Soil & Tillage Research 150 (2015) 139–146

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Changes in temperature sensitivity of soil respiration in the phases of a three-year crop rotation system

Jishao Jiang [a,b], Shengli Guo [a,b,c,d,*], Yanjun Zhang [c], Qingfang Liu [d], Rui Wang [d], Zhiqi Wang [c], Nana Li [c], Rujian Li [c]

[a] *Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, PR China*
[b] *University of Chinese Academy of Sciences, Beijing 100049, PR China*
[c] *State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, PR China*
[d] *College of Resources and Environment, Northwest A&F University, Yangling, Shaanxi 712100, PR China*

ARTICLE INFO

Article history:
Received 21 September 2014
Received in revised form 7 January 2015
Accepted 2 February 2015

Keywords:
Soil respiration
Soil temperature
Soil moisture
Winter wheat
Millet
Pea

ABSTRACT

Understanding the temperature sensitivity of soil respiration (Q_{10}) and its controlling factors plays an important role in accurately estimating soil respiration and carbon cycling in agro-ecosystems. This manuscript presents a case study on how the Q_{10} value for soil respiration changes with soil temperature and moisture in the rotation phases. In a three-year crop rotation system (wheat/wheat/millet/pea) in a semi-arid region of China, the soil respiration rate, temperature and moisture were measured under different crop phases from July 2010 to June 2013. The soil respiration rate was significantly lower in the winter wheat phase (1.63 $\mu mol\, m^{-2}\, s^{-1}$) than the millet phase (2.40 $\mu mol\, m^{-2}\, s^{-1}$) and pea phase (2.21 $\mu mol\, m^{-2}\, s^{-1}$). However, the Q_{10} value was significantly higher in the wheat phase (2.76) than in the millet phase (1.85) and pea phase (1.47). The relationship between the Q_{10} values and soil temperature followed an exponential decay function in the rotation system, and the Q_{10} value was stable (1.8) with no obvious variation when the temperature exceeded 15 °C. The Q_{10} value tended to increase with soil moisture until reaching a threshold of 14.7% soil moisture and then declined. Our results indicate that temperature-respiration empirical models should be parameterized according to crop type in the rotation phases, especially when estimating soil respiration in cold-resistant crops under global warming.

1. Introduction

Soil respiration is an important carbon flux between the terrestrial ecosystem and the atmosphere, and it plays a critical role in global carbon cycling (Cox et al., 2000; Raich and Schlesinger, 1992). Among all of the factors controlling soil respiration, soil temperature (Lloyd and Taylor, 1994; Zhang et al., 2013) and soil moisture (Davidson et al., 2000; Suseela et al., 2012) remain dominant, and their effects may interact (Davidson et al., 1998). Understanding the response of soil respiration to temperature change is important for predicting possible feedback between the global carbon cycle and climate system (Davidson et al., 2006) and improving C cycle models (Del Grosso et al., 2005).

Numerous temperature-response functions have been developed (Janssens and Pilegaard, 2003), but the Q_{10} function is the most widely used in simulations of temperature sensitivity (Hoff, 1899). The Q_{10} value for soil respiration is the factor by which soil respiration increases with a 10 °C increases in temperature (Raich and Schlesinger, 1992). Numerous terrestrial carbon models, such as the Century, PnET, and Roth-C models, assume that Q_{10} is constant (2); however, there is increasing evidence suggesting that Q_{10} does not remain constant but tends to increase with decreasing soil temperature and increasing moisture (Janssens and Pilegaard, 2003; Kirschbaum, 1995; Qi and Xu, 2001; Schleser, 1982). Unfortunately, studies on the effects of soil temperature and moisture on Q_{10} were focused on forest ecosystems (Janssens and Pilegaard, 2003; Kirschbaum, 1995; Qi and Xu, 2001,b; Chen et al., 2010a,b; Luan et al., 2013), and limited information is available on Q_{10} in agro-ecosystems, especially in crop rotation systems.

---

* Corresponding author at: Institute of Soil and Water Conservation, Xinong Road 26, Yangling, Shaanxi 712100, PR China. Tel.: +86 29 87012411; fax: +86 29 87012210.
E-mail address: slguo@ms.iswc.ac.cn (S. Guo).

http://dx.doi.org/10.1016/j.still.2015.02.002
0167-1987/© 2015 Elsevier B.V. All rights reserved.

Crop rotation is a significantly beneficial practice for agriculture because it minimizes soil erosion, improves water use efficiency (Huang et al., 2003b; Toillon et al., 2013), improves soil C sequestration (Bell et al., 2012; Bolinder et al., 2010), and maintains high yields (Drury et al., 2004; Huang et al., 2003b), particularly in rain-fed farming regions. Two or three crop types are selected for the rotation cycle based on their different planting and harvesting dates, physiological properties, and demand for water and nutrients (Huang et al., 2003b). By alternating crop types, root and plant residues, the ratio between the above- and below-ground biomass (Govaerts et al., 2007), as well as soil nutrition (Huang et al., 2003b; Li et al., 2011) varies quantitatively and qualitatively. More importantly, soil temperature and moisture vary greatly among different crop types because of differences in the growth characteristics. For example, cold-resistant crops such as wheat and potato grow at low temperatures, whereas thermophilic crops such as maize, prosomillet and millet grow at high temperatures. Overall, changes in these factors can eventually alter the soil respiration rates and Q_{10} values of different cropping phases in a rotation system. However, no information is available on the variations of Q_{10} or the relationships between Q_{10} and soil temperature and moisture under different cropping phases in a rotation system.

The objectives of this study were to (1) quantify the variations in soil respiration rates and Q_{10} values, (2) examine the variations in the soil temperature and moisture during different rotation phases, and (3) explore the relationships between the Q_{10} values and soil temperature and moisture in a wheat/wheat/millet/pea (W/W/M/P) rotation system in the semiarid Loess Plateau, China.

2. Materials and methods

2.1. Site description

In the Loess Plateau, China, the area of arable land is 14.5×10^4 km^2, and more than 70% of the crops are planted in rain-fed land, which is highly susceptible to climate change impacts (Wang et al., 2013). This region has an annual rainfall of less than 600 mm, and over 60% of the annual precipitation falls during summer (Huang et al., 2003b). Because of the distribution of the precipitation, bare soil is at risk of erosion from heavy rainstorms (Kang et al., 2001) and there is insufficient water supply in the planting season after summer (Huang et al., 2003a). Considering the high risk of soil erosion and the importance of soil water in the planting season, wheat monoculture is not a sustainable management practice in the region (Huang et al., 2003a). Crop rotation practices in the Loess Plateau are beginning to replace winter wheat monoculture.

