in LAI (Fig. 2D). Although no obvious effects of soil temperature and LAI on Q_{10} could be found for wheat, the declining trend of Q_{10} with increasing soil temperature and the influence of LAI on Q_{10} amplitude were remarkable (Fig. 2A,C). The Q_{10} value fluctuated considerably and was easily affected by environmental factors under low LAI. When LAI for wheat was larger than 1 or 2, Q_{10} became more stable at a value close to 3.0, which indicates that it is feasible to use a fixed Q_{10} value to simulate ecosystem respiration when the ground is fully covered with vegetation. Because of a dearth of data on maize growing stages, the influence of LAI on Q_{10} and R_0 were unclear (Fig. 2C,D). However, there were obvious trends for Q_{10} declines and for R_0 increases with increasing soil temperature (Fig. 2A,B).

Annual Q_{10} values decreased linearly with increasing R_0 for wheat but for maize the relationship between them was not significant (Fig. 3A). Monthly average Q_{10} decreased logarithmically with increasing R_0 and Q_{10} varied significantly with R_0 when R_0 was low (Fig. 3B), which resulted from a Q_{10} decline and a R_0 increase with increasing temperature.

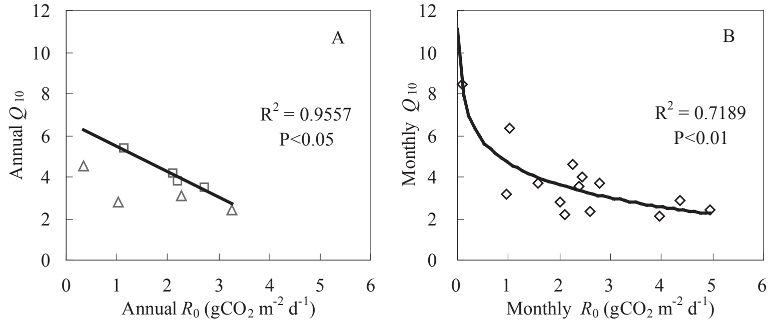


Fig. 3 Relationship between annual **A**, and monthly **B**, Q_{10} and R_0. □, wheat; △, maize; ◇, wheat-maize rotation system.

Influence of LAI on ecosystem respiration

In addition to temperature, soil moisture is an important factor controlling ecosystem respiration (Franzluebbers et al. 2002; Xu & Baldocchi 2004; Kato et al. 2004; Flanagan & Johnson 2005; Byrne et al. 2005; Powell et al. 2006). In this study, soil moisture had no obvious influence on ecosystem respiration (data not shown) because of the ample irrigation in cropland. Nevertheless, the effect of plant growth on ecosystem respiration could not be ignored. Ecosystem respiration was significantly determined by LAI (Suyker & Verma 2001; Yu et al. 2005). Suyker et al. (2005) found that variations of ecosystem respiration were of the order of 82–91% and could be explained by the change of LAI in maize and soybean fields. Our results showed that R_{ec} was overestimated using the Q_{10} model when temperature was high and LAI was low from late May to early July in a wheat-maize rotation system. So, it was necessary to correct the Q_{10} model using LAI before simulating ecosystem respiration during this period.

To understand the influence of LAI on ecosystem respiration, it was necessary to calculate residual ecosystem respiration as follows:

$$R_{ec,r} = ln(R_{ec,m}) - ln(R_{ec,s}) \tag{2}$$

where $R_{ec,r}$ is residual night time mean ecosystem respiration; $R_{ec,m}$ and $R_{ec,s}$ are observed and simulated night time mean ecosystem respiration, respectively. $R_{ec,s}$ can be obtained by Eqn (1). Ecosystem respiration in the wheat-maize rotation system was clearly affected by LAI (Fig. 4, 5). From 2004 to 2006, before LAI for wheat reached its peak, $R_{ec,r}$ was generally positive and first increased and then declined with increasing LAI (Fig. 4B–D), which could be expressed by a conic function. In 2003 wheat behaved differently from other years, $R_{ec,r}$ declined logarithmically with an increase of LAI (Fig. 4A), which may be related to the low temperature at the revival stage. After LAI reached its peak, $R_{ec,r}$ became negative and decreased with decreases in LAI (Fig. 4E–H). Although the relationship between $R_{ec,r}$ and LAI for maize was unclear in most years, it became clear in year 4 (Fig. 5). The relationship between $R_{ec,r}$ and LAI can be expressed as:

$$R_{ec,r} = f(LAI) \tag{3}$$

Eqn (3) can be described by conic, linear or other functions. The relationship between $R_{ec,r}$ and LAI can be used to solve the overestimation of ecosystem respiration using the Q_{10} model when LAI is low in summer. At the elongation stage of wheat, R_{ec} was clearly underestimated when plants grew well and LAI increased rapidly. Canopy respiration increased and more photosynthetic products were transferred below ground which enhanced both root respiration and soil microbe metabolism, which led to an increase of R_{ec}.

