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Diurnal and seasonal variability of soil CO_2 efflux in a cropland ecosystem on the Tibetan Plateau

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Abstract

Seasonal variation of soil CO_2 efflux is highly dependent on climate and plant phenology. On the Tibetan Plateau with an average altitude about 4000 m a.s.l., variations of CO_2 efflux may be strongly associated with the unique ecophysiology and climate over there. Our objectives were to quantify diurnal and seasonal variations of soil CO_2 efflux, and to investigate the effects of daily and seasonal variations of soil temperature and phenology on soil CO_2 efflux. CO_2 efflux was measured in Lhasa River valley on the Tibetan Plateau using a static closed chamber technique and gas chromatography for 2 full years from September 1999 to August 2001. Soil CO_2 effluxes showed similar diurnal change patterns and fluctuated from minimum at 5:00 h to maximum at 11:00–14:00 h in different phenological stages. Soil CO_2 efflux exhibited pronounced variation corresponding to crop phenology and soil temperature, with a minimum value of 0.4 g CO_2 m^{-2} d^{-1} in January and a maximum value of 15.0 g CO_2 m^{-2} d^{-1} in mid June. The observed mean soil CO_2 effluxes were 6.6 g CO_2 m^{-2} d^{-1} in the growing season and 2.8 g CO_2 m^{-2} d^{-1} in the non-growing season, with an average of 6.0 g CO_2 m^{-2} d^{-1} in the 2 full measured years. While soil CO_2 efflux was strongly dependent on soil temperature with highest correlation found with 5 cm depth temperature, maximum values of CO_2 efflux coincided with maximum values of leaf area index (LAI) and live root biomass (LRB) in mid June but not with maximum soil temperature in July. CO_2 efflux was positively correlated with LAI and LRB in the growing season from March to August. Soil moisture had relatively little effect on soil CO_2 efflux due to frequent irrigation. Simulation of soil CO_2 efflux with soil temperature in the whole 2 years of observation led to overestimates in non-growing season and underestimates in the growing season. Taking account of the influence of crop phenology, a temperature dependent exponential model was separately used to fit CO_2 efflux in growing season and non-growing season. This alteration increased 7.5% of explained variance of seasonal variability and provided more accurate prediction of soil CO_2 efflux. Q_{10} values ranged 2.0 in growing season and 2.5 in non-growing season. Total annual loss of C from soil respiration was estimated to be 579 ± 13 g C m^{-2} per year at the site. The results suggest that soil temperature is the determinant factor controlling temporal variation of soil CO_2 efflux and crop phenology modifies the temperature dependence of soil CO_2 efflux in different growing periods. Our results also indicate that root respiration in the growing season can be estimated approximately by using the discrepancy between CO_2 efflux relations in the growing season and non-growing season of cropland ecosystem.

Keywords: Soil CO_2 efflux; Soil temperature; LAI; Phenology; Cropland ecosystem; Tibet Plateau

1. Introduction

Worldwide concern with global change and its effects on our future environment requires a better understanding and quantification of the processes of greenhouse gas emission (Ohashi et al., 1999). Soils are

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the largest carbon pool in terrestrial ecosystems, containing more than 1500 Pg C (Raich and Schlesinger, 1992; Eswaran et al., 1993). CO_2 efflux from soil to atmosphere is a major component of greenhouse gas emission and is a crucial pathway of the C cycle. It is highly sensitive to temperature and global changes may have a great influence on the magnitude of soil CO_2 efflux. The potential increase in CO_2 release from the soil caused by future elevated temperature may have a positive feedback effect on atmospheric CO_2 and global change (Kirschbaum, 1995). In the context of increasing CO_2 concentration in the atmosphere and the related potential change in climate, knowledge of soil CO_2 emission is of great importance to estimate future atmospheric CO_2 concentration and global change (Liang et al., 2004). Therefore, it is important to obtain accurate estimates of soil CO_2 efflux and to understand controls on the underlying process.

Soil CO_2 efflux is a complex process controlled by biotic an abiotic factors (Buchmann, 2000). Soil temperature and soil moisture are among the most important factors controlling the CO_2 efflux (Raich and Schlesinger, 1992; Raich and Potter, 1995; Davidson et al., 1998). The direct relationship between CO_2 efflux and temperature is well documented (Raich and Schlesinger, 1992; Lloyd and Taylor, 1994; Fang and Moncrieff, 2001). A temperature dependent exponential model in respect of soil CO_2 efflux is commonly accepted (Lloyd and Taylor, 1994; Fang and Moncrieff, 2001) although it is observed for biological systems over a limited range of temperatures (O'Connel, 1990; Thierron and Laudelout, 1996; Winkler et al., 1996). A limitation of it use is that it may underestimate the response of soil CO_2 efflux at low temperature and overestimate it at higher temperature (Fang and Moncrieff, 2001). The contribution of biotic factors (i.e. plant activity) might be overshadowed because this component of CO_2 efflux was simplified as a temperature dependent process.

In fact, soil CO_2 efflux is a combined efflux from roots and microorganisms from different soil depths. It may depend on a variety of factors and their interactions, such as soil properties and plant growth (Litton et al., 2003; Epron et al., 2004). Plant phenology may play an important role in root respiration through its influence on root growth rhythms. Root growth is strongly correlated with leaf area index (LAI), which is not a simple temperature dependent factor, and thus phenology can modify the temperature dependence of soil CO_2 efflux. The key question that should be addressed is the influence of plant phenology on soil CO_2 efflux and how it modulates the temperature response and its variability through time, but there is little information on assessing the effect of plant phenology on soil CO_2 efflux (Högberg et al., 2001; Janssens et al., 2001; Litton et al., 2003; Liang et al., 2004). Most vegetation types, especially ecosystem dominated by annual plants, such as cropland, show pronounced phenological variation through the year, and thus a quantitative evaluation of the influence of plant phenology on soil CO_2 efflux and its modification of the effect of temperature would enhance our insight to the process of soil respiration and be helpful to estimate accurate CO_2 efflux.

The Tibetan Plateau is called the world's roof and has an average elevation above 4000 m. Over the past decades, high altitude soil has attracted more attention in the debate on the potential impact of environmental change on the global C cycle (Beniston, 1997; Diaz and Bradley, 1997; Goulden et al., 1998; Christensen et al., 1999; Oechel et al., 2000). This interest has arisen due to (i) predicted greater than average climate warming at high altitude (Beniston, 1997; Sjögersten and Wookey, 2002); (ii) unique climate and plant physiology (Li and Zhou, 1998); (iii) more sensitive response of ecosystem to climate change (Tang et al., 1986; Li and Tang, 1988; Beniston, 1997). Ecosystem function and its response to climate change have been studied since the 1990s. Soil CO_2 efflux was studied over major Chinese ecosystems (Luo et al., 2000; Cao et al., 2001, 2004; Liu et al., 2001; Zhang et al., 2003). Observations showed that soil temperature is the major environmental driving factor. However, biotic factors, such as phenology, live root biomass and LAI were not considered as factors determining soil CO_2 efflux. There is also little information about the effect of biotic factors on controlling soil CO_2 efflux on the plateau.