A long-term field experiment was established in September 1984 at the State Key Agro-Ecological Experimental Station in the Loess Plateau (35°12′N, 107°40′E; 1220 m.a.s.l.) in Changwu County, Shaanxi Province, China. The study area is representative of a typical rain-fed farming region and is characterized by a semiarid continental monsoon climate, with a mean annual rainfall of 560 mm (1984–2013). The wettest period is July–September, the driest period is May–June, and light precipitation is common during December and January. The open pan evaporation is 1440 mm. The mean annual temperature is 9.4 °C, but the average air temperature is 19.4 °C during July and September. All meteorological data were obtained from the Changwu Meteorological Station, which is 200 m from the experimental site. The daily mean air temperature and precipitation data during the study (July 2010–June 2013) are presented in Fig. 1.

The soil at the site is a loam (Cumulic Haplustoll; USDA Soil Taxonomy System) that developed from loess deposits; it contains 24% clay (<0.002 mm), 10.5% $CaCO_3$, 6.5 g kg^{-1} organic C, and 0.80 g kg^{-1} total N. The soil has a field water-holding capacity (WHC) of 0.29 cm^3 cm^{-3}, a pH of 8.4 (1:1 soil:H_2O suspension), and a bulk density of 1.3 Mg m^{-3} of the top soil layer (0–20 cm).

2.2. Experimental design and crop management

One three-year rotation system from the long-term field experiment was chosen for its regionally representative crop types, i.e., winter wheat (*Triticum aestivum* L., cv. 'Changwu 89 (1) 3–4′), millet (*Panicum miliaceum*, a local cultivar), pea (*Pisum sativum* L., a local cultivar). To explore the effect of each cropping phase on the soil respiration and Q_{10} values, three treatments were devised with different crop sequences: wheat/millet/pea/wheat (W/M/P/W), millet/pea/wheat/wheat (M/P/W/W) and wheat/wheat/millet/pea (W/W/M/P). Detailed information on the cropping system is given in Fig. 2. To determine the effects of previous crops on the soil respiration and Q_{10} values, we separated the winter wheat phases into a P–wheat phase (where the previous crop is peas) and a W–wheat phase (where the previous crop is wheat).

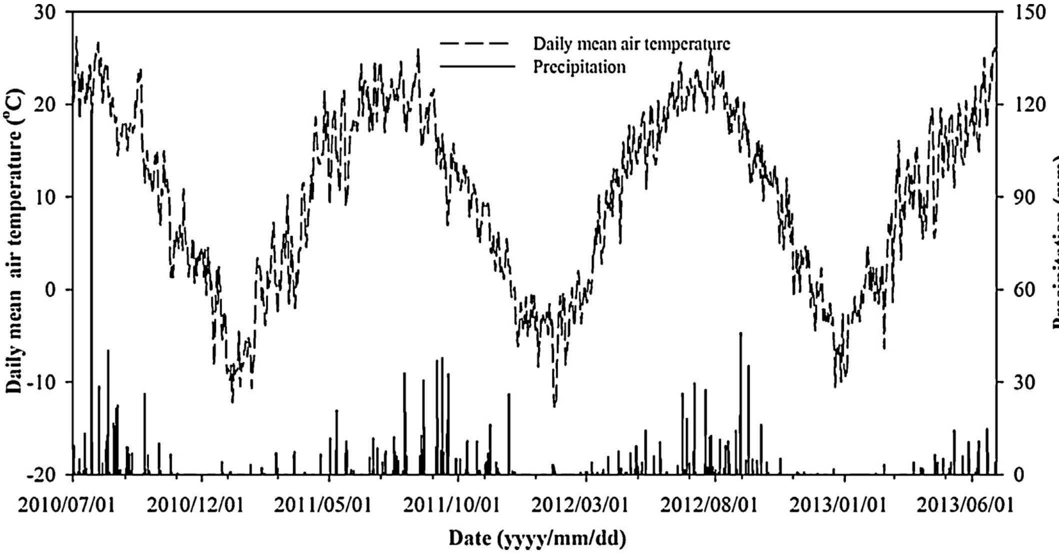

Fig. 1. Seasonal air temperature and precipitation during the study.

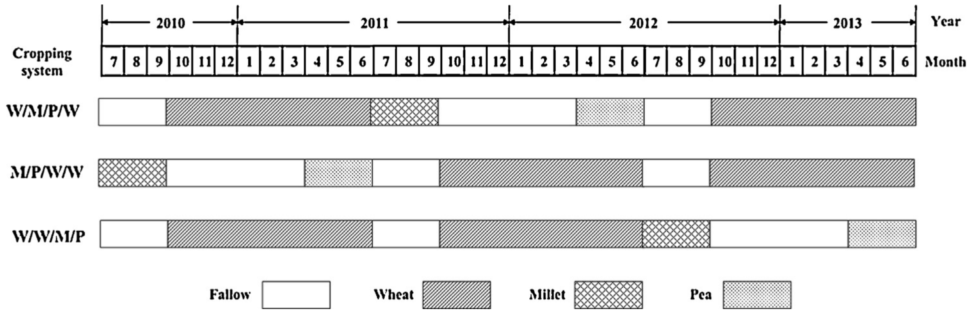

Fig. 2. The rotation schemes for all crops in the rotation system (W/M/P/W, M/P/W/W, and W/W/M/P). W, M and P indicate wheat, millet and peas, respectively. The values are the mean ± SD.

All treatments were arranged in a randomized block design with three replicates. The plot size was 10.3 m by 6.5 m; the plots were spaced 0.5 m apart, and the blocks were separated by a 1 m strip. All the crops were sown and harvested at fixed dates. Winter wheat was sown in late September (150–190 kg ha^{-1}) and was harvested in late June. Millet was sown after the winter wheat harvest as a fallow crop (15–24 kg ha^{-1}) and was harvested in late September, and peas were sown in late March (165–210 kg ha^{-1}) and were harvested in late June. All of the crops were sown using a no-till disk drill (Huang et al., 2003b). During the fallow periods, including the summer and winter fallow, all plots were tilled by hand-hoeing to a depth of 20 cm and kept bare. Fertilizers were added to the rotation system per crop at a rate of 120 kg ha^{-1} N and 13 kg ha^{-1} P for each plot prior to planting. The fertilizer was broadcast and then incorporated after 5–7 days at a depth of 20 cm prior to sowing. Weeds were removed manually, if necessary, and plant protection measures were applied as required. All crops were harvested manually (the stubble height was about 5 cm), and all harvested biomass and leaf litter was removed from the plots at physiological maturity each year (Guo et al., 2011).

