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Research Article

The Blocking Effect is the Key Factor for the Sharp Descending of Soil Respiration Between Late Autumn and Early Winter in a Larch Forest

[1]Xiyang Wang, [1]Zhongkui Jia, [1, 2]Lvyi Ma and [1]Liming Jia
[1]Key Laboratory for Silviculture and Conservation,
[2]National Energy R and D Center for Non-food Biomass, Beijing Forestry University, Beijing,
P.R. China

Abstract: Throughout the year 2013 (from April to November), we measured the CO_2 efflux and investigated the soil physical properties weekly to characterize seasonal patterns of soil respiration and to examine blocking effect on winter soil respiration using Open Dynamic Chamber (ODC) method. We first affirmed that the local morning 10:00 o'clock with the smallest sampling errors of 0.5 to 2% was the optimal measurement point. The diurnal variation of soil respiration displayed as a single-crest curve which ascended with the increasing soil temperature in morning to a crest in early afternoon (about 13:30-15:30 o'clock), then descended. There was a significant difference in soil respiration among seasons. Hence, two separate models were used to describe the temperature sensitivity of R_s (Q_{10}) in growing season and non-growing season better. The fitted Q_{10} value of R_s was 2.1 in time scale of a whole year. The obvious fluctuation of Q_{10} values between dormancy season (90.0) and growing season (1.6) indicated a high sensitivity of soil respiration to soil temperature in early winter. The maintenance respiration of roots in the dormant period was calculated as 0.11 μmol CO_2/m^2/sec. The annual mean R_s and R_a were 2.53 and 1.12 μmol CO_2/m^2/sec, separately. The proportion of R_a in R_s had a relative smaller range of 14 to 55% in different seasons, higher in summer and lower in winter. The soil respiration decreased sharply in the early winter, especially after the melt of the first snow. In this study, we first defined the blocking effect of a thin ice layer on soil respiration and considered the transformation of soil water from liquid to solid as the reason of soil respiration descending in early winter. This theory may raise more concerns on the physical blocking effect on soil respiration in future researches.

Keywords: Blocking effect, Q_{10}, soil respiration, the FTCs (the Freezing Thawing Cycles)

INTRODUCTION

Soil Respiration (R_s) is an ecosystem process that releases CO_2 from soil via root Respiration (R_a), microbial decomposition of litter and soil organic matter (R_h) and fauna respiration. There are two keys for the extraordinary active research on soil respiration in the past decades. One is that it is among the least understood subjects in ecosystem ecology and the other is that it represents the second largest flux of carbon cycling between the atmosphere and terrestrial ecosystems (Luo, 2007).

Soil respiration displays strong temporal variation over time. Because it is the environment factor that changes strongly on a diurnal scale, a close function of soil temperature can explain the diurnal variation in soil respiration in most cases (Bajracharya *et al*., 2000; Xu and Qi, 2001; Liu *et al*., 2006). The diurnal variation must be accounted appropriately to avoid errors when point measurements of soil respiration are used to estimate annual soil carbon efflux. Davidson *et al*. (1998) pointed out that the midmorning efflux closely approximate the 24-h mean efflux. There is no certain time point that is given to determine the diurnal mean of soil respiration. Thus, assuring an optimal sampling point not only can estimate the annual CO_2 efflux more precisely, but also can save the sampling time and labor.

Seasonal variation in soil CO_2 efflux has been observed in almost all ecosystems. On a global scale, soil CO_2 efflux peaks in summer when plants grow fastest in both temperate zones and near-equatorial regions (Raich and Potter, 1995; Raich *et al*., 2002). The seasonal variation is largely driven by changes in temperature, moisture, photosynthate production and/or their combinations (Raich and Schlesinger, 1992; Raich *et al*., 2002; Gaumont-Guay *et al*., 2006a). Wang *et al*. (2013) reported that in a temperate forest the empirical R_s-T_s-SWC models explained 65.3 to 94.1% of the variability in the R_s data, but the number of the regression terms and their coefficients varied with seasons. It indicates that the models should be fitted to the seasonal data sets separately to explicitly describe the seasonality of R_s.