There are 1.08×10^6 ha of arable cropland on the Tibetan Plateau, in which 1.76×10^5 ha are distributed in the Yarlung Zangbo River watershed and its tributary watersheds in middle and eastern Tibet, accounting for 16.1% of the total (Yang et al., 1996). Although cropland covers only 1% of land area in Tibet, it represents an important type of artificial ecosystem in which 80% of the population lives (Yang et al., 1996). Average annual air temperature is 5.3 °C and precipitation ranges from 300 to 500 mm in the agricultural area (Comprehensive scientific exploration team, Chinese Academy of Sciences, 1984; Yang et al., 1996). The traditional farming system is a wheat–maize–rape rotation system, but the most common tillage system is winter wheat or Tibet barley continuous farming. Maize and rape are also common but these are cultivated in small areas (Yang et al., 1996). The

growing period of winter wheat and barley cover nearly 11 months from mid or later October for sowing to early next September for harvest.

The cropland ecosystem is of interest since it allows easy manipulation to examine the effect of global change on biological response. In the present study, cropland provides an ideal site to test the modification of plant phenology to the influence of temperature on soil respiration. Also annual crops exhibit apparent and relatively short-term seasonal variation of growth rhythm in contrast to perennial ecosystems. Phenology may play a great role in the diurnal and seasonal variation of soil CO_2 efflux, which will influence the carbon budget. The main objectives are therefore to: (1) quantify diurnal and seasonal CO_2 effluxes and their variability; (2) investigate the effects of seasonal changes in soil temperature and phenology; (3) further analyze the response of soil CO_2 efflux to phenology at the site.

2. Materials and methods

2.1. Site description

This study was conducted in winter wheat cropland at the Lhasa Plateau Ecosystems Research Station, a member of the Chinese Ecosystem Research Network (CERN). The station is located in the lower reaches of the Lhasa River valley (29°40′40″N, 91°20′37″E) on the Tibetan Plateau, with an elevation of 3688 m.

Winter wheat (*Triticum aestivum* L. var. Bussyd) was planted in October. Before sowing, the farmland was plowed for soil preparation and residues were removed to prevent from impeding farming activities. One hundred kilograms per hectare of winter wheat seed was planted at a spacing 0.25 m in early October. Basal fertilizer of N, P_2O_5, K_2O was applied at 40, 18 and 11 kg ha^{-1}, respectively, during planting. Sheep manure was spread with 1500 kg ha^{-1} on the surface and covered with shallow soil after seeding. Before heading, 150 kg ha^{-1} of urea was applied to the cropland. The crop was frequently irrigated with the appearance of wilting to avoid drought. Field management was the same as that of local farmers. Weeding was performed in early May and middle June. Winter wheat was harvested in early September every year and the whole production period is about 320 days.

The site is characterized by a continental temperate climate with annual mean, maximum and minimum air temperature of 7.5, 27.4 and −11.8 °C, respectively. Annual precipitation is 425.4 mm, with 94% concentrated from June through September. Annual atmospheric pressure is 650.3 mbar, one third less than that at sea level (Comprehensive scientific expedition to the Qinghai-Xizang (Tibet) plateau, Chinese Academy of Sciences, 1984). The soil at the site is sandy loam developed from inundated materials in the river valley. The soil had pH value of 7.0–8.5, organic matter of 1.5–2.5% and total nitrogen of 0.15% at 10 cm depth (Shi and Yu, 2003).

2.2. Field measurements

Soil CO_2 efflux was measured by using a static closed chamber technique and gas chromatography over the period from September 1999 to August 2001. Gas samples were collected in the field and brought to the laboratory for gas chromatography. Biotic and abiotic variables including biomass, LAI, air temperature, soil temperature and soil moisture were also measured at the same time.

The closed chamber was made from 8 mm thick acrylic materials with a 0.25 m^2 (50 cm × 50 cm) surface area, and 30 cm tall. The top square edges were rubber-sealed in order to prevent from leakage when the top lid was put on it. The chamber was fitted with a 12 V dc electric fan, a temperature sensor and a three-way valve for gas sampling.

Three 50 cm × 50 cm steel frames were randomly inserted into the soil 1 day before measurement to minimize soil surface disturbance. Two rows of winter wheat plants were included in each frame. The plants in the frames were cut at ground level and litter in the frames removed (Norman et al., 1992). The cut plants were used to measure leaf area index (LAI) and aboveground biomass. After gas sampling, roots in three soil frames were dug out to determine root biomass.

During the measurement, the chamber was mounted on a frame by a water seal, and the fan was started. A 0.5 L volume of gas was extracted using syringe at 0, 10, 20 and 30 min after the chamber was put in place. Air samples were collected in polyethylene-coated aluminum bags and brought to the laboratory for gas chromatography (Dong et al., 2001).

Gas sampling was conducted every 2 weeks from April to August, and monthly for the rest of the year. In total, there were 32 measurements in the 2 years, including 10 sets of diurnal measurements at typical phenological stages and 22 sets of daytime measurements. Diurnal variation in CO_2 fluxes were examined using eight measurements, beginning at 19:00, 22:00, 1:00, ..., 16:00 h, local time. Daytime measurements were made twice daily, beginning at 7:00 and 14:00 h. Every measurement had three replicates, each of which took 30 min to extract the four samples and measure temperature in the chamber at 0, 10, 20 and 30 min.

Between each replicate there was a 10 min interval for moving the chamber between the steel soil frames. Each set of measurements thus required 110 min. Mean values of CO_2 efflux of three replicates represented the mid time of the measurement, i.e. 20:00, 23:00, 2:00, ..., 17:00 h for diurnal measurement, and 8:00 and 15:00 h for daytime measurements.

Leaf area was measured using a leaf area meter (Model AM200-001, ACD BioScientific Ltd., UK). The leaves were oven-dried and weighed for calculation of specific leaf area (SLA) and LAI. Root systems in three soil frames were dug out and separated into live and dead roots according to their color. All separated fractions were dried and weighed for measurement of dead and live root biomass.

Soil temperature was simultaneously measured by using bent ground thermometers at the soil surface and at 5, 10, 15 and 20 cm depth near the measuring site while gas sampling was conducted. Air temperature was taken from meteorological observations at the Lhasa Plateau Ecosystems Research Station. Soil moisture was measured with the gravimetric method using 35 mm soil cores taken every 10 cm to a total depth of 40 cm. Soil cores were dried in an oven at 105 °C for 24 h to determine soil water content.

