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Annual ecosystem respiration variability of alpine peatland on the eastern Qinghai–Tibet Plateau and its controlling factors

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Abstract Peatlands are widely developed in the eastern Qinghai–Tibet Plateau, but little is known about carbon budgets for these alpine peatland ecosystems. In this study, we used an automatic chamber system to measure ecosystem respiration in the Hongyuan peatland, which is located in the eastern Qinghai–Tibet Plateau. Annual ecosystem respiration measurements showed a typical seasonal pattern, with the peak appearing in June. The highest respiration was 10.43 μmol CO_2/m^2/s, and the lowest was 0.20 μmol CO_2/m^2/s. The annual average ecosystem respiration was 2.06 μmol CO_2/m^2/s. The total annual respiration was 599.98 g C/m^2, and respiration during the growing season (from May to September) accounted for 78 % of the annual sum. Nonlinear regression revealed that ecosystem respiration has a significant exponential correlation with soil temperature at 10-cm depth ($R^2 = 0.98$). The Q_{10} value was 3.90, which is far higher than the average Q_{10} value of

terrestrial ecosystems. Ecosystem respiration had an apparent diurnal variation pattern in growing season, with peaks and valleys appearing at approximately 14:00 and 10:00, respectively, which could be explained by soil temperature and soil water content variation at 10-cm depth.

Keywords Alpine peatland · Ecosystem respiration · Soil temperature · Auto chamber · Qinghai–Tibet Plateau · Annual variability

Introduction

Ecosystem respiration (ER or Re) is the sum of autotrophic respiration (Ra) and heterotrophic respiration (Rh) (Campbell et al. 2014; Falge et al. 2002; Jägermeyr et al. 2014). Autotrophic respiration includes leaf, stem, and root respiration, and heterotrophic respiration is the total CO_2 production resulting from the activities of microorganisms and animals. The annual terrestrial ecosystem respiration flux is estimated to be 103 Pg C/year (Yuan et al. 2011), and peat decomposition accounted for almost half of the flux (Moore et al. 2002). Though covering only 3 % of the Earth's land surface, peatlands contain 455–612 Pg C, which is 1/3 of the total world soil carbon pool (Gorham 1991; Turunen et al. 2002; Yu et al. 2010). With higher carbon densities than other ecosystems, peatlands are essential to the global carbon cycle and thus merit monitoring.

To date, studies on carbon cycling and greenhouse gas emission in peatlands have focused on equatorial

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regions and high-latitude areas in the northern hemisphere (Mitsch et al. 2010; Yu et al. 2010). Little is known about the CO_2 exchange patterns and its controlling factors of alpine peatlands in the Qinghai–Tibetan Plateau. The total area of peatlands in the eastern Qinghai–Tibetan Plateau was estimated to be 4.6×10^9 m^2, making it the largest alpine peatland in the world (Chai 1981; Chen et al. 2014). Existing studies in this region have primarily focused on patterns of methane emission (Chen et al. 2010; Jin et al. 1999; Wang et al. 2002). Therefore, long-term observations of CO_2 exchange fluxes from peatland ecosystems to the atmosphere should be made to increase our understanding of the role that alpine peatlands play in the carbon cycle.

Eddy covariance method has been extensively used in measuring ecosystem respiration and can also measure fluxes over areas as large as hundreds to thousands of hectares. However, this method can give erroneous results under stable atmospheric conditions (fraction velocity <0.1 m/s) (Baldocchi 2003; Billesbach 2011). While gradient methods have overcome the uncertainties associated with estimating ecosystem respiration under stable atmospheric conditions, but uncertainties still exist when precipitation events occur (Myklebust et al. 2008). The manual chamber method is an economical and convenient technique but provides poor temporal resolution due to the long sampling interval (McDermitt et al. 2011; Pumpanen et al. 2004). Thus, to reduce uncertainties and improve temporal resolution, the automatic chamber method was developed. An automatic chamber system typically consists of an in situ gas analyzer and a chamber that can automatically open and close. Therefore, this method can be used to measure respiration continuously in difficult weather conditions such as rain or snow (Koskinen et al. 2014; Yu et al. 2013). In this paper, we report the results of ecosystem respiration measurements from an alpine peatland in Qinghai–Tibet Plateau using an LI-8100A automated soil flux system.