Corresponding Author: Lvyi Ma, Key Laboratory for Silviculture and Conservation, Beijing Forestry University, Beijing, P.R. China

While most of the carbon influx to terrestrial ecosystems can be attributed to photosynthesis only during the spring and summer months, soil respiration occurs throughout a whole year. For this reason, when estimating annual carbon budgets, wintertime soil respiration can be quantitatively considerable. For example, more than half of the carbon sequestered by trees during the growing season can be consumed by winter respiration in forests (Sommerfeld *et al*., 1993; Winston *et al*., 1997; Monson *et al*., 2002). However, winter respiration is highly variable and may be regulated by fluctuations in environmental variables such as soil temperature and moisture (Brooks *et al*., 1997; Mikan *et al*., 2002; Schimel and Mikan, 2005; Liptzin *et al*., 2009). Du *et al*. (2013) proposed a "freeze-thaw critical point" hypothesis, which stated that the Q_{10} value above freeze-thaw critical point was much higher than that below it (16.0 vs. 3.5) and that was probably regulated by the steep change in soil free water availability during the soil-freezing process. They ascribed the sharp decreasing of soil respiration to the shortage of free water caused by subzero soil temperature. We know that except in excessively wet or compacted conditions, CO_2 movement in soil occurs through a continuous network of air-filled pores that connect the surface to the deeper layers of the soil (Hillel, 1998). However, usually in winter, a thin ice layer covers the surface of frozen soil particles and reduces the porosity in soil. This ice layer serves as a diffusion barrier which reduces oxygen supply to the microbes and partly prevents the effusion of CO_2 (Teepe *et al*., 2001; Koponen *et al*., 2006). We believed that the subzero soil temperature in early winter was not the exclusive factor conducing the sharp decreasing of soil respiration in early winter. A more reasonable possibility is that the soil frozen which is induced by low soil temperature changes the soil physical properties totally. Most water in soil exists in a solid form of ice, fills most former air-filled pores and blocks the gas diffusion from soil to atmosphere. In this condition, we called this condition "blocking effect" and believed that it was a significant reason for the steep shift of soil respiration in early winter.

Though the diversity of sources of CO_2 efflux, accurate partitioning of observed soil respiration to various source components is a critical step towards mechanistic understanding of soil respiration itself and its responses to environmental changes. Usually root respiration accounts for approximately half of the total soil respiration but varies from 10 to 90% among different studies (Hanson *et al*., 2000). Root respiration is often conceptually separated into growth respiration and maintenance respiration. Growth respiration produces the energy and building blocks (i.e., metabolic intermediates) for the biosynthesis of structural compounds and maintenance respiration yields the energy used by the normal activities of viable cells. The start and stop of fine root growth are closely related to soil temperature (Barber *et al*., 1988). When the soil temperature drops to 4°C, the fine roots stop growing (Cheng *et al*., 2006). In this study, we defined this soil temperature as the "R_a dormancy critical point" under which the root start to be dormant with a maintenance respiration, then we estimated the root dormancy respiration.

The objectives of this study were to:

- Determine an optimal measurement time point and characterize seasonal patterns of soil respiration.
- Establish separate models to describe the sensitivity of R_s better in growing season and non-growing season.
- Analyze blocking effect on winter soil respiration and argue its rationality.

MATERIALS AND METHODS

Site description: The study area is locate in the Saihanba National Forest Park (SNFP) of Weichang Manchu and Mongolian Autonomous County. More details about our sample plots can be found in Wang *et al*. (2014).

In this study, we selected a 16-year-old (in 2013) larch forest (*Larix principis-rupprechtii*) with ast and density of 3415±128 trees/ha. The average Diameter at Breast Height (DBH) and tree height are 8.65±1.63 cm and 8.56±1.15 m, respectively. *L. principis-rupprechtii*is the dominant species whose vertical structure includes the tree layer (>2 m); the shrub layer (0.3-2 m), with composition including *Malus baccata*, *Rosa davurica*, *Crataegi cuneatae*, *Rhododendron micranthumand* and *Potentilla fruticosa*; and the floor layer (<0.3 m), consisting of *Maianthemum bifolium*, *Saussurea japonica* and *Thalictrum aquilegifolium*. The gray forest soil with pH values of 6.32 to 6.71 is deeper than 1.5 m. Soil parent materials are eluvium, saprolite and alluvium.