2.3. Air sample analysis and data processing

Air samples were analyzed for CO_2 content by gas chromatography (GC, Hewlett-Packard 5890II) with an electron capture detector (ECD). The detector temperature was maintained at 330 °C (Dong et al., 2001). Soil CO_2 efflux was calculated as (Dong et al., 2001; Drewitt et al., 2002):

$$R_s = \frac{PV}{RTA}\frac{dC}{dt} = \frac{P}{RT}\frac{dC}{dt}h \quad (1)$$

where R_s is the soil CO_2 efflux (μmol m^{-2} s^{-1}), P the air pressure, 650.3 mbar (0.642 atm), R the gas constant (8.21×10^{-5} m^3 atm K^{-1} mol^{-1}), V and A the volume (m^3) and surface area (m^2) of chamber, T the absolute temperature (K) in the chamber, h the chamber height (m) and dC/dt is the rate of change of CO_2 concentration (μmol mol^{-1}) during the period dt (s).

The relationship between soil respiration and temperature was modeled by an exponential function (Lloyd and Taylor, 1994):

$$R_s = a\exp(bT) \quad (2)$$

where a and b are the constants and T is the soil temperature. The Q_{10} value, as the multiplier to the respiration rate for a 10 °C increase in temperature, was calculated as:

$$Q_{10} = \exp(b \times 10) \quad (3)$$

where b is the value from Eq. (2) (Boone et al., 1998; Xu and Qi, 2001). Data analysis was done by SPSS 10.0 (SPSS, Inc., Chicago, IL, USA).

2.4. System testing

CO_2 accumulation in the chamber headspace may result in decrease in flux by suppressing the CO_2 concentration gradient (Drewitt et al., 2002). To test the reliability of the chamber design and sampling method in this study, a comparison was conducted between soil CO_2 effluxes calculated from CO_2 concentration change from 0 to 20, 0 to 30 min and those from 0 to 10 min. Slopes were calculated for the two intervals, 0–20 min and 0–30 min versus 0–10 min of chamber closure for assessing estimation error. There are 5% and 10% underestimates, respectively, when the chamber closed for 20 and 30 min with comparison to CO_2 efflux calculated from closed chamber for 10 min (Fig. 1). This indicated that accumulation of CO_2 in the closed chamber headspace inhibited diffusion from the soil surface, so results were multiplied by a calibration factor of 1.1 when the slopes of CO_2 concentration change during 0–30 min were used to calculate CO_2 effluxes. Comparison of soil respiration measurements with different chamber size showed that middle-sized dark chamber (with 40 cm × 40 cm of surface area and 25 cm of height) is suitable for soil respiration measurement in temperate areas (Du et al., 2001). The air temperature and moisture in the chamber and outside were similar throughout all measurements though difference of surface soil temperature is larger. The maximum difference of surface temperature can arrived at 1–3 °C during the 30-min measuring interval in May. The production (through soil respiration) and reduction (by air sample taking) of CO_2 is almost in balance within 30 min and air sample taking will not influence gas exchange (Du et al., 2001).

2.5. Estimation of daily average and total annual CO_2 efflux

Although daily average CO_2 efflux can be accurately calculated from continuous diurnal CO_2 measurements, it is a time consuming work and not suitable for long-term seasonal and inter-annual variation measurement. A solution to this problem is to use daytime measurements for daily average estimation and calibra-

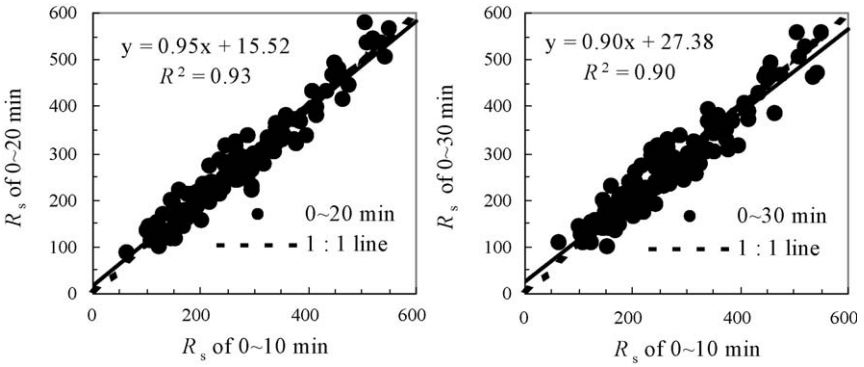

Fig. 1. Soil CO_2 effluxes (μmol CO_2 m^{-2} s^{-1}) calculated from CO_2 concentration change during 0–20 and 0–30 min vs. the effluxes calculated from the change during 0–10 min.

tion (Dugas et al., 1999; Mielnick and Dugas, 2000). The data for diurnal soil CO_2 efflux was used to analyze the effectiveness of using the daytime average to represent that of the whole day. The daytime average was calculated from two measurements at 7:00–8:00 and 14:00–15:00 h, while the diurnal average was calculated from eight measurements in a day. Data from 10 days of diurnal measurements from this study were combined with selected data from 10 days of measurements in 1997 and 1998, made using a CID-301 PS CO_2 infrared gas analyzer (CID, Inc., Camas, WA, USA), to compare the similarity between daytime and diurnal averages.

Diurnal and daytime averages were similar for 20 full days of CO_2 efflux measurements in different seasons of winter wheat growth (Fig. 2). The linear regression of daytime average versus diurnal is close to the 1:1 line.

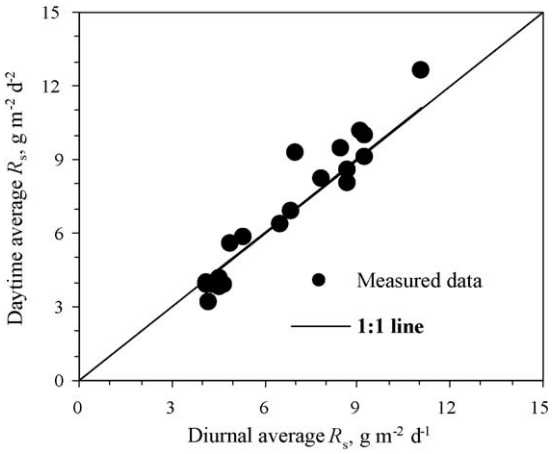

Fig. 2. Daytime average CO_2 effluxes (g CO_2 m^{-2} s^{-1}) calculated from twice-daily measurement at 7:00–9:00 h and at 14:00–16:00 h vs. daily average calculated from 8-time diel measurement in different phenological stages of winter wheat development. The 1:1 and the linear regression lines are shown ($R_{daytime} = 1.16R_{diurnal} - 0.97$, $r^2 = 0.96$, $p < 0.001$).