Materials and methods

Site description

The Hongyuan peatland (32° 46′ N, 102° 30′ E) is a portion of the Zoigê wetlands located on the eastern Tibet Plateau, and its altitude is 3510 m above sea level. The accumulation of extensive peat in this region

benefits from the unique climate and topographic conditions. The annual mean temperature and precipitation range from 0.6 to 1.2 °C and 560 to 860 mm, respectively. The rainfall and temperature are synchronized in this region; the winter season is long, the summer season is short (Fig. 1), and sunshine is abundant all year round. The Hongyuan peatland is a typical mountain valley peatland that developed in a valley of the White River (Chen et al. 2014), and its accumulation history can be traced back to 12,000 years before present (Hong et al. 2003). The dominant plants in the peatland are *Carex mulieensis* and *Kobresia tibetica*. In late August 2012, we prospected the spatial distribution of peat deposited in Hongyuan peatland by using an improved Russian Peat Corer and a MALÅ proEx ground penetrating radar with a 50-MHz RTA antenna (MALÅ Geosciences, Sweden). Results indicated that the peatland has a bowl-like spatial form, and its depth was between 2 and 6.5 m. Once this was determined, we established a LI-8100A automated soil flux system in the center where the terrain is flat and the peat depth is 6.5 m.

Ecosystem respiration measurements

Ecosystem respiration was measured by a LI-8100A automated soil flux system (LI-COR, USA) with an 8100-104 opaque long-term chamber (LI-COR, USA). A PVC soil collar (inner diameter 20.3 cm) was installed on the soil surface. In case leaking gas, 3 cm of the collar was vertically pressed into the soil. Measurements automatically started every 10 min and lasted for 90 s each. Solar panels and batteries were installed to provide a continuous power supply for the measuring system. Every month, the system was stopped for data collection and chamber system maintenance.

Environmental factor measurements

Soil temperature and soil water content were measured by a HOBO U30-NRC weather station (Onset Computer Corporation, USA) at a frequency of once per hour. Soil temperature at 10- and 25-cm depth were measured by a 12-Bit Temp Smart Sensor (S-TMB-M006, Onset Computer Corporation, USA). Soil water content at 10-cm depth was measured by a 10HS Soil Moisture Smart Sensor (S-SMD-M005, Onset Computer Corporation, USA). Lastly, rainfall was measured by a Rainfall Smart Sensor (S-RGB-M002, Onset Computer Corporation, USA). We also drilled a 2-m-deep hydrological well,
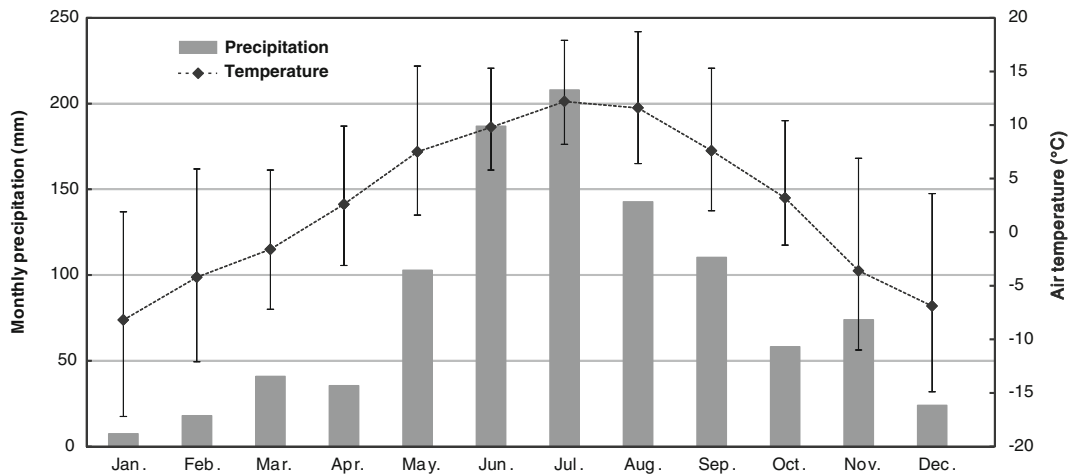
Fig. 1 Monthly precipitation and air temperature from January 2012 to December 2012 in Hongyuan County. The *black panes* represent monthly mean air temperature, and the *error lines* represent the temperature range. Raw data are from the National Benchmark Climate Station in Hongyuan