Field measurement: Soil respiration, soil temperature and volumetric water content at 5 cm depth were measured on 3 trenched matrixes (1×1 m) and 3 accompanying untrenched ones. A PVC soil collar, with a height of 5 cm and a diameter of 20 cm, was permanently inserted in the soil at each sampling location with the help of a piece of wood and a hammer. The collar extended 3 cm above the soil surface and inserted 2 cm in soil. R_h was measured on the trenched locations and R_s was measured on the untrenched ones and R_a was calculated by difference of R_s and R_h. Soil respiration was measured with a Li-8100A-103 survey chamber connected to an analyzer control unit of the Li-8100A Automated Soil CO_2 Flux System (Li-Cor Inc., Lincoln, NE, USA) for data collection and storage. In this study, from the end of April to early November, to determine a suitable measuring point in day, we take measurements every half hour in a selected fine day weekly and compare the diurnal mean value with the point measurements. Simultaneously, soil temperature and moisture at 5 cm depth were measured nearby each collar using an auxiliary soil temperature probe (Omega Engineering Inc., USA) and a Theta probe (Delta-T Devices, Cambridge, UK), respectively. The soil bulk density, capillary porosity and field capacity were determined on the same day.

Data analysis and modeling:

R_s and R_a in growing season and non-growing season: In 2013, *L. principis-rupprechtii* started to bud in early May and to wither at the end of September. We regarded June to September as growing season and April, May, October and November as non-growing season. The significances of R_s and R_a between growing season and non-growing season were verified by using the paired t-test.

Effects of soil temperature and soil moisture: After the correlation analysis, R_s and T_s were correlated significantly ($p<0.01$), but R_s and SWC were not significant correlated ($p = 0.212$). The correlations of R_a and T_s, R_a and SWC were both significant ($p = 0$, $p = 0$). Soil respiration was fitted to model (1):

$$R_s = A_0 e^{kT} \tag{1}$$

where, T was soil temperature (°C) at 5 cm soil layer, A_0 and k were parameters. The Q_{10} value, a quotient of change in respiration caused by change in temperature by 10°C, was calculated as in Eq. (2):

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

Considering the integrated effects of SWC and soil temperature, model (3) was used:

$$R_a = A_0 e^{(k+qW)\,T} \tag{3}$$

where, W (volumetric water content, VWC %) was the soil moisture at 5 cm soil layer and A_0, k and q were parameters.

The variations of soil bulk density, capillary porosity and field capacity in different seasons also were verified by using the paired t-test. All statistics were calculated using PASW Statistics 18 (IBM, Armonk, NY, USA) with a level of significance of $p<0.05$. All figures were made using SigmaPlot 12 (Systat Software Inc., San Jose, CA, US).

RESULTS

Diurnal variations of R_s and the optimal sampling point: The diurnal variation of soil respiration in growing season was similar to that in non-growing season. In 24 h, the rate of R_s had the minimum around 04:30 o'clock (local time) and it followed the increasing trend of soil temperature to a peak around early afternoon (about 13:30-15:30 o'clock), but then leveled off with slight fluctuations while soil temperature kept increasing in the afternoon. From evening to early morning of the next day, the rate of R_s followed the declining trend of soil temperature with little fluctuations (Fig. 1). The diurnal range was normally less than 1 μmol CO_2/m^2/sec, or about 15 to 40% of its diurnal mean.