2.3. Measurements of soil respiration, temperature and moisture

The soil respiration rate was measured twice for each plot using an automated closed soil CO$_2$ flux system equipped with a portable chamber (20 cm in diameter, Li-8100, Lincoln, NE, USA). All visible living organisms were removed before the measurements. If necessary, one or more additional measurements were recorded until the variation between two consecutive measurements was less than 15%. The final instantaneous soil respiration for a given collar was the average of the two measurements, with a 90 s enclosure period and a 30 s delay between measurements. The

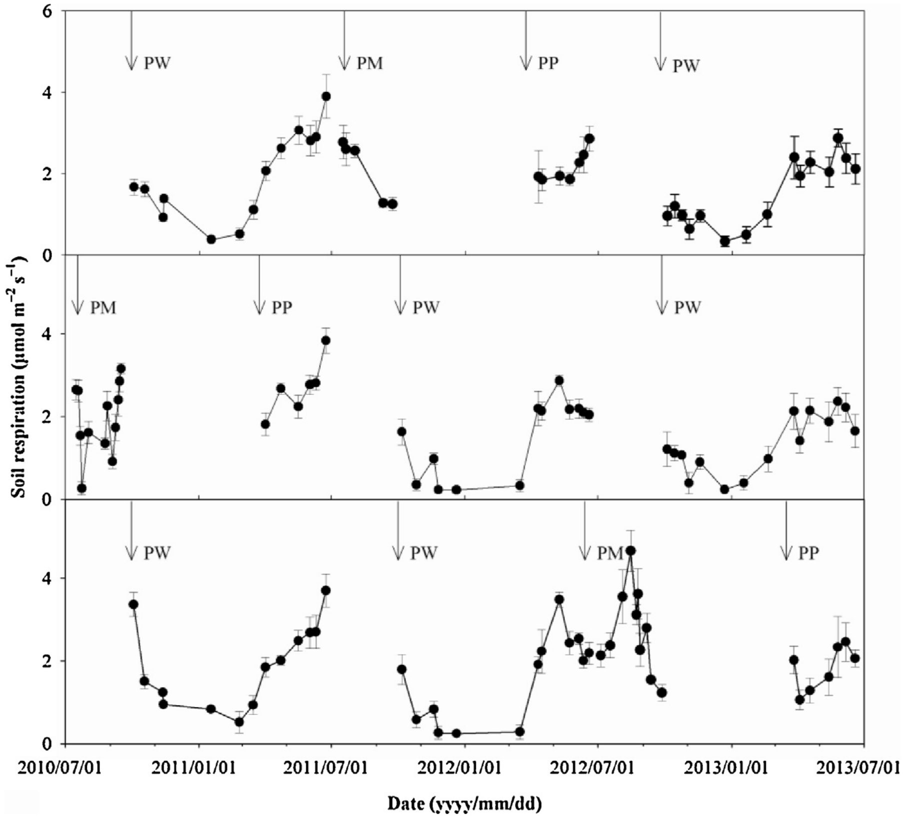

Fig. 3. Changes in the soil respiration rate under different rotation phases during the study. PW, planting wheat; PM, planting millet; and PP, planting pea.

measurements were performed from 09:00 am to 11:00 am from July 2010 to June 2013 during the crop growing seasons; an average of 10 days were measured a time.

The soil temperature was measured simultaneously with the soil respiration in the vicinity of the soil collars using a Li–Cor thermocouple probe. The soil samples (0–5 cm) were collected near each collar with a 1-cm diameter soil auger and oven dried at 105 °C for 24 h, and the soil moisture content was determined gravimetrically.

2.4. Data analysis

2.4.1. The relationship between soil respiration rate (R_s) and temperature

An exponential function was used to simulate the relationship between soil respiration rate and temperature (Lloyd and Taylor, 1994):

$$R_s = ae^{bT} \tag{1}$$

where R_s (μmol m^{-2} s^{-1}) is the measured soil respiration rate; T (°C) is the measured soil temperature at a 5 cm depth; and a and b are regression coefficients.

2.4.2. Q_{10} calculation

The Q_{10} value, which is the multiplier for the soil respiration rate for a 10 °C increase in temperature, was calculated as follows:

$$Q_{10} = e^{10b} \tag{2}$$

where b is obtained from Eq. (1).

2.4.3. Statistical analysis

Data in this study are presented as the mean ± SD. The data for the soil respiration rate, temperature and moisture were processed in an Excel 2007 spreadsheet. A one-way ANOVA was used to test the differences in the soil respiration rate, temperature, and moisture and the Q_{10} values under the different crop phases. A correlation analysis was used to examine the relationships between the Q_{10} values and the soil temperature and moisture. A statistical analysis was performed using SPSS 17.0 for Windows. Significance levels were set to $P = 0.05$.

3. Results

3.1. Effects of cropping phases on soil respiration and Q_{10}

The soil respiration rate significantly varied among the three cropping phases (wheat, millet and pea) (Fig. 3). The fluctuations in the soil respiration in the wheat, millet and pea phases reflected the changes in the soil temperature associated with these crops (Fig. 5). During the study period, the soil respiration was 1.63 μmol m^{-2} s^{-1} with a range of 0.23–3.90 μmol m^{-2} s^{-1} for wheat, 2.40 μmol m^{-2} s^{-1} with a range of 0.92–4.66 μmol m^{-2} s^{-1} for millet, and 2.21 μmol m^{-2} s^{-1} with a range of 1.06–3.84 μmol m^{-2} s^{-1} for peas, respectively. The soil respiration in the wheat phase was significantly lower than that in the pea and millet phases ($P < 0.05$), but no significant difference occurred between the pea and millet phases ($P > 0.05$). In our study, the previous crop had no significant effect on the soil respiration.

The soil respiration rates increased exponentially with the soil temperature (0.05 m) for every cropping phase during the three-year study ($P < 0.05$). The Q_{10} value varied significantly across the cropping phases (Fig. 4). The Q_{10} values in the wheat phase (2.76 ± 0.70) were significantly higher than those in the millet (1.85 ± 0.29) and the pea (1.47 ± 0.29) phases ($P < 0.05$), but the difference was not significant between the millet and the pea phases ($P = 0.142$). In this study, the previous crop had no significant effect on Q_{10}.