its side wall was supported by a 7.8-cm-diameter and pierced PVC pipe, and the water table depth was measured by a ZKGD3000-M digital water level gauge (Beijing Zhongke Guangda Automation Technology CO., LTD, China) at a frequency of once per hour.

Data processing and calculation

For preliminary analysis, all of the raw data were filtered using Excel 2010 (Microsoft Corporation, USA). SPSS 19.0 (SPSS Inc., USA) was used for statistical analysis and graphing, and SAS 9.1 (SAS Institute Inc., USA) was used for model fitting and regression. The Q_{10} value was used to express the temperature sensitivity of ecosystem respiration and was calculated according to $Q_{10} = e^{10b}$ (Reichstein et al. 2002), where b is obtained from the model $Re = ae^{bT}$ (Raich and Potter 1995), in which Re is the daily averaged ecosystem respiration; T is the daily averaged soil temperature at 10-cm depth; and a and b are the regression coefficients.

Linear regression is commonly applied in calculating fluxes from chamber measurements. However, it has been noted that linear regression will generally underestimate fluxes (Kutzbach et al. 2007; Levy et al. 2011). Thus, we choose a nonlinear regression method to calculate fluxes, and the formulas are listed below:

$$F_c = \frac{10VP_0\left(1 - \dfrac{W_0}{1000}\right)}{RS(T_0 + 273.15)}\frac{\partial C'}{\partial t} \tag{1}$$

$$\frac{\partial C'}{\partial t} = a\left(C'_s - C'_{(0)}\right)e^{-at} \tag{2}$$

$$C' = C'_s + \left(C'_{(0)} - C'_s\right)e^{-at} \tag{3}$$

where F_c is ecosystem respiration flux, V is volume, P_0 is initial pressure, W_0 is initial water vapor mole fraction, S is soil surface area, T_0 is initial air temperature, C' is the instantaneous water-corrected chamber CO_2 mole fraction, C'_s is the CO_2 concentration in the soil surface layer communicating with the chamber, and a is a rate constant.

Results

Annual variation of ecosystem respiration

The LI-8100A system was set up at the research station on April 18, 2013, and measurement was initiated that day and was stopped on June 12, 2014. Although the continuous measuring in the winter did not last long due to malfunctions of the system, the large number of observations ($N = 38{,}653$) covered a large majority of the spectrum of ecosystem respiration fluxes. The flux data with weak correlation coefficients were removed from further analysis by filtering out all 10-min flux values with correlation coefficients R^2 below 0.9. The use of this rather conservative cutoff

limit removed 2087 flux values, and the 94.6 % of observations (N = 36,566) remaining for further analysis covered most growing seasons and captured the annual variation pattern (Fig. 2a).