The slope k and correlation coefficient r^2 are 1.16 and 0.96 ($p < 0.001$). However, the absolute deviation of diurnal averages from daytime averages is 0.1% in the dataset of 20 days in different typical phenological stages of winter wheat. Linear regression was used to calibrate daily averages from estimates of daytime measurements. Therefore, daytime average efflux from measurements in the morning and afternoon provided a reasonable estimate of the diurnal averages in this study. The asymmetric diurnal pattern of daily soil temperature cycle could cause errors in estimating daily average from daytime measurements (Liang et al., 2004) because daytime temperatures are greater than at night and efflux is an exponential function of temperature.

Daily soil CO_2 efflux was estimated by using the established exponential function of average daily soil temperature from the long-term record of meteorological data. Annual total is the sum of daily efflux in the whole year.

3. Results

3.1. Diurnal variation of soil CO_2 efflux

Fig. 3 shows soil CO_2 efflux (R_s) and soil temperature at 5 cm depth of five representative days in different phenological stages of winter wheat development. Diurnal variations of soil CO_2 efflux were highly associated with variations of soil temperature at 5 cm depth. Soil CO_2 efflux showed a similar daily variation with a minimum value at 5:00 h and a maximum value between 11:00 and 14:00 h, coinciding with the minimum and maximum values of soil temperature at 5 cm. The daily variation increased with the growth of wheat from sowing to graining filling stage, reached maximum in the grain filling period, and decreased when the wheat turned yellow and ripened

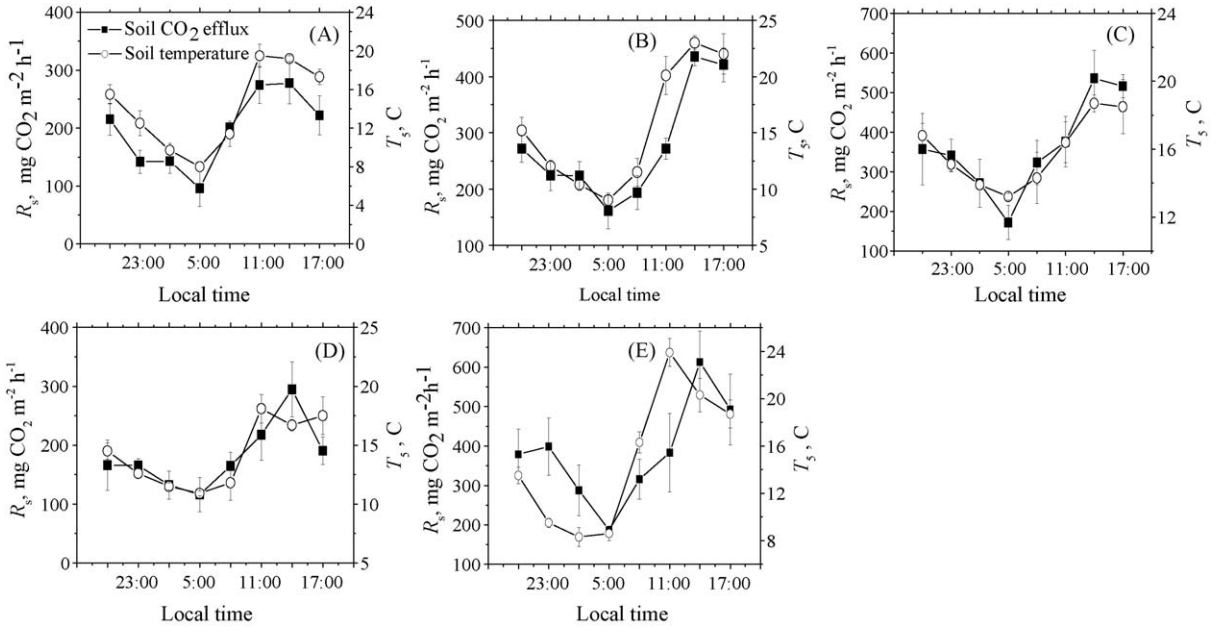

Fig. 3. Daily variation of soil CO_2 efflux in five representative phenological stages. (A) Seedling period after hibernation (30 March, 2000); (B) elongation (14 May, 2001); (C) grain filling (14 July, 2000); (D) ripening (15 September, 2000); (E) sowing (29 September, 1999). Solid box is soil CO_2 efflux (R_s, mg CO_2 m^{-2} h^{-1}) and circle is 5 cm soil temperature (T_5).

(Table 1). In early spring, daily amplitudes were considerably lower ranging between 106 and 306 mg m^{-2} h^{-1}. The highest amplitude occurred in the grain filling period, ranging from 189 to 586 mg m^{-2} h^{-1}. In the ripening period, the amplitude and average of CO_2 efflux decreased despite soil temperatures that were similar to that of grain filling period (Table 1). The highest amplitude of daily variation also occurred in the sowing period (Fig. 3).

Although daily variation of soil temperature was higher in winter and spring, higher variation of CO_2 efflux did not occur in these seasons. The highest variation of CO_2 efflux occurred in the grain filling period in early summer. It is clear that it was warmer soil temperature not higher daily variation that resulted in higher average and daily variation in of CO_2 efflux. Furthermore, disturbance caused by plowing after harvest enhanced the daily variation of soil CO_2 efflux in the sowing period in October. This phenomenon is common in cropland and also found in the barley land in central Spanish Plateau (Sánchez et al., 2003).

3.2. Seasonal change of soil CO_2 efflux

In the 2 years of measurement, soil CO_2 efflux exhibited a pronounced seasonal variation with minimum values lower than 0.4 g m^{-2} d^{-1} in January and a maximum value of 15.0 g m^{-2} d^{-1} in June (Fig. 4). Even though maximum values of soil CO_2 efflux in June did not coincide with maximum values of air and soil

Table 1
Daily variation and amplitude of soil CO_2 efflux and corresponding soil temperature at 5 cm depth in five representative phenological stages of winter wheat growth

Phenology	Date	DOY	Soil CO_2 efflux (mg m^{-2} h^{-1})				Soil temperature at 5 cm depth (°C)			
			Minimum	Maximum	Amplitude	Average	Minimum	Maximum	Amplitude	Average
Seedling	30 March	90	105.8	305.3	199.5	216.0	0.8	16.2	14.4	8.3
Elongation	14 May	135	177.4	479.1	301.6	302.9	7.5	20.4	12.9	14.1
Grain filling	16 July	198	189.2	589.3	400.1	397.7	13.0	19.2	6.2	15.9
Ripening	15 September	259	127.4	324.5	197.1	199.0	10.5	20.5	10.0	14.2
Sowing	29 September	272	205.3	673.6	468.4	420.1	9.2	19.4	10.2	13.8