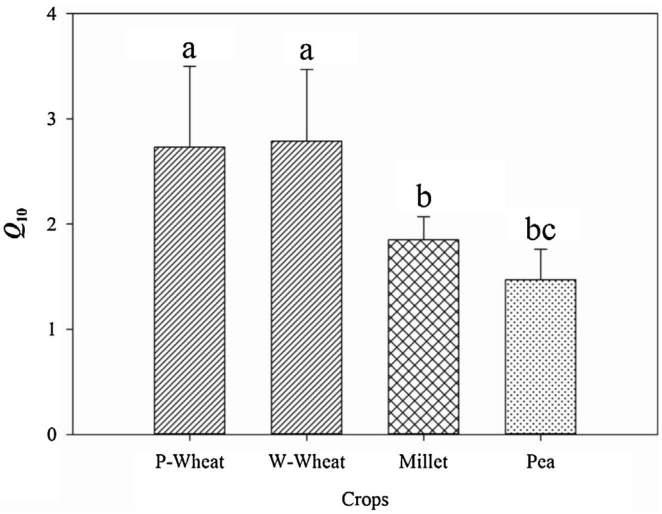

Fig. 4. Variations in the Q_{10} value in different cropping phases (P–wheat, W–wheat, millet, and pea). The values of Q_{10} of every cropping phase were the mean value of the three same cropping phases in the three treatments during the three years. The letters (a, b or c) within the columns indicate significant differences between the crops at the 5% level based on Duncan's Multiple-Range Test. The values are the mean ± SD.

3.2. Changes in soil temperature and moisture under different cropping phases

The changes in the soil temperature coincided with the air temperature during the study period (Fig. 5 and Fig. 1). The soil temperature varied significantly ($P < 0.05$) among the crop phases, and the soil temperature ranges were −3 to 28 °C, 15–30 °C, and 10–31 °C in the wheat, millet and pea phases, respectively. The mean soil temperature in the wheat phase (12.2 °C) was significantly lower than that in the pea (17.1 °C) and the millet (20.5 °C) phases ($P < 0.05$), while there was no significant difference between the pea and the millet phases ($P > 0.05$).

The soil moisture at the depth of 0–5 cm greatly fluctuated in response to the irregular rainfall (Fig. 6). The soil moisture varied significantly with crop phases ($P < 0.05$), with values ranging from 4.1 to 26.9%, 9.5 to 25.2%, and 3.5 to 21.5% in the wheat, millet, and pea phases, respectively. The mean moisture tended to be higher in the millet phase (17.5%) than in the wheat (13.3%) or the pea (10.6%) phases.

3.3. Relationship of Q_{10} to soil temperature and moisture across the rotation system

The Q_{10} values were significantly and negatively associated with the soil mean temperatures of their cropping phases ($P < 0.001$), and the exponential decay regression models explained 70% of the variance in the Q_{10} values (Fig. 7a). As shown in Fig. 7a, a 1 °C increase in the soil temperature at the 0.05 m depth will reduce the Q_{10} value by 0.05–1, particularly below 15 °C (the wheat phase). Q_{10} has a stable value (1.8) with no obvious variation when the soil temperature exceeds 15 °C (the millet and pea phases).

The Q_{10} values were significantly correlated with the mean soil moisture of the crop phases based on a quadratic relationship ($P < 0.1$) (Fig. 7b). The Q_{10} value tended to increase with soil moisture until reaching a threshold value (14.7%) and then declined. The equation could explain 40% of the variance in the

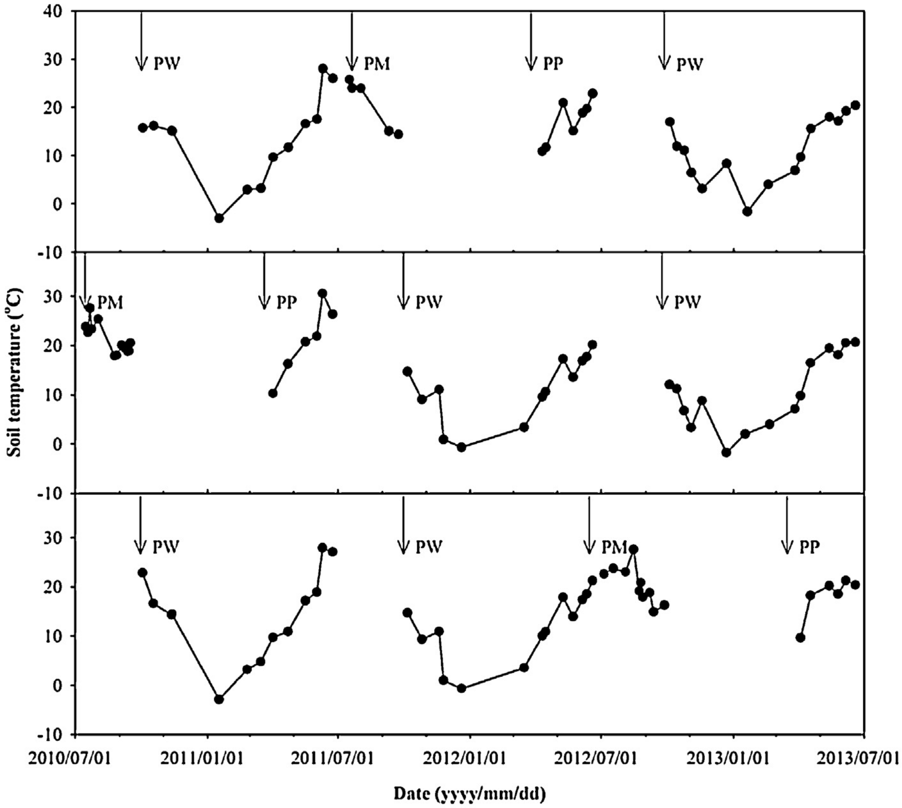

Fig. 5. Changes in the soil temperature at a depth of 5 cm under different rotation phases during the study. PW, planting wheat; PM, planting millet; and PP, planting pea.