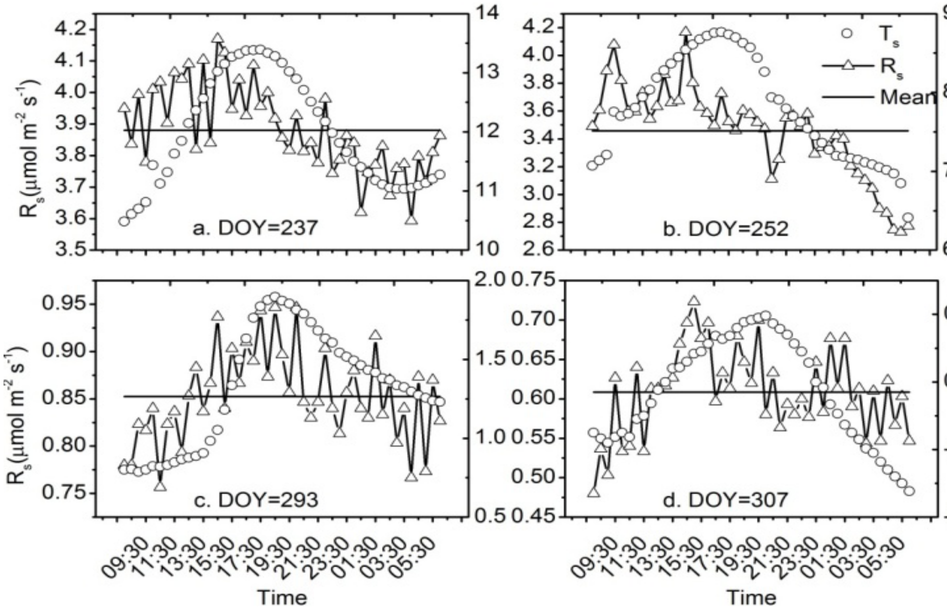

Fig. 1: Diurnal variations of R_s and T_s in the DOY of 237, 252, 293, and 307, respectively. The intersections mean the optimal sampling time points

The optimal measurement point confirmed by comparing the daily mean of R_s with point measurements was local morning 10:00 o'clock, at which the measurements had the smallest sampling errors of 0.5 to 2% (Fig. 1). The entire daytime measurements in growing season tended to overestimate the daily mean rates by 2 to 7% and in non-growing season usually equaled to the daily mean.

Seasonal variations of R_s and R_a and maintenance respiration of root: The annual mean of R_s (from April to November) was 2.53 µmol CO_2/m^2/sec with a mean of 3.97 µmol CO_2/m^2/sec in growing season and 0.98 µmol CO_2/m^2/sec in non-growing season. The seasonal trend of R_s ascended from April. The values of R_s had a very significant difference ($p<0.001$) between growing season and non-growing season. R_s was 1.19 µmol CO_2/m^2/sec in April and the peak value in later July was 5.03 µmol CO_2/m^2/sec. Then it descended gradually to a minimum of 0.6 µmol CO_2/m^2/sec (Fig. 2).

R_a also had great difference between growing season and non-growing season ($p<0.01$). R_a had a similar monthly pattern with that of R_s. The annual R_a averaged 1.12 µmol CO_2/m^2/sec. It was 0.21 µmol CO_2/m^2/sec and 1.51 µmol CO_2/m^2/sec in non-growing and growing season, separately. The obtained root dormancy respiration was 0.11 µmol CO_2/m^2/sec, 9.8% of the annual R_a.

The proportions of R_a in R_s had a very significant variation in different seasons ($p<0.01$). The R_a/R_s in root dormancy period when the soil temperature dropped to less than 4°C had a minimum of 14%, while in summer reached to a maximum of 55%, averaged 32% annually (Fig. 2).

The sensitivity of R_s and R_a in different seasons: Combining the data in growing season and non-growing season, three exponential models based on soil temperature accounted for 40 to 70% of the variation in CO_2 fluxes (Fig. 3). The fitted Q_{10} values of R_s were 90, 1.62 and 2.12 in dormancy season, growing season and a whole year, separately. The fundamental soil respiration was 0.57 µmol CO_2/m^2/sec when the soil temperature was 0°C.

In root dormancy period, the root respiration was highly sensitive to soil temperature and had a very great Q_{10} value of 602. The Q_{10} were 2.6 and 3 in growing season and a whole year separately. The ratio of Q_{10} in non-growing season and in growing season was a prodigious value of 232 (Fig. 4). The fundamental root respiration was 0.11 µmol CO_2/m^2/sec.

The steep decreasing of T_s and SWC in early winter: In early winter when the soil temperature dropped sharply to 0°C, The R_s decreased to a minimum of 0.48 µmol CO_2/m^2/sec and the free water in soil declined from 30 to 6% (Fig. 5). The previous air-filled pores

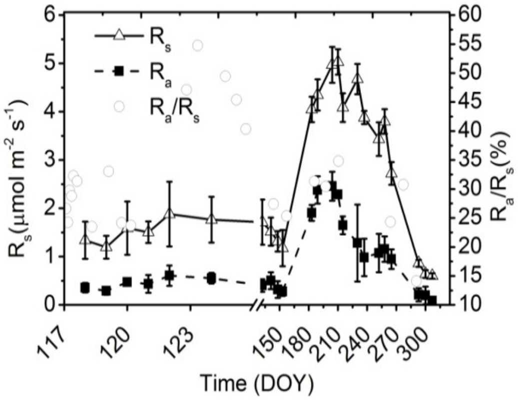

Fig. 2: Seasonal variations of R_s (triangle up), R_a (square), and the ratio of R_a to R_s (circle); bars are means±S.E., n = 72