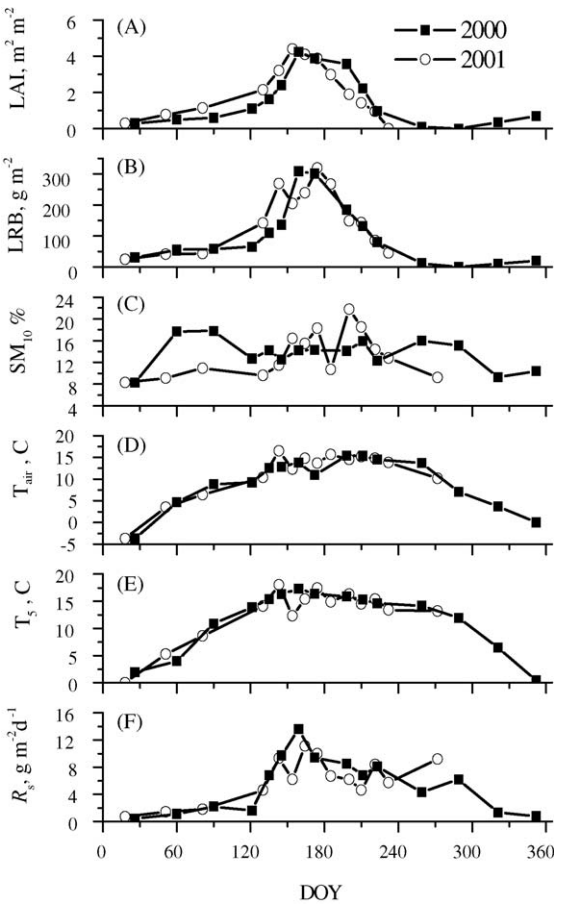

Fig. 4. Seasonal courses of the change of (A) LAI, (B) live root biomass, (C) soil moisture at 10 cm depth, (D) air temperature, (E) soil temperature at 5 cm depth and (F) soil CO_2 efflux.

temperatures in July, the general pattern of seasonal variation reflected the change of temperature, which increased from January to June and decreased after July (Fig. 4; Table 2).

Minimum CO_2 effluxes took place in January, the coldest month in a year. Minimum effluxes were 0.4 g m^{-2} d^{-1} (day 26 in 2000) and 1.0 g m^{-2} d^{-1} (day 18 in 2001), respectively. Mid December through next February is the hibernation period of wheat seedlings and CO_2 efflux was fairly low. Average values of efflux were 0.8 and 1.1 g m^{-2} d^{-1} in 2000 and 2001, respectively (Table 2). CO_2 efflux started to increase from March. In April, soil CO_2 efflux increased sharply and reached a maximum in June. Maximum efflux occurred around day 160–170 (early and mid June) in the 2 years of measurements. The maximum effluxes of 15.0 and 12.2 g m^{-2} d^{-1} occurred at day 159 (June 7) and day 164 (June 13), respectively, in 2000 and 2001. This was around the booting and flowering stage of winter wheat, corresponding with the peaks of LRB and LAI in Tibet. High CO_2 efflux continued till mid July, the milking–ripening period. Soil CO_2 efflux began to decrease in late July when wheat began to mature. After harvest in late September it usually had a high soil CO_2 efflux due to disturbance through human activities (refer to Fig. 3; Table 1). Although soil CO_2 efflux decreased sharply in autumn due to decreases in temperature and live root biomass.

Soil CO_2 efflux exhibited similar seasonal variation coincident with patterns of temperature in the two growing periods although there were some difference between the two growing seasons, especially in summer (Fig. 4). In contrast, there was a better correlation between soil CO_2 efflux and soil temperature at 5 cm depth (Fig. 4; Table 2). It indicated that soil temperature was a significant controlling factor of soil CO_2 efflux. Soil CO_2 efflux in cropland of the Tibet Plateau ranged from 0.4 to 15.0 g m^{-2} d^{-1}, with average values of 6.5 and 5.6 g m^{-2} d^{-1}, respectively, in 2000 and 2001 growing periods. On average, soil CO_2 efflux in the 2-year duration was 5.8 g m^{-2} d^{-1}.

3.3. Temperature and soil moisture controls on soil CO_2 efflux

An exponential function provided the best fit for describing the relationship between soil CO_2 efflux and temperature, with highest correlation found with 5 cm depth temperature. Table 3 shows results of modeling CO_2 efflux versus air temperature and soil temperature and the estimated parameter values. Soil temperature at 5 cm depth gave the highest correlation coefficient and accounted for 47% of seasonal variation in soil CO_2 effluxes. The possible reason may lie in the fact that 5 cm soil is in the arable layer and root system and microorganism were active in that layer. Q_{10} values of soil CO_2 effluxes increased from 1.6 to 3.7 in respect with soil temperature from 0 to 20 cm depth (Table 3).

Although an exponential function provided the best fit for CO_2 efflux with temperature, residuals exhibited great dispersion especially when soil temperature was above 15 °C (data not show). This suggested that precision of the prediction decreased when comprehensive modeling of soil CO_2 efflux with temperature was made in the two growing seasons.

Variation of soil CO_2 efflux did not coincide with soil temperature change in July and August. Soil CO_2 efflux went up to a maximum value in June while soil temperature reached maximum value in July. The discrepancy suggested that the exponential model established in the period of 2 years might overestimate

Table 2
Summary of average values of soil CO_2 efflux (R_s), air temperature (T_{air}), 5 cm soil temperature (T_5), live root biomass (LRB) and leaf area index (LAI) in different phenological periods of growing season in year 2000 and 2001

Phenological stage	Date	Duration day	R_s (g m^{-2} d^{-1})	T_{air} (°C)	T_5 (°C)	LRB (g m^{-2})	LAI (m^2 m^{-2})
Growing season in year 2000							
Sowing	29 September, 1999	–	10.1	10.2	13.2	–	–
Seedling	10 October–25 December	76	1.7	5.3	5.8	12.7	0.3
Hibernation	26 December–29 February	65	0.8	−0.3	1.0	37.1	0.4
Seedling	01 March–30 March	30	2.1	3.5	9.2	57.2	0.6
Tillering	01 April–25 April	25	5.4	7.8	13.3	62.4	0.9
Elongation	26 April–24 May	28	8.8	10.9	12.7	104.3	1.7
Booting	25 May–07 June	13	12.8	14.3	18.0	222.6	3.3
Flowering	08 June–25 June	18	14.2	14.9	20.7	305.0	4.1
Grain filling	26 June–29 July	34	11.0	16.2	22.6	205.7	3.2
Milking–ripening	30 July–15 August	17	9.6	13.3	19.2	106.4	1.6
Yellowing ripening	16 August–01 September	15	4.8	13.0	18.0	46.8	0.5
Harvest	10 September, 2000	–	5.0	9.7	17.9	0.0	0.0
Growing season in year 2001							
Sowing	15 October, 2000	–	5.3	9.7	14.2	–	–
Seedling	25 October–31 December	68	1.1	4.6	5.1	10.2	0.4
Hibernation	01 January–28 February	58	1.2	1.2	3.3	33.2	1.0
Seedling	01 March–02 April	33	2.0	3.7	9.3	43.0	1.5
Tillering	03 April–26 April	24	3.4	6.8	14.3	92.9	2.7
Elongation	27 April–20 May	24	9.4	10.1	17.2	206.0	3.3
Booting	21 May–08 June	19	10.4	12.1	19.0	236.9	3.9
Flowering	09 June–24 June	15	11.4	13.6	19.2	279.1	4.0
Grain filling	25 June–31 July	36	10.7	15.2	21.0	219.6	2.5
Milking–ripening	01 August–20August	20	9.6	14.3	21.3	85.7	1.0
Yellowing ripening	21 August–4 September	14	6.3	13.1	19.2	44.9	–