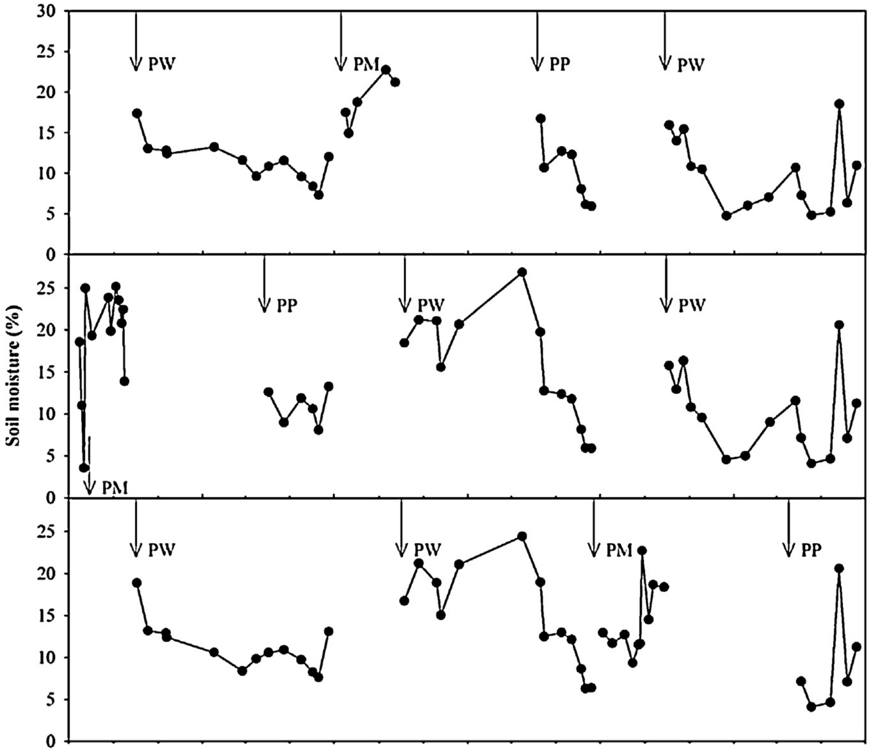

Fig. 6. Changes in the soil moisture at at a depth of 5 cm under different rotation phases during the study. PW, planting wheat; PM, planting millet; and PP, planting pea.

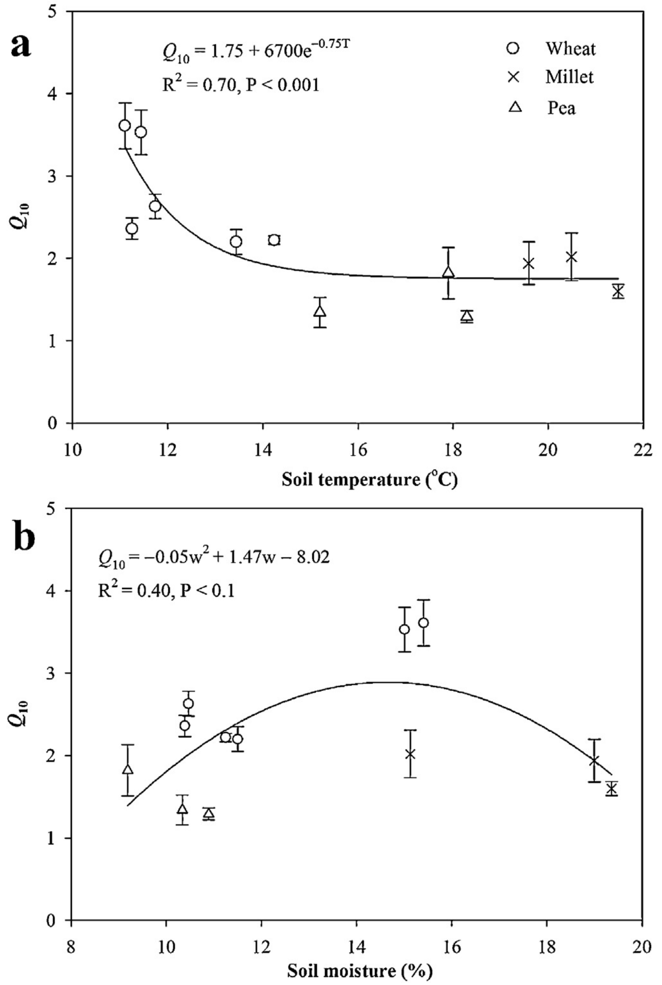

Fig. 7. Relationship between the Q_{10} and soil temperature or moisture values. The Q_{10} and temperature or moisture values of each point represent the Q_{10} and average temperature or moisture during every cropping phase.

Q_{10} values, and it showed that the soil temperature explained more of the variance in the Q_{10} values compared with the soil moisture.

4. Discussion

4.1. Soil respiration under different rotation phases in the semi-arid Loess Plateau

The average soil respiration values in every cropping phase ranged from 1.66 to 2.40 μmol $CO_2\,m^{-2}\,s^{-1}$ in the three-year rotation system, which was consistent with the range reported in a meta-analysis of soil respiration in global cropland (0.47–4.16 μmol $CO_2\,m^{-2}\,s^{-1}$) (Chen et al., 2010b). The average soil respiration value in the pea phase was 2.21 μmol $CO_2\,m^{-2}\,s^{-1}$, which was slightly higher than that in central Iowa, USA (1.98 μmol $CO_2\,m^{-2}\,s^{-1}$) (Tufekcioglu et al., 1998). However, the average value was less than that in the soybean phase (3.62 μmol $CO_2\,m^{-2}\,s^{-1}$) in the North China Plain (Hu et al., 2013), and both of these crops are leguminous. In our study, the soil respiration rate in the wheat phase ranged from 0.23 to 3.9 μmol $CO_2\,m^{-2}\,s^{-1}$ with the average value of 1.66 μmol $CO_2\,m^{-2}\,s^{-1}$, which was consistent with that in the Tibetan Plateau (1.73 μmol $CO_2\,m^{-2}\,s^{-1}$) (Shi et al., 2006) and Lonzée, Belgium (1.76 μmol $CO_2\,m^{-2}\,s^{-1}$) (Moureaux et al., 2008). However, the value was much smaller than the values in the temperate region of the North China Plain (5.25 μmol $CO_2\,m^{-2}\,s^{-1}$) (Zhang et al., 2013) and Julich, Germany (5.25 μmol $CO_2\,m^{-2}\,s^{-1}$) (Prolingheuer et al., 2010). Furthermore, Hu et al. (2013) also reported that soil respiration in the wheat phase ranged from 2.05 to 3.64 μmol $CO_2\,m^{-2}\,s^{-1}$, and these values were greater than those in our study. These values indicate that soil respiration of the same crop in different regions might vary with climate and cropland management practice. The lower soil respiration observed in our semi-arid cropland compared with that observed in other regions may have been caused by poor soil properties, such as the low SOC content (6.5 $g\,kg^{-1}$ in this study, 11.3 $g\,kg^{-1}$ in Zhang et al. (2013) and 19.4 $g\,kg^{-1}$ in Hu et al. (2013)) and shortage of precipitation (560 mm in this study, 698 mm in Prolingheuer et al. (2010), and 1100 mm in Hu et al. (2013)).