The highest, lowest, and mean ecosystem respiration that occurred during our measuring was 10.43, 0.20, and 2.06 μmol CO_2/m^2/s, respectively. The ecosystem respiration exhibited a clear annual pattern (Fig. 2a, b). From late October 2013 to late April 2014, the ecosystem respiration fluctuated from negligible to 1.0 μmol CO_2/m^2/s. An abrupt increase and decline in the ecosystem respiration occurred in May 2013 and September 2013, respectively, which was apparently an effect of the beginning and ending of the growing season. By assuming that adjacent fluxes varied linearly, and on the basis of the filtered data, we calculated the ecosystem respiration from April 18, 2013 to April 18, 2014, and the results showed that the annual ecosystem respiration was 599.98 g C/m^2, and the growing season (May 1, 2013 to September 31,

2013) flux was 468.61 g C/m^2, which accounts for 78 % of the annual ecosystem respiration.

Diurnal variation of ecosystem respiration

In growing season, ecosystem respiration rates showed a clear diurnal pattern that corresponded well with the pattern of soil temperature at 10-cm depth (Fig. 3a, b) on a diurnal time scale. For example, in the time series from August 2 to 8, 2013, ecosystem respiration for the first 5 days exhibited an obvious diurnal pattern, with the highest respiration occurring at approximately 14:00 and the lowest respiration occurring at approximately 10:00. Compared with soil temperature at 10-cm depth, soil temperature at 25-cm depth fluctuated negligibly (Fig. 3b). The water table depth and soil water content at 10-cm depth reached a new maximum level after the 27.4-cm rainfall event occurred, and the ecosystem respiration and soil temperature at 10-cm depth decreased to a new minimum level (Fig. 3).
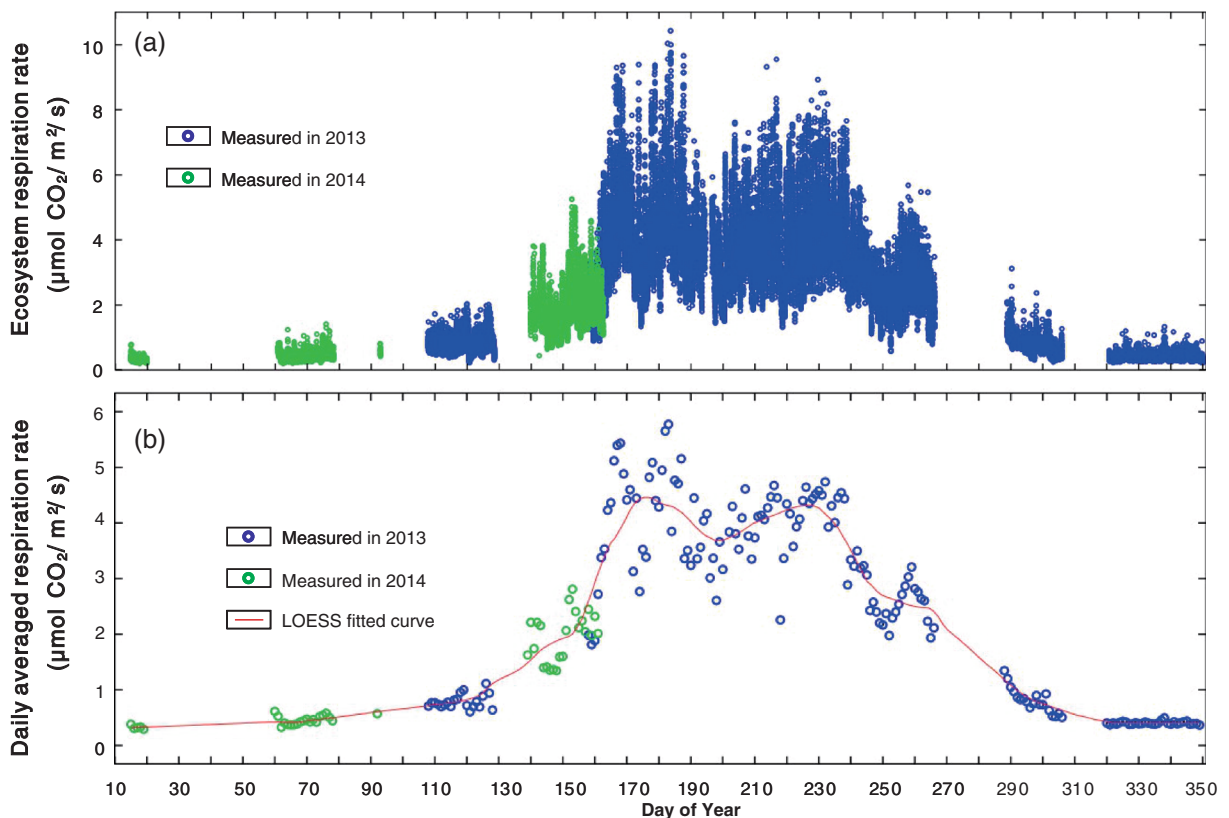
Fig. 2 Annual variation of 10-min ecosystem respiration (**a**) and mean daily ecosystem respiration (**b**) from April 18, 2013 to June 12, 2014. The LOESS fitted curve reveals the variation tendency of ecosystem respiration
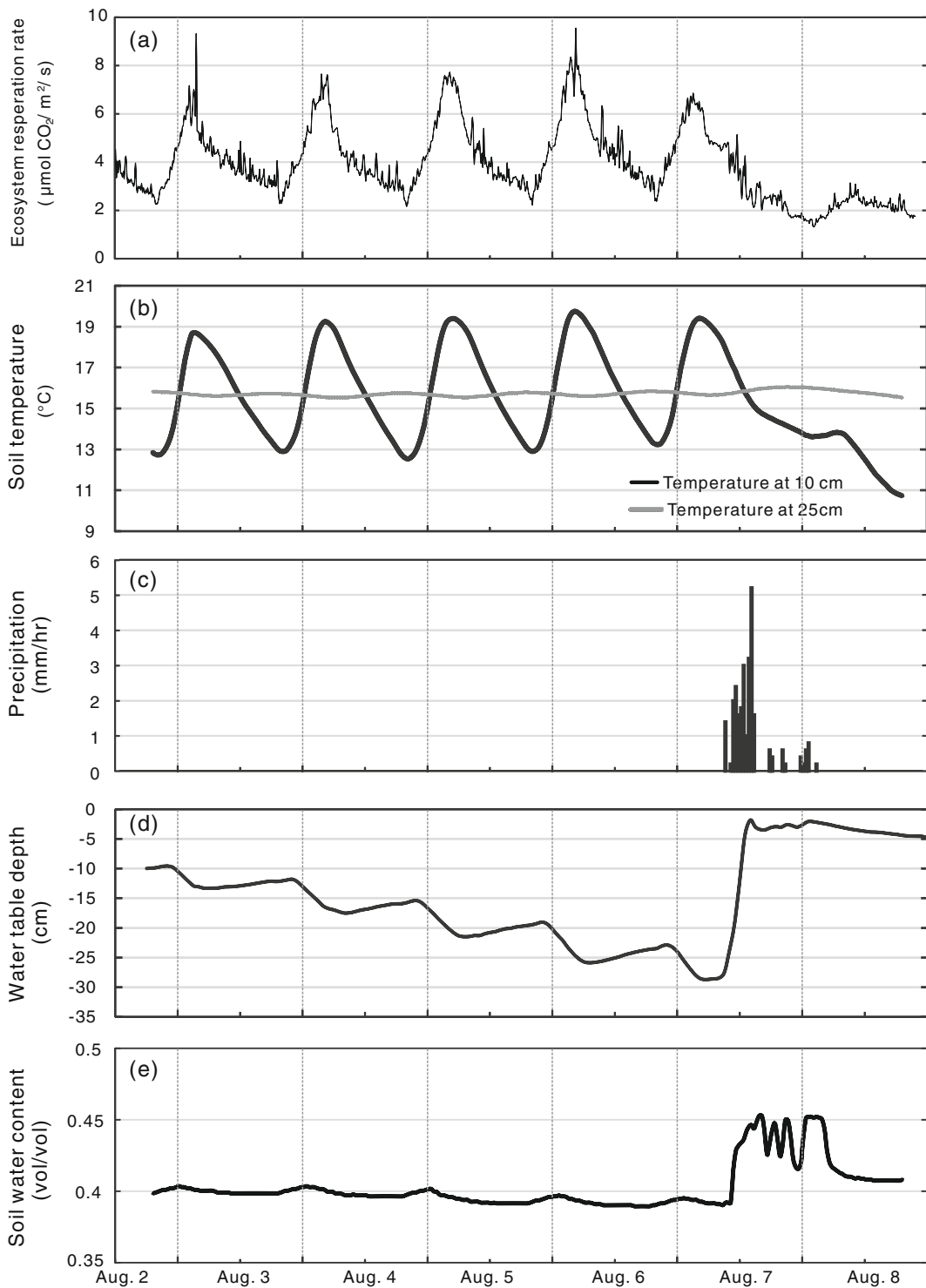
Fig. 3 Relationships between ecosystem respiration and several environmental factors during the 7 days from August 2 to 8 2013: **a** 10-min ecosystem respiration measured by LI-8100A; **b** soil temperature at 10- and 25-cm depth obtained from the weather station; **c–e** hourly measured precipitation, water table depth, and soil water content, respectively