Table 3
Parameters estimated for the models describing the relationship between soil CO_2 efflux and air temperature (T_{air}), soil temperature from ground surface to 20 cm depth (T_0–T_{20}), soil moisture from 10 to 40 cm depth (M_{10}–M_{40}), live root biomass (R) and leaf area index (L)

Environmental factors	Equation	Fitted and derived parameters				r^2	n	Significance
		a	b	c	Q_{10}			
Air temperature								
T_{air}	$R_s = a\exp(bT)$	119.50	0.0439	–	1.6	0.39	254	***
Soil temperature								
T_0		84.53	0.0517	–	1.7	0.26	254	***
T_5		95.59	0.0677	–	2.0	0.47	254	***
T_{10}		69.61	0.0951	–	2.6	0.37	254	***
T_{15}		45.19	0.1267	–	3.6	0.32	254	***
T_{20}		44.85	0.1295	–	3.7	0.36	254	***
Soil moisture								
M_{10}	$R_s = Am^2 + bM + c$	−2.81	90.74	−411.99	–	0.31	92	**
M_{20}		−1.78	66.80	−322.07	–	0.16	92	*
M_{30}		−1.13	47.86	−194.95	–	0.12	92	*
M_{40}		−1.67	62.13	−279.88	–	0.11	92	*
Live root biomass								
R	$R_s = aR + b$	1.63	93.29	–	–	0.77	28	***
Leaf area index								
L	$R_s = aL + b$	113.87	86.77	–	–	0.69	28	***

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

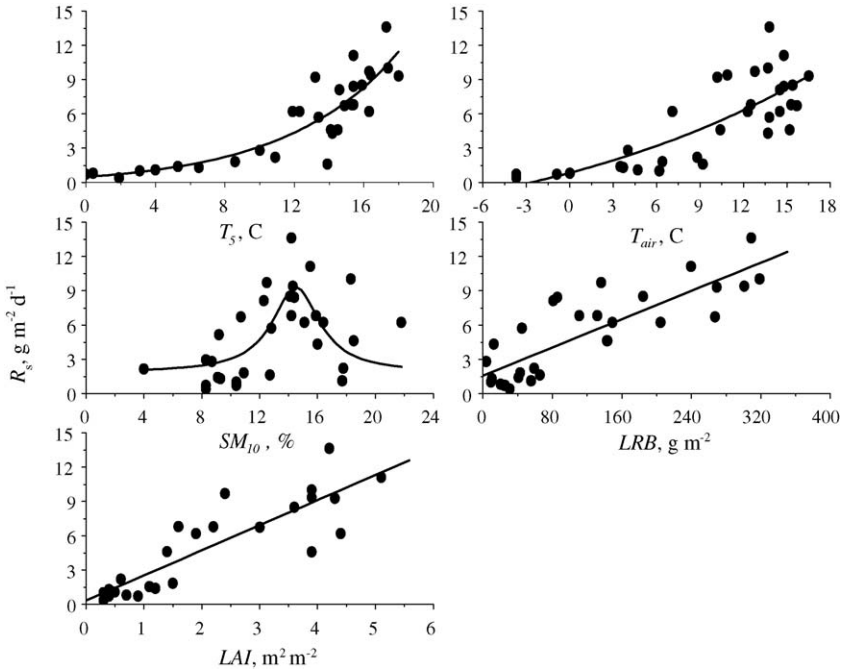

Fig. 5. Dependence of soil CO_2 efflux on soil temperature at 5 cm depth (T_5), air temperature (T_{air}), soil moisture at 10 cm depth (SM_{10}), live root biomass (LRB) and leaf area index (LAI).

soil CO_2 efflux at low temperatures. This is the case in the non-growing season.

Because the cropland was regularly irrigated, there was little seasonal change in soil moisture (Fig. 4) and therefore soil moisture had relatively little effect on soil CO_2 efflux. However, a quadric equation can be used to estimate the effect of soil moisture on CO_2 efflux and Fig. 5; Table 3 show that soil moisture at 10 cm accounted for more variance of soil CO_2 efflux. Soil respiration reached a maximum when soil moisture at 10 cm was 15% and this value might be the optimal soil water status for soil respiration. Sandy soil in the experimental site has limited water holding capacity, Either drought caused by insufficient irrigation or waterlogging by flood is not appropriate environment for soil CO_2 release.

3.4. Influence of phenology on soil CO_2 efflux

Fig. 4(A) shows the observed course of LAI in the growing seasons of 2000 and 2001. LAI increased from March to June, with maximum values in June. The maximum values of LAI coincided with the flowering period from middle June to early July. After that stage the green leaf turned yellow and as a result LAI reduced sharply (Fig. 4). Simultaneously, live root also presented the same course of biomass change in the same phenological stages. LRB began to increase in the seedling stage after hibernation in March and reached a maximum in June or early July (Fig. 4). Correlations between soil CO_2 efflux with LAI and with LRB show significant linear relationships (Fig. 5). Soil CO_2 efflux was more highly correlated with the *LRB* ($r^2 = 0.77$, $p < 0.001$) than with LAI ($r^2 = 0.69$, $p < 0.001$) (Fig. 5; Table 2). The linear models in Table 3 provided accurate and unbiased predictions of soil CO_2 efflux. This agrees with recent conclusion that roots exert a strong influence on the temperature dependence of soil respiration (Boone et al., 1998; Litton et al., 2003; Epron et al., 2004). An apparent effect of phenological stage on soil CO_2 efflux was observed in the growing season.