4.2. Effects of growing season temperature and moisture on Q_{10} under different rotation phases

In our study, the Q_{10} values varied from 1.47 to 2.79 across the different cropping phases, which were within the range of the global values (mean: 2.4; range: 1.3–3.3) (Raich and Schlesinger, 1992). The average in our study (2.21) was close to the value (2.25 ± 0.28) obtained by compiling the Q_{10} values for croplands in China in previous studies (Peng et al., 2009).

Although the mean soil respiration rate in the wheat phase was 47% and 36% lower than in the millet and pea phases, respectively, the Q_{10} values in the winter wheat phase were 33% and 47% higher than in the millet and pea phases, respectively. The behavior of the Q_{10} values and soil respiration under different rotation phases may be associated with the growing season temperature, which has a different effect on the soil respiration rate and Q_{10} values in this rotation system. Generally, high temperatures enhance microbial activity and root activity and increase soil respiration (Lloyd and Taylor, 1994; Zhang et al., 2013; Kuzyakov and Gavrichkova, 2010). In our rotation system, the growing season temperature varied with the cropping phase (Fig. 4). Low growing season temperatures decrease the soil microbial activity (Kuzyakov and Gavrichkova, 2010), microbial species richness (Andrews et al., 2000) and crop growth; however, the increase in soil respiration with increasing temperature was large because of the sensitivity of soil respiration to temperature (Balser and Wixon, 2009; Davidson and Janssens, 2006). In addition, in the high growing season temperatures, the increase in soil respiration with increasing temperature was small because of temperature acclimation (Bradford et al., 2008).

In a rotation system, the crop sequences are arranged according to differences in their photo-thermal characteristics. Winter wheat is a cold-resistant crop that must complete vernalization at 0–5 °C. Thus, the temperature during its growing season is low (Yan, 2009). However, millet is a thermophilic crop that grows under high temperatures (from 22 °C to 30 °C). Peas have characteristics between cold-resistant and thermophilic crops, and the suitable temperature range for their growth is from 12 °C to 16 °C (Yan 2009). Low temperatures (wheat phase) decrease the richness of microbial species and may result in higher Q_{10} values (Andrews et al., 2000; Chen et al., 2010a). Furthermore, the effect of temperature on microbial populations is stronger at low temperatures than at high temperatures (Andrews et al., 2000; Janssens and Pilegaard, 2003). The variation in Q_{10} values is also controlled by the maximum enzyme activity at low temperatures and substrate limitations at high temperatures resulting from temperature-mediated shifts (Atkin and Tjoelker, 2003). Thus, the Q_{10} value in the wheat phase was higher than that in the millet and pea phases (Fig. 7). Previous studies have also reported Q_{10} values that tended to be higher at lower temperatures and lower at higher temperatures (Andrews et al., 2000; Janssens and Pilegaard, 2003). Wang et al. (2008) also reported that the Q_{10} value for winter wheat (2.97) was greater than that for summer maize (2.03), whereas the mean soil temperature for winter wheat (9.8 °C) was lower than that for maize (25.3 °C) in a maize–wheat rotation.

Within the range of 15–30 °C (millet and pea phases), soil respiration acclimated to the temperature and resulted in a Q_{10} of approximately 1.8. Temperature acclimation is related to the microbial species richness (Zogg et al., 1997). Andrews et al. (2000) found that species richness was significantly lower at 4 °C (6 morphology types) than at 22 °C (17 types), but only 1 more species type was added from 22 to 40 °C (18 types) when the soil was incubated at the three temperatures. Thus, the Q_{10} values gradually became stable when the temperature was above 15 °C in the millet and pea phases. The phenomenon in which the Q_{10} value varies with increasing temperature was also reported by Kirschbaum (1995). Because of soil respiration (root and microbial) acclimation to temperature, the stimulatory effects on soil respiration rates produced by increasing temperatures may be lower than the current predictions (Bradford et al., 2008).

Our results demonstrated a strong quadratic correlation between the Q_{10} and soil moisture values in the rotation system. Such a phenomenon has also been reported for forest ecosystems in many studies (Chen et al., 2010a; Wang et al., 2006), but little information is available on croplands. Lower moisture can suppress microbial activity (Davidson and Janssens, 2006) and root respiration (Chen et al., 2010a) regardless of the temperature, which should decrease the temperature sensitivity of soil respiration. Desiccation stress is relieved with increasing soil moisture, causing the Q_{10} values to increase. When the soil water content is above the threshold value (14.7% for gravimetric and 20.3% for volumetric soil moisture in our study), it may inhibit oxygen diffusion and microbial activity (Skopp et al., 1990), resulting in a decline of Q_{10} values. In our study, the threshold value was 20.3% (volumetric soil moisture), which is consistent with a previous study in a coppice Oak forest in central Italy (20%) (Rey et al., 2002).

In addition to the soil temperature and the soil moisture, Q_{10} is also controlled by other factors, such as root-biomass quantity and activity, litter input (Curiel Yuste et al., 2007) and organic matter decomposition rate (Davidson and Janssens, 2006); other unknown variables may also affect Q_{10}.

4.3. Applications

Our study clearly showed that soil respiration under cold-resistant crops was more sensitive to temperature changes compared with thermophilic crops in agro-ecosystems (Fig. 7). Temperatures are increasing on the Loess Plateau, especially in winter (Li et al., 2012a). Over the past 50 years, a drying trend with decreasing precipitation and warming temperatures has been observed in the Yellow River Basin. Prior to the year 2000, significant warming and extreme temperature and precipitation events were more severe and frequent in the Loess Plateau (Li et al., 2012b), and Li et al. (2010) reported 0.7–2.2 °C increases in maximum temperature and 1.2–2.8 °C increases in minimum temperature. Increases of temperature in winter were greater than in summer from 2010–2039, and the trend may increase in the future (Li et al., 2010). In addition, the changes in soil respiration in cold-resistant crops with increasing temperature showed higher sensitivity compared with that of thermophilic crops. Moreover, winter wheat is an important cold-resistant crop and primary contributor to the food supply of the Loess Plateau. The region contains 1.3 million ha of cropland, and winter wheat accounts for 82% of that area (Zhu, 1989). In our study, the Q_{10} value in the winter wheat cropping system was greater than 2.76. Therefore, the Q_{10} value could not be treated as a constant value (2.0) for estimations of soil respiration in a rotation system, especially the soil respiration under the cold-resistant cropping phase. Thus, accurate Q_{10} values are required to estimate soil respiration in an agro-ecosystem, and the crop growing season temperature must be considered.