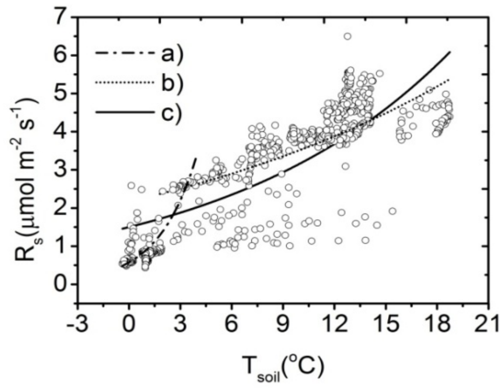

Fig. 3: Soil temperature sensitivities of R_s in different seasons. The fitted functions were; (a) in root dormancy period when the $T_s<4°C$, $R_s = 0.57e^{0.45T}$, $R^2 = 0.65$ $p<0.01$; (b) in growing season when $T_s>4°C$, $R_s = 2.17e^{0.048T}$, $R^2 = 0.41$ $p<0.01$; and (c) in a whole year, $R_s = 1.50e^{0.075\ T}$, $R^2 = 0.69$ $p<0.01$

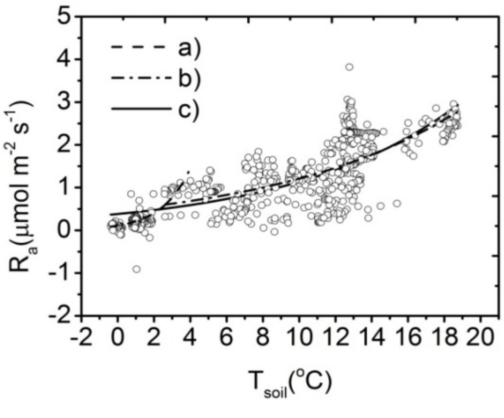

Fig. 4: Soil temperature sensitivity of R_a in different seasons. The fitted functions were (a) in root dormancy period when the $T_s<4°C$, $R_a = 0.11e^{0.64T}$, $R^2 = 0.65$ $p<0.01$; (b) in growing season when $T_s>4°C$, $R_a = 0.47e^{0.095\ T}$, $R^2 = 0.44$ $p<0.01$; and (c) in a whole year, $R_a = 0.38e^{0.11\ T}$, $R^2 = 0.63$ $p<0.01$

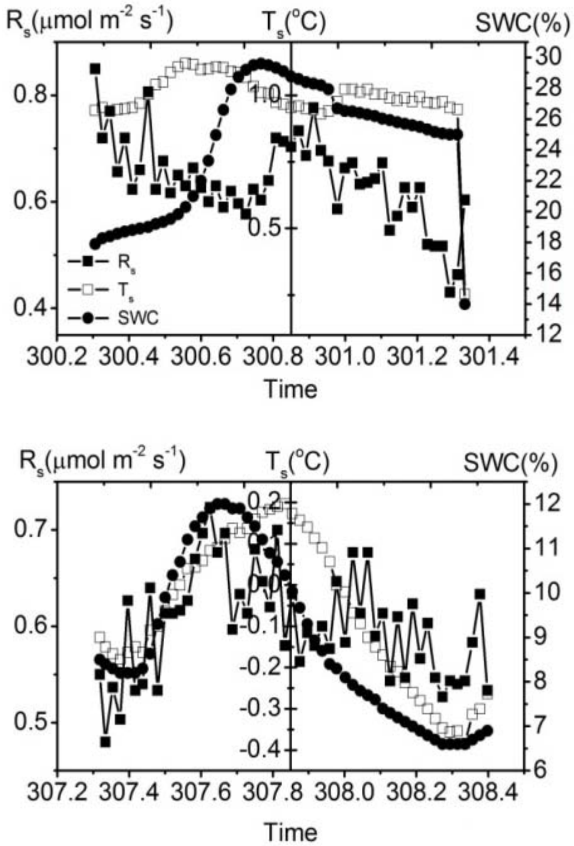

Fig. 5: Sharp variations of R_s, soil temperature and soil moisture in the early winter of DOY of 300 and 307