Effect of soil temperature and soil water content on ecosystem respiration

We averaged ecosystem respiration, soil temperature at 10-cm depth and soil water content at 10-cm depth on a daily scale and compared the relationships between them. The daily mean ecosystem respiration showed significant exponential correlation ($R^2 = 0.98$) with daily mean soil temperature at 10-cm depth (Fig. 4a), while the correlation coefficient (R^2) representing the relationship between daily mean ecosystem respiration and daily mean soil water content at 10-cm depth was only 0.50. The daily mean ecosystem respiration fluctuated below 1.0 mol CO_2/m^2/s, while daily mean soil water content at 10-cm depth was less than 0.37 vol/vol (Fig. 4b). Moreover, the situation that soil water content varied below 0.37 vol/vol only happened in the period from October 2013 to March 2014 when soil temperature at 10-cm depth varied below 0 °C, indicating that the value 0.37 probably is the critical point at which the frozen peat completely melted.

Linear model of peatland ecosystem respiration

Soil temperature and soil water content are the main factors controlling ecosystem respiration. Thus, ecosystem respiration can be predicted using these two parameters (Chang et al. 2008; Levy et al. 2011). We imported the daily average ecosystem respiration, soil temperature, and soil water content and ran a regression analysis on SAS 9.1 (SAS Institute Inc., USA). Results showed that the dependence of ecosystem respiration on soil temperature and soil water content could be best described by the equation:

$$ER = 1.93 + 0.26T - 5.48W, R^2 = 0.95 \quad P < 0.0001 \quad (4)$$

where ER is ecosystem respiration (µmol CO_2/m^2/s), T is soil temperature at 10-cm depth (°C), and W is soil water content at 10-cm depth (vol/vol).