5. Conclusions

Soil respiration rate, temperature and moisture were measured in a three-year rotation system in the semiarid Loess Plateau to explore the relationships between Q_{10} and soil temperature and moisture. Although the soil respiration rate in the winter wheat phase was significantly lower than that of the millet and pea phases, higher Q_{10} values were observed in the wheat phase than in the millet and pea phases. The changes in Q_{10} values were primarily related to the growing season temperature and moisture of the different rotation phases. Therefore, the soil temperature and moisture in the rotation phases should be considered when using Q_{10} values to estimate soil respiration in agro-ecosystems, especially for cold-resistant crops.

Acknowledgements

This work is supported by the Special Fund for the Agricultural Profession (201103039), and the “Strategic Priority Research Program-Climate Change: Carbon Budget and Related Issues” of the Chinese Academy of Sciences (XDA05050504).

References

Andrews, J.A., Matamala, R., Westover, K.M., Schlesinger, W.H., 2000. Temperature effects on the diversity of soil heterotrophs and the delta C-13 of soil-respired CO_2. Soil Biol. Biochem. 32, 699–706.

Atkin, O.K., Tjoelker, M.G., 2003. Thermal acclimation and the dynamic response of plant respiration to temperature. Trends Plant Sci. 8, 343–351.

Balser, T.C., Wixon, D.L., 2009. Investigating biological control over soil carbon temperature sensitivity. Glob. Change Biol. 15, 2935–2949.

Bell, L.W., Sparling, B., Tenuta, M., Entz, M.H., 2012. Soil profile carbon and nutrient stocks under long-term conventional and organic crop and alfalfa-crop rotations and re-established grassland. Agric. Ecosyst. Environ. 158, 156–163.

Bolinder, M.A., Katterer, T., Andren, O., Ericson, L., Parent, L.E., Kirchmann, H., 2010. Long-term soil organic carbon and nitrogen dynamics in forage-based crop rotations in Northern Sweden (63–64 degrees N). Agric. Ecosyst. Environ. 138, 335–342.

Bradford, M.A., Davies, C.A., Frey, S.D., Maddox, T.R., Melillo, J.M., Mohan, J.E., Reynolds, J.F., Treseder, K.K., Wallenstein, M.D., 2008. Thermal adaptation of soil microbial respiration to elevated temperature. Ecol. Lett. 11, 1316–1327.

Chen, B.Y., Liu, S.R., Ge, J.P., Chu, J.X., 2010a. Annual and seasonal variations of Q_{10} soil respiration in the sub-alpine forests of the Eastern Qinghai-Tibet Plateau, China. Soil Biol. Biochem. 42, 1735–1742.

Chen, S., Huang, Y., Zou, J., Shen, Q., Hu, Z., Qin, Y., Chen, H., Pan, G., 2010b. Modeling interannual variability of global soil respiration from climate and soil properties. Agric. For. Meteorol. 150, 590–605.

Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A., Totterdell, I.J., 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 408, 184–187.

Curiel Yuste, J., Baldocchi, D., Gershenson, A., Goldstein, A., Misson, L., Wong, S., 2007. Microbial soil respiration and its dependency on carbon inputs: soil temperature and moisture. Glob. Change Biol. 13, 2018–2035.

Davidson, E., Belk, E., Boone, R.D., 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Glob. Change Biol. 4, 217–227.

Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173.

Davidson, E.A., Janssens, I.A., Luo, Y., 2006. On the variability of respiration in terrestrial ecosystems: moving beyond Q_{10}. Glob. Change Biol. 12, 154–164.

Davidson, E.A., Verchot, L.V., Cattânio, J.H., Ackerman, I.L., Carvalho, J., 2000. Effects of soil water content on soil respiration in forests and cattle pastures of eastern Amazonia. Biogeochemistry 48, 53–69.

Del Grosso, S., Parton, W., Mosier, A., Holland, E., Pendall, E., Schimel, D., Ojima, D., 2005. Modeling soil CO_2 emissions from ecosystems. Biogeochemistry 73, 71–91.

Drury, C.F., Yang, X.M., Reynolds, W.D., Tan, C.S., 2004. Influence of crop rotation and aggregate size on carbon dioxide production and denitritication. Soil Till. Res. 79, 87–100.

Govaerts, B., Mezzalama, M., Unno, Y., Sayre, K.D., Luna-Guido, M., Vanherck, K., Dendooven, L., Deckers, J., 2007. Influence of tillage residue management, and crop rotation on soil microbial biomass and catabolic diversity. Appl. Soil Ecol. 37, 18–30.

Guo, S., Wu, J., Coleman, K., Zhu, H., Li, Y., Liu, W., 2011. Soil organic carbon dynamics in a dryland cereal cropping system of the Loess Plateau under long-term nitrogen fertilizer applications. Plant Soil 353, 321–332.

Hoff, J.H., 1899. Lectures on Theoretical and Physical Chemistry. Edward Arnold.

Hu, Z.H., Cui, H.L., Chen, S.T., Shen, S.H., Li, H.M., Yang, Y.P., Li, C.Z., 2013. Soil Respiration and N_2O flux response to UV-B radiation and straw incorporation in a soybean–winter wheat rotation system. Water Air Soil Pollut. 224, 1393–1405.

Huang, M., Dang, T., Gallichand, J., Goulet, M., 2003a. Effect of increased fertilizer applications to wheat crop on soil–water depletion in the Loess Plateau, China. Agric. Water Manage. 58, 267–278.

Huang, M., Shao, M., Zhang, L., Li, Y., 2003b. Water use efficiency and sustainability of different long-term crop rotation systems in the Loess Plateau of China. Soil Till. Res. 72, 95–104.

Janssens, I.A., Pilegaard, K., 2003. Large seasonal changes in Q_{10} of soil respiration in a beech forest. Glob. Change Biol. 9, 911–918.