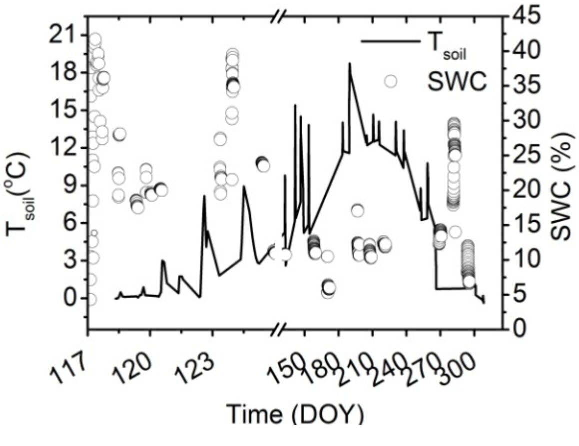

Fig. 6: Continual variations of T_s and SWC at 5 cm soil layer

observed were ice-filled. There was a shield covered the surface of soil since the thawed snow refrozen into ice.

The annual variations of soil physical properties: At the end of April, the soil moisture was great (about 40%) for the melting snow. Then it kept a comparative wet condition (always more than 20%) in the following rainy season until the autumn when a drought occurred.

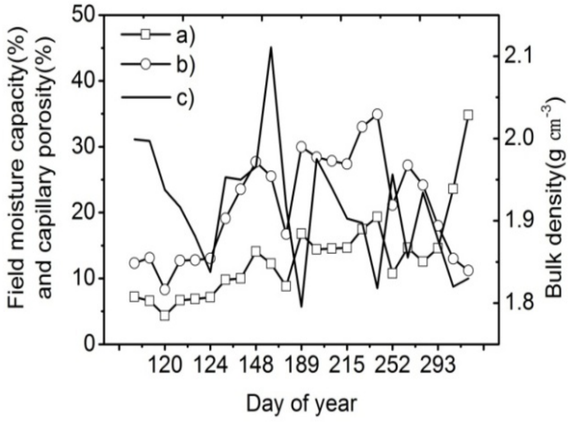

Fig. 7: Seasonal variations of (a) field moisture capacity (%); (b) capillary porosity (%); and (c) bulk density (g/cm^3)

Two snow event occurred in early winter (10 and 27 October) when the soil temperature was still above 2°C. The melting snow water provided greater soil water content (30%). With the soil temperature decreased to freezing point and free soil water frozen, the soil moisture dropped gradually to less than 8% (Fig. 6). All the seasonal variations of field moisture capacity, capillary porosity and bulk density were very significant ($p<0.01$) (Fig. 7).

Field moisture capacity had a similar trend with soil water content (Fig. 6 and 7). The capillary porosity in non-growing season was about 15% and in growing season around 30%. In the early winter (the end of October), the soil had a greater water content (34.8%, both in the form of liquid water and solid ice), relatively lower capillary porosity (11.2%) and bulk density (1.83).

DISCUSSION

The temporal variations of R_s and R_a: In some forests where the leaf area index is great, the soil temperature varied gently for a heavy shade, thus the diurnal variation for soil respiration may not be very apparent (Davidson *et al.*, 2000; Betson *et al.*, 2007). Our studying forest which had a relative great canopy density of 0.8 and a thick litter layer of almost 10 cm, the soil temperature in upper soil layer had a small daily variation of 2 to 3°C in growing season, thus the temperature-dependent soil respiration fluctuated slightly over a day.

We confirmed a comparative precise measuring point by comparing the daily mean values of R_s with the measurements taken at 10:00 o'clock (local time) and found that both of them were almost equal. Xu and Qi (2001) also found that the measurements taken between 09:00 and 11:00 o'clock can better represent the daily mean soil respiration than the entire daytime measurements which tend to overestimate the daily mean rates by 4 to 6%. This finding could lightening the working intensity of soil respiration measurement to a very great extent, especially when there are a lot of positions to be measured in one study, on the condition of measurement accuracy guaranteed. If the daily means were estimated from the measurements that were taken in the warmest period of the day, usually around 14:00 o'clock, the estimation of daily and monthly rates of soil respiration both can be substantially biased.