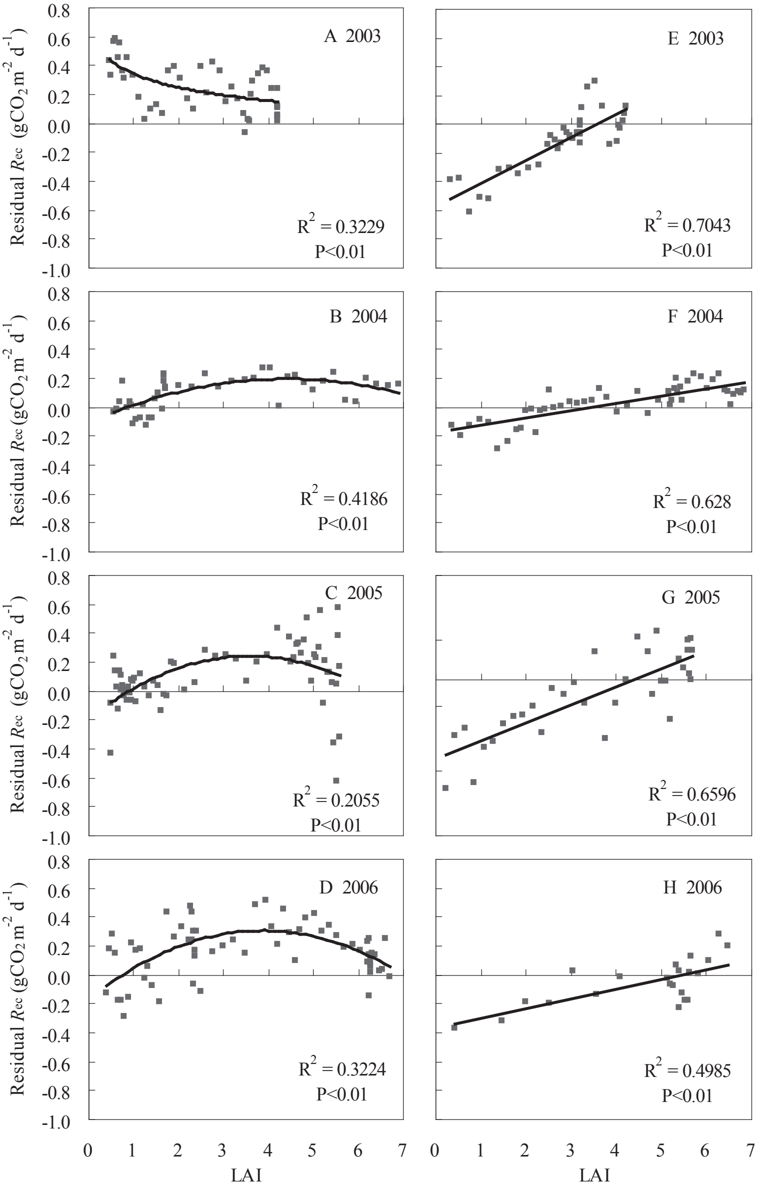
Estimation of ecosystem respiration

Although daytime ecosystem respiration cannot be measured directly using the eddy covariance technique, it can be obtained by the relationship between night time ecosystem respiration and environmental factors. However, as we discussed above, Q_{10} and R_0 are mutable parameters of the Q_{10} model. They varied with bio-environmental factors such as soil temperature and LAI. It is necessary to revise the traditional Q_{10} model because it will lead to large errors in estimating ecosystem respiration, especially in a double cropping system. Since it is difficult to determine Q_{10} using its relation to soil temperature and LAI, we turn to use a multiplicative model to simulate ecosystem respiration:

$$R_{ec} = R_0 e^{bT_s} e^{f(LAI)} \tag{4}$$

where R_0 and b were described in Eqn (1); T_s is daily mean soil temperature at 5 cm depth and R_{ec}

Fig. 4 Relationship between night time residual R_{ec} and leaf area index (LAI) in a wheat field. **A–D**, before LAI reached its maximum; **E–H**, after LAI reached its maximum.



daily average ecosystem respiration. In this study, ecosystem respiration was calculated by Eqn (1) before LAI reached 0.4 at the revival stage of winter wheat, by Eqn (4) in the period from the revival stage (LAI >0.4) to milking stage (LAI >0.2) for wheat and all the maize growing stage when LAI was up to 0.2. Net ecosystem carbon exchange was regarded as ecosystem respiration when the ground was nearly bare (LAI <0.2) from harvest to next sowing. After considering LAI, the modified Q_{10} model (multiplicative model, Eqn (4)) could estimate R_{ec} better than the traditional one (Eqn (1)) in both of winter wheat and summer maize (Fig. 6).