4. Discussion

Soil CO_2 efflux has been studied intensively in cropland ecosystems in the world other than in Tibet Plateau. Singh and Gupta (1977) reviewed six papers on soil CO_2 efflux in cropland and found that the effect of a particular crop on soil biological processes and soil respiration is unknown and data available are sometimes controversial (Buyanovsky et al., 1986). Lundegard (1927) reported that the average soil respiration under oats in summer was 411 mg m^{-2} h^{-1}, and under

cabbage it was 280 mg m^{-2} h^{-1}, both crops were grown on sandy loam soil that contained 10% humus (see Buyanovsky et al., 1986). Monteith et al. (1964) found that CO_2 efflux from barley cropland in Rothamsted, England varied from 62.5 mg m^{-2} h^{-1} in winter to between 250 and 292 mg m^{-2} h^{-1} in summer. De Jong and Schappert (1972) showed that soil respiration in wheat cropland was more than 830 mg m^{-2} h^{-1} after fallow in summer. Kowalenko and Ivarson (1978) observed that CO_2 efflux in fallow sand was six to seven times less than was computed by De Jong and Schappert (1972). Buyanovsky et al. (1986) measured seasonal variation of soil respiration at a rate from less than 40 mg m^{-2} h^{-1} in winter to 790 mg m^{-2} h^{-1} in summer during a 3-year period for winter wheat cropland in Columbia, Missouri. Sánchez et al. (2002, 2003) reported soil CO_2 effluxes of 312 and 318 mg m^{-2} h^{-1} in cereal and barley land in the central Spanish Plateau. The seasonal CO_2 effluxes observed in the present study were within the ranges of the above reports but total annual soil efflux was low. Lower temperature, greater diurnal change of temperature and low concentration of soil organic matter may be the reasons.

Seasonal variations in soil CO_2 efflux are generally attributed to changes in soil temperature (Longdoz et al., 2000; Drewitt et al., 2002; Cao et al., 2004; Liang et al., 2004), soil moisture alone (Kelliher et al., 1999; Xu and Qi, 2001) or both (Davidson et al., 1998; Subke et al., 2003) in the sites, which have dry season or seasonal drought. In this study, variation in soil CO_2 efflux was better explained by parallel change in soil temperature rather than soil moisture. In the present study site, there was no evidence for seasonal drought because irrigation was frequently conducted in the Lhasa River valley. Thus, soil moisture is less important in influencing soil CO_2 efflux, in contrast with soil temperature; despite the sand loam soil in the cropland site is prone to drought.

Soil respiration is the sum of an autotrophic component by roots and the associated rhizosphere and a heterotrophic component by soil microorganisms that decompose the organic materials from both above- and below-ground litter (Epron et al., 1999). Some publications indicated a strong correlation between soil CO_2 efflux and plant phenology in grassland and forests (Fitter et al., 1998; Högberg et al., 2001; Janssens et al., 2001; Litton et al., 2003; Liang et al., 2004). Högberg et al. (2001) argued that seasonal patterns of soil CO_2 efflux in a boreal Scots pine ecosystem are driven by both current photosynthesis and photosynthate allocation to roots. Janssens et al. (2001) compared the effects of productivity and soil temperature and conclude that productivity overshadow temperature in determining soil and ecosystem respiration in European forests. Litton et al. (2003) showed that soil CO_2 efflux was correlated with biotic (plant and microbial biomass) and not abiotic variables, which suggested that plant activity controls soil CO_2 efflux in forests recovering from stand replacing fire. Liang et al. (2004) suggested that the rapid increase in soil CO_2 efflux from larch forest in the spring and early summer (until about 15 July) resulted not only from an increase in soil temperature but also the result of an increase in foliage photosynthesis. Our findings in the cropland ecosystem on the Tibetan Plateau show that soil CO_2 efflux is strongly correlated with biotic variables, such as LRB and LAI (Fig. 5; Table 3). Moreover, soil CO_2 efflux was more dependent on LRB of winter wheat in the growing period between March and July. This might be partly due to increased root respiration in this season. The results suggest that plant activity also controlled soil CO_2 efflux and could modify the temperature response of soil CO_2 efflux in the growing season of winter wheat (Fig. 6).

Soil CO_2 efflux predicted with the whole-season temperature response equation (T_5 in Table 3) underestimated observations in the growing season from late March to early August and overestimated the observations respectively in the non-growing season from the ripening period in late August to hibernation period in next March (Fig. 7). This is because the importance of the effect of phenology was not taken into account. Modeling the dependence of soil CO_2 efflux on soil temperature was thus separated into growing and non-growing seasons to account for the differing temperature dependencies of CO_2 efflux during the two seasons.

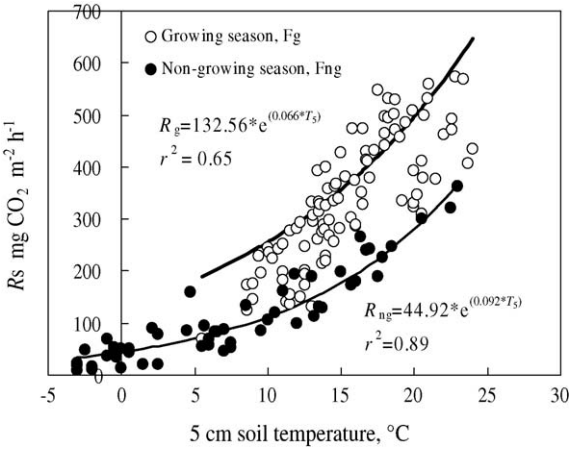

Fig. 6. Soil CO_2 efflux modeling in growing season and non-growing season showing the modification of phenology on efflux in growing period.

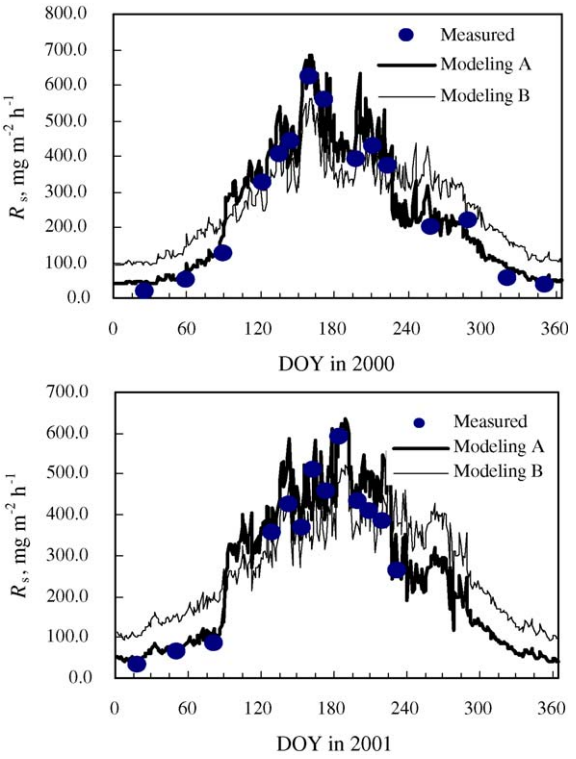

Fig. 7. Modeling soil CO_2 effluxes of 2 whole years in 2000 and 2001. Modeling A (thick line) is the estimation by separated functions in growing season and non-growing season in Fig. 6 showing modification of phenology. Modeling B (thin line) is the prediction by equation $R_s = 95.59\,e^{0.0677\,T_5}$.