Kang, S., Zhang, L., Song, X., Zhang, S., Liu, X., Liang, Y., Zheng, S., 2001. Runoff and sediment loss responses to rainfall and land use in two agricultural catchments on the Loess Plateau of China. Hydrol. Processes 15, 977–988.

Kirschbaum, M.U.F., 1995. The temperature dependence of soil organic matter decomposition: and the effect of global warming on soil organic C storage. Soil Biol. Biochem. 27, 753–760.

Kuzyakov, Y., Gavrichkova, O., 2010. REVIEW: time lag between photosynthesis and carbon dioxide efflux from soil: a review of mechanisms and controls. Glob. Change Biol. 16, 3386–3406.

Li, L.L., Huang, G.-B., Zhang, R.-Z., Cai, L.-Q., Luo, Z.-Z., Jin, X.-J., Zhang, E.-H., Bellotti, B., Unkovich, M., 2011. Effects of lucerne removal time on soil water and productivity in a lucerne–wheat rotation on the western Loess Plateau. Acta Agron. Sin. 37, 686–693.

Li, Z., Liu, W., Zhang, X., Zheng, F., 2010. Assessing and regulating the impacts of climate change on water resources in the Heihe watershed on the Loess Plateau of China. Sci. China Earth Sci. 53, 710–720.

Li, Z., Zheng, F.-L., Liu, W.-Z., Jiang, D.-J., 2012a. Spatially downscaling GCMs outputs to project changes in extreme precipitation and temperature events on the Loess Plateau of China during the 21st century. Glob. Planet. Change 82, 65–73.

Li, Z., Zheng, F.L., Liu, W.Z., Jiang, D.J., 2012b. Spatially downscaling GCMs outputs to project changes in extreme precipitation and temperature events on the Loess Plateau of China during the 21st Century. Glob. Planet. Change 82-83, 65–73.

Lloyd, J., Taylor, J.A., 1994. On the temperature-dependence of soil respiration. Funct. Ecol. 8, 315–323.

Luan, J.W., Liu, S.R., Wang, J.X., Zhu, X.L., 2013. Factors affecting spatial variation of annual apparent Q_{10} of soil respiration in two warm temperate forests. PLoS One 8, 1–8.

Moureaux, C., Debacq, A., Hoyaux, J., Suleau, M., Tourneur, D., Vancutsem, F., Bodson, B., Aubinet, M., 2008. Carbon balance assessment of a Belgian winter wheat crop (*Triticum aestivum* L.). Glob. Change Biol. 14, 1353–1366.

Peng, S., Piao, S., Wang, T., Sun, J., Shen, Z., 2009. Temperature sensitivity of soil respiration in different ecosystems in China. Soil Biol. Biochem. 41, 1008–1014.

Prolingheuer, N., Scharnagl, B., Graf, A., Vereecken, H., Herbst, M., 2010. Spatial and seasonal variability of heterotrophic and autotrophic soil respiration in a winter wheat stand. Biogeosci. Discuss. 7, 9137–9173.

Qi, Y., Xu, M., 2001. Separating the effects of moisture and temperature on soil CO_2 efflux in a coniferous forest in the Sierra Nevada mountains. Plant Soil 237, 15–23.

Raich, J., Schlesinger, W., 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus B 44, 81–99.

Rey, A., Pegoraro, E., Tedeschi, V., De Parri, I., Jarvis, P.G., Valentini, R., 2002. Annual variation in soil respiration and its components in a coppice oak forest in Central Italy. Glob. Change Biol. 8, 851–866.

Schleser, G., 1982. The response of CO_2 evolution from soils to global temperature changes. Z. Naturforsch. Teil A 37, 287–295.

Shi, P.L., Zhang, X.Z., Zhong, Z.M., Ouyang, H., 2006. Diurnal and seasonal variability of soil CO_2 efflux in a cropland ecosystem on the Tibetan Plateau. Agric. For. Meteorol. 137, 220–233.

Skopp, J., Jawson, M., Doran, J., 1990. Steady-state aerobic microbial activity as a function of soil water content. Soil Sci. Soc. Am. J. 54, 1619–1625.

Suseela, V., Conant, R.T., Wallenstein, M.D., Dukes, J.S., 2012. Effects of soil moisture on the temperature sensitivity of heterotrophic respiration vary seasonally in an old-field climate change experiment. Glob. Change Biol. 18, 336–348.

Toillon, J., Rollin, B., Dalle, E., Feinard-Duranceau, M., Bastien, J.C., Brignolas, F., Marron, N., 2013. Variability and plasticity of productivity water-use efficiency, and nitrogen exportation rate in Salix short rotation coppice. Biomass Bioenergy 56, 392–404.

Tufekcioglu, A., Raich, J., Isenhart, T., Schultz, R., 1998. Fine root dynamics, coarse root biomass, root distribution, and soil respiration in a multispecies riparian buffer in Central Iowa, USA. Agrofor. Syst. 44, 163–174.

Wang, C., Yang, J., Zhang, Q., 2006. Soil respiration in six temperate forests in China. Glob. Change Biol. 12, 2103–2114.

Wang, W., Liao, Y., Wen, X., Guo, Q., 2013. Dynamics of CO_2 fluxes and environmental responses in the rain-fed winter wheat ecosystem of the Loess Plateau, China. Sci. Total Environ. 461, 10–18.

Wang, X.G., Zhua, B., Gao, M.R., Wang, Y.Q., Zheng, X.H., 2008. Seasonal variations in soil respiration and temperature sensitivity under three land-use types in hilly areas of the Sichuan Basin. Aust. J. Soil Res. 46, 727–734.

Yan, F., 2009. Crops Photo-thermo Characteristics. Chinese Agricultural Science and Technology Press (in Chinese).

Zhang, Q., Lei, H.M., Yang, D.W., 2013. Seasonal variations in soil respiration: heterotrophic respiration and autotrophic respiration of a wheat and maize rotation cropland in the North China Plain. Agric. For. Meteorol. 180, 34–43.

Zhu, X., 1989. Soil and agriculture in the Loess Plateau. Agric. Press, Beijing, pp. 248–253.

Zogg, G.P., Zak, D.R., Ringelberg, D.B., MacDonald, N.W., Pregitzer, K.S., White, D.C., 1997. Compositional and functional shifts in microbial communities due to soil warming. Soil Sci. Soc. Am. J. 61, 475–481.