Luo *et al*. (2001) and Luo (2007) found high soil respiration during summer and low respiration in winter, a distinct seasonal pattern. In forest (Epron *et al*., 1999; Savage and Davidson, 2001; Epron *et al*., 2004) and cropland (Beyer, 1991) ecosystems, the seasonal patterns of soil respiration also exist. For example, King *et al*. (2004) indicated that over one year, soil respiration was nearly 0 μmol CO_2/m^2/sec in the winter, was about 10 μmol CO_2/m^2/sec in the summer in the Duke Forest, North Carolina. From 1997 to 2002, the seasonal pattern repeats, but different peaks in summer and roughs in winter appear to inter-annual variation. Our results of R_s rates which varied from 0.43 μmol CO_2/m^2/sec in November to 6.5 μmol CO_2/m^2/sec in August 2013, had a significant seasonal variation that with a maximum in August which lagged behind the soil temperature peak and lower values in spring and early winter when soil temperature was relative lower. In summer, both of the soil temperature and moisture were great and good for microbe activities and litter decomposition. Thus soil respiration in summer had a higher rate. In early winter the soil temperature were too low to support the proper activities of microbe. The mineralization of organic carbon retarded to a very slow level. The related soil respiration displayed a decreasing trend.

The Q_{10} of R_s and R_a and the dormancy critical point: Estimated at different geographic locations of various ecosystems, the estimated Q_{10} values for soil respiration vary widely from little more than 1 (low sensitivity) to more than 10 (high sensitivity) (Wildung *et al*., 1975; Bouma *et al*., 1997; Davidson *et al*., 2000; Reichstein *et al*., 2003; Gaumont-Guay *et al*., 2006a). Based on data compiled nearly 20 years ago, Raich and Schlesinger (1992) calculated that a 2.4 for the global median Q_{10} value, with a range of 1.3 to 3.3. Lloyd and Taylor (1994) suggested that the effective mass of carbon per unit area leads to variation in Q_{10} values in different studies. In European and North American forest ecosystems, Q_{10} values range from 2.0 to 6.3 (Davidson *et al*., 1998; Janssens *et al*., 2001; Gaumont-Guay *et al*., 2006b). The corrected respiration from our study followed a similar temperature-respiration response function. The annual mean Q_{10} of R_s in our studying plots was 2.1, which was in the middle of the Q_{10} range of 1.3-3.3 reported by Raich and Schlesinger (1992), smaller than the global median Q_{10} value of 2.4. It suggested that the soil respiration was more sensitive to the ascending temperature, depending on the special soil texture and environment characteristics in our studying plots. The fitted Q_{10} value of R_s was 90 in dormancy season. This greater Q_{10} showed that the soil respiration in dormant period was very sensitive to the soil temperature elevating.

At the end of September, the soil temperature dropped to less than 4°C under which the root started to dormant and kept a maintenance respiration (Fig. 6) and most leaves withered and fell to earth. The ratio of R_a to R_s decreased from 34% at the end of September to 24% in dormant period, almost 30%. Our data suggested that there were different temperature control mechanisms for root respiration at temperatures above and below the R_a dormancy critical point. It indicated that root respiration could not be effectively defined by a single temperature equation to accurately predict annual C budget in the cold regions. The Q_{10}value (602) of R_a in dormant period was likely to overestimate the Q_{10} (2.6) above 4°C and underestimate the Q_{10} (16.0) in a whole year. The great differences among the Q_{10} values at different soil temperatures indicated an obvious existence of the "R_a dormancy critical point".

The blocking effect on soil respiration: The results of Koponen *et al*. (2006) study showed that the respiration rate of completely frozen soils never reached zero and freezing and thawing of boreal soils did not have a strong effect on microbial biomass or community structure. This likely supports a viewpoint that soil respiration is not affected by the blocking effect of frozen soil. However, Teepe *et al*. (2001) detected two higher N_2O emissions, respectively in continuous soil freezing and thawing period. They found that microorganisms during continuous soil freezing in an unfrozen water film on the soil matrix can produce gases. Nevertheless, these gases were prevented to release by a layer of frozen water in form of ice which represents a diffusion barrier. Peak emissions during soil thawing were explained by the physical release of trapped gases. Du *et al*. (2013) also pointed out that soil respiration might be inhibited when the snow depth increases to a critical depth which blocks gas diffusion. The soil was wet after the first snow melt in the early winter. On the one hand, when the soil temperature dropped to ice point, the soil top layer was covered by a thin ice layer which stopped the gas exchange between soil and the atmosphere. On the other hand, the original air-filled pores were filled with ices. Only few gases were allowed to pass through. In our study, the sharp drops of SWC, capillary porosity and bulk density in the early winter indicated the forming of thin ice lay and the increasing blocking effect on the CO_2 release.

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