Seasonal and inter-annual variations of ecosystem respiration

Seasonal variation of ecosystem respiration was obvious in the wheat-maize rotation system (Fig. 7). There were two peaks of daily ecosystem respiration,

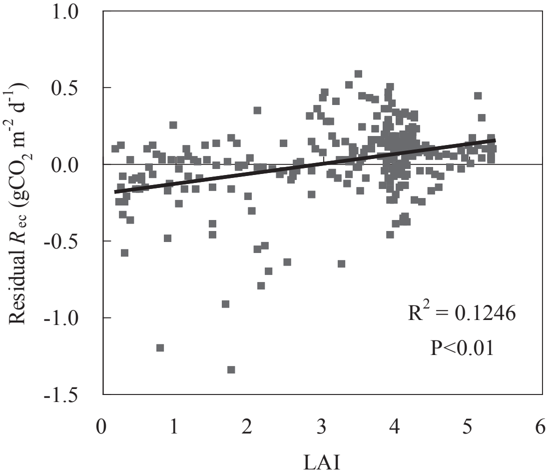


Fig. 5 Relationship between night time residual R_{ec} and leaf area index (LAI) in maize.

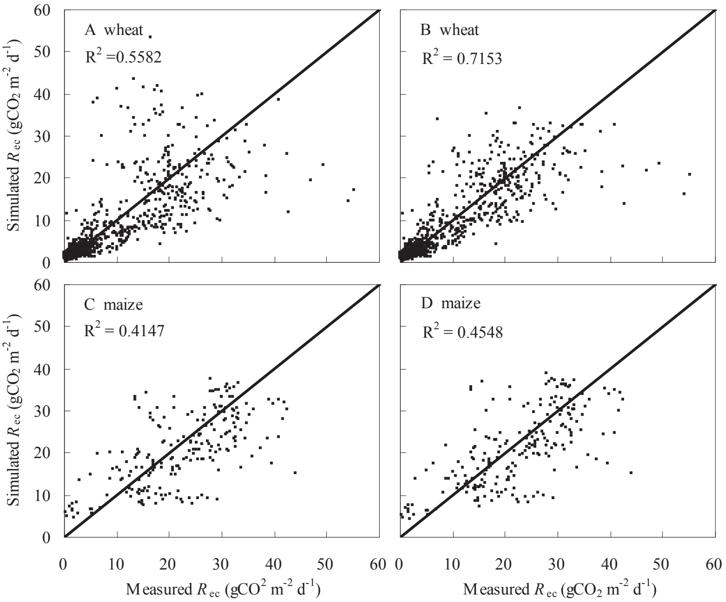


Fig. 6 Relationship between measured and simulated night time R_{ec} using Q_{10} model, **A,C**, and the multiplicative model considering leaf area index (LAI) **B,D**, over 4 years (——1:1 line).

one in the wheat growing stage (late April for most years) and another in the maize growing stage (mid–late July for most years). The annual maximal daily average ecosystem respiration generally appeared in the wheat growing season (Fig. 7). Based on vegetation status, ecosystem respiration over the entire year could be divided into four stages, two growing seasons for wheat and maize (LAI >0.2) and the two bare ground periods between them (LAI <0.2). Average ecosystem respiration was 2.60 and 6.09 gC m^{-2} day^{-1} in the wheat and maize growing seasons, and 2.39 and 2.02 gC m^{-2} day^{-1} for the summer and autumn bare ground periods. Although the average ecosystem respiration in maize was much higher than in wheat, their difference of seasonal total ecosystem respiration was not significant due to the longer growing season of wheat. Ecosystem respiration was 566 and 520 gC m^{-2} for the wheat and maize growing seasons, and 78 and 57 gC m^{-2} for the summer and autumn bare ground periods. The 4-year average ecosystem respiration in wheat and maize growing seasons accounted for 46.4 and