The exponential equations in the growing season and the non-growing season are described, respectively, as:

$$R_g = 132.56\,e^{0.066\,T_5} \quad (4)$$

and

$$R_{ng} = 44.92\,e^{0.092\,T_5} \quad (5)$$

In contrast with the whole season T_5 modeling, separated seasonal T_5 modeling increased the explained variance with r^2-values of 0.65 and 0.89 in the growing season and non-growing seasons, respectively. This improved the prediction of seasonal variation of soil CO_2 efflux (Figs. 6 and 7).

Q_{10} values are a convenient index for comparing the sensitivity of soil respiration with soil temperature, tend to be large in cooler regions as compared with warm regions (Kirschbaum, 1995). Q_{10} value varied over season as the importance of temperature to soil CO_2 efflux varies (Sjögersten and Wookey, 2002). In the present study, Q_{10} values are 2.0 in the growing season and 2.5 in the non-growing season. There is a clear tendency toward higher Q_{10} values at low temperatures. During the growing season, the importance of temperature might decrease and other parameters, such as LRB and LAI in relation to phenology, increase significance in controlling the flux rates. This result agrees with finding of Lloyd and Taylor (1994) that higher Q_{10} values in the season of low temperature. Compared to the 2.4, the global median Q_{10} value (Raich and Schlesinger, 1992), our values are similar to the global median in the non-growing season and lower than the global median in the growing season.

Based on soil temperature in the growing season, the difference between Eqs. (4) and (5) can be assumed to result from root respiration because CO_2 efflux in the growing season represents soil plus root respiration while that of the non-growing season exhibited no effect of root activity. Although microbial population or biomass may change in concert with season and root exudates, here we can use this assumption to roughly estimate the ratio of root respiration in growing season. The soil temperature at 5 cm ranged from 10 to 25 °C in the growing season. Average root respiration, calculated as the difference between Eqs. (4) and (5), is about 4.4 g CO_2 m^{-2} d^{-1}, accounting for some 45% of total soil CO_2 efflux. It is higher than the ratio of root respiration (15%) estimated in winter wheat cropland in Columbia (Buyanovsky et al., 1986). This might be due to underestimation of root respiration in their study. Buyanovsky et al. (1986) used the method of Kucera and Kirkham (1971) to assume that the difference between C input (plant residues input) and output (soil CO_2 efflux) is an indicator of live root respiration. The problem of this method is that all residues are assumed to decompose as heterotrophic respiration. In most cases, especially in cropland with lower temperature or in arid areas, this method would overestimate microbial respiration due to residues that could not decompose fully in the coming year and therefore ratio of root respiration would be underestimated.

Based on long-term meteorological records of soil temperature at 5 cm depth, total annual soil CO_2 efflux could be estimated according to different dependence of soil CO_2 efflux on temperature in the growing and non-growing seasons. Annual totals were calculated for 2000 and 2001 and annual sums are given in Table 4. A comparison of separated season T_5 modeling (modeling A in Fig. 7) and whole season T_5 modeling (modeling B in Fig. 7) of CO_2 effluxes using regression Eqs. (4) and (5) illustrates the effect of the modification of phenology on the temperature response of CO_2 effluxes in the growing season (Fig. 7). On average, the former

Table 4
Total annual CO_2 efflux estimations

Year	Annual mean T_5 (°C)	Whole season T_5 model (WT5) (g C m^{-2} $year^{-1}$)	Separated season T_5 model (ST5) (g C m^{-2} $year^{-1}$)	WT5–ST5 (g C m^{-2} $year^{-1}$)	Over-estimate (%)
2000	12.0	616	570	46	7.4
2001	12.6	635	588	48	7.5
Mean	12.3	626 ± 13	579 ± 13	47 ± 1	7.5 ± 0.1
CV		2.3	2.1		

modeling leads to overestimate 39.3% in the non-growing season and underestimate 18.1% in growing season in contrast with the latter model. In combination, the former modeling leads to 7.5% of overestimation in 2 whole years (Table 4). On the base of separated modeling as considering the effect of phenology, total annual soil CO_2 effluxes were 570 and 588 g C m^{-2} $year^{-1}$, respectively, in 2000 and 2001, with an average of 579 g C m^{-2} $year^{-1}$ (Table 4). The inter-annual difference is due to higher mean air temperature in 2001 than that in 2001. Our estimation of C loss from soil is lower than the range of values in other reported cropland ecosystem (Buyanovsky et al., 1986; Sánchez et al., 2002, 2003). It is likely due to relatively lower soil temperature and low soil organic matter in the Lhasa River valley on the Tibetan Plateau. The sandy loam soil of present study site is thin (less than 40 cm depth) and has low organic matter content (0.77%) with carbon density of 4.1 kg m^{-2} in pedon profile (Shi and Yu, 2003). Hence, recent carbon is the main source for microbial and root respiration. Phenology is thus very important. As a result, there is a close correlation between soil respiration (microbial plus roots) and crop phenology. Phenology plays an important role in controlling soil CO_2 efflux and should take into account in accurate annual soil respiration.

5. Conclusion

The measurements of soil CO_2 effluxes over 2 years in a cropland ecosystem on the Tibetan Plateau revealed that:

- Using daytime measurements to estimate daily soil CO_2 efflux could cause overestimation due to asymmetric diurnal pattern of temperature and greater temperatures in daytime than at night. The established relation of daytime averages versus daily averages of diurnal measurements in different phenological stages can be used to calibrate daily estimates from daytime measurements.
- Soil CO_2 efflux presented pronounced diurnal and seasonal variation corresponding to soil temperature changes. Soil temperature at 5 cm depth was one key factor determining soil CO_2 efflux variability.
- The phenology of winter wheat modified the dependence of soil CO_2 efflux on soil temperature in growing season. Soil CO_2 efflux was strongly influenced by dynamics of LAI and root activity in the cropland ecosystem with low carbon pool. In growing season, soil CO_2 effluxes were linearly correlated with LAI and live root biomass.
- It is necessary to take modification of phenology on the dependence of soil CO_2 efflux on soil temperature into modeling soil respiration. Separated modeling of soil respiration in growing and non-growing season due to different influence of phenology of crop reduced prediction error of seasonal soil CO_2 efflux.

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