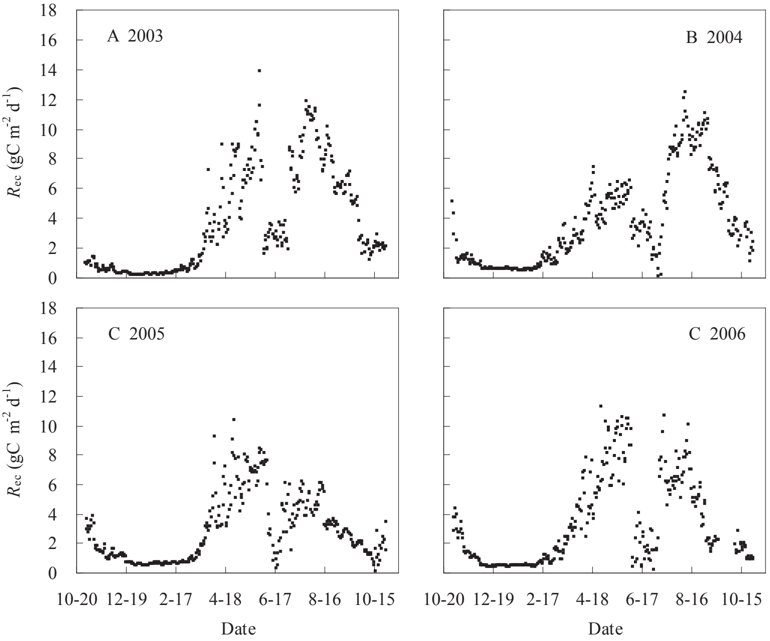


Fig. 7 Seasonal variation of daily ecosystem respiration (R_{ec}) in a wheat-maize rotation system.

Table 3 Seasonal and annual ecosystem respiration (R_{ec}) in a wheat-maize rotation system.

	Total R_{ec} (gC m^{-2})				Average R_{ec} (gC m^{-2} day^{-1})			
Stage	2003	2004	2005	2006	2003	2004	2005	2006
Wheat growing season	510	499	609	647	2.36	2.30	2.76	2.98
Maize growing season	661	678	323	419	7.78	7.79	3.33	5.45
Summer bare ground stage	85	99	81	48	2.74	2.68	2.69	1.47
Autumn bare ground stage	70	72	27	57	2.14	2.89	1.58	1.49
Annual	1327	1348	1040	1171	3.64	3.68	2.85	3.21

42.6% of the entire year. Ecosystem respiration in the two bare ground periods (combined) accounted for 11% of that for the entire year and cannot be ignored.

The inter-annual differences between the seasonal average and total ecosystem respiration were large (Table 3). Especially in the maize growing season, the low ecosystem respiration in 2005 and 2006 might be linked to a change in maize varieties and to reduced fertilisation (Tables 1 and 3). In the 4 years from October 2002 to October 2006, annual ecosystem respirations in the wheat-maize rotation system were 1327, 1348, 1040 and 1171 gC m^{-2} yr^{-1}. The small ecosystem respiration in the maize growing season led to a lower annual total ecosystem respiration in 2005 and 2006 than in 2003 and 2004. Our result was similar to that reported by Law et al. (2002) for wheat but lower than the results of Koizumi et al. (1993) for wheat and maize. The difference among observation results on ecosystem respiration may be interpreted by regional diversity of climate and soil.

CONCLUSIONS

In conclusion, average daily night time ecosystem respiration in a cropland increased exponentially with increases of soil temperature at 5 cm depth. During the 4 years of observation, Q_{10} ranged from 3.51 to 5.35 for wheat (average 4.20) and from 2.39 to 4.51 for maize (average 3.20). Monthly average

R_0 for wheat increased linearly with soil temperature and logarithmically with LAI. Monthly average Q_{10} decreased logarithmically with R_0.

In most years, the residual ecosystem respiration increased with increasing LAI at first but then decreased with further increases in LAI. After LAI reached its peak value, the residual ecosystem respiration changed from positive to negative and declined linearly with decreasing LAI. The residual ecosystem respiration in maize increased linearly with increasing LAI.

After considering LAI, the modified Q_{10} model can estimate ecosystem respiration better than the traditional one. The simulation results show that from October 2002 to October 2006 annual ecosystem respiration in the wheat-maize rotation system in the north China plains was 1327, 1348, 1040 and 1171 gC m^{-2} yr^{-1}, and the inter-annual differences of ecosystem respiration were large. The 4-year average values showed that seasonal mean ecosystem respiration in wheat (2.60 gC m^{-2} day^{-1}) was much lower than in maize (6.09 gC m^{-2} day^{-1}). However, the integrated magnitude of ecosystem respiration for the wheat growing season (566 gC m^{-2}) was slightly higher than that for maize (520 gC m^{-2}). These account for 46.4 and 42.6% of the annual value, respectively.

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