Discussion

Estimation of peatland ecosystem respiration

Accurate measurements of ecosystem respiratory flux are essential to net ecosystem exchange (NEE) estimating (Chapin III et al. 2006; Falge et al. 2002; Lafleur et al. 2005). The chamber method can be used to measure ecosystem respiration only in low-vegetation ecosystems such as wetlands and grasslands (Koskinen et al. 2014). The tower-based eddy covariance (EC) method can be used to measure the NEE of large-scale ecosystems, and carefully analyzed nighttime EC measurements can be used to estimate ecosystem respiration (Baldocchi et al. 2001; Hollinger et al. 1994; Lafleur et al. 2005). Unfortunately, the EC method does not reveal any small-scale spatial variation or separate fluxes from different components (e.g., roots, litter, and soil) (Koskinen et al. 2014). It is crucial to avoid methodological limitations and afterwards conduct cross-comparison. Though it is feasible to estimate ecosystem respiration using satellite data and model predictions (Jägermeyr et al. 2014; Yuan et al. 2011), field monitoring is still needed to understand the temporal and spatial variability of ecosystem respiration. It has been reported that the annual ecosystem respiratory flux of the Moanatuatua peatland in New Zealand was 906.0
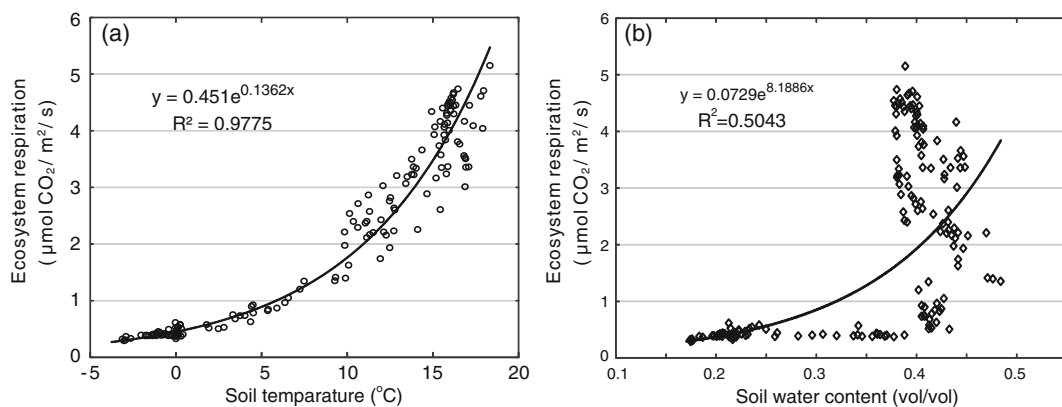
Fig. 4 Relationship between daily mean ecosystem respiration and diurnal mean soil temperature at 10-cm depth (**a**); relationship between diurnal mean ecosystem respiration and daily mean soil water content at 10-cm depth (**b**)

and 897.8 g C/m^2 in the years 1999 and 2000, respectively (Campbell et al. 2014). In addition, the annual ecosystem respiration of an extreme-rich peatland in northern Alberta was only approximately 400.0 g C/m^2 (Adkinson et al. 2011). Our results for the Hongyuan peatland showed that the annual respiration is 599.98 g C/m^2, which is lower than the previous measurement in the "Southern peatland" and higher than the value measured for the "Northern peatland". This spatial heterogeneity was probably caused by the climate and peat thickness differences.

Controlling factors of peatland ecosystem respiration

Numerous studies have suggested that ecosystem respiration is strongly positively correlated to soil temperature within different ecosystems (Chang et al. 2008; Hibbard et al. 2005; Raich and Schlesinger 1992). The study that Lafleur et al. (2005) conducted in Mer Bleue peatland also suggested that the dominant control factor in peatland ecosystem respiration is soil temperature rather than water table depth (Lafleur et al. 2005). The variation of ecosystem respiration corresponded well with the variation of soil temperature at 10-cm depth on an annual (Fig. 4a) as well as diurnal (Fig. 3a, b) time scale, suggesting that soil temperature at 10-cm depth is the dominant controlling factor of peatland ecosystem respiration. The Q_{10} value is an important parameter describing the temperature sensitivity of ecosystem respiration. The average Q_{10} value of terrestrial ecosystems is 2.4 (Raich and Schlesinger 1992), and the Q_{10} value of the Mer Bleue peatland (Lafleur et al. 2001), a peatland in northern Alberta (Adkinson et al. 2011), and a grassland in Inner Mongolia (Qi et al. 2010) are 3.0, 1.8–2.2 and 2.16–2.98, respectively. While the Q_{10} values in this study were 3.9 at an annual time scale, 3.1 at growing season and 3.4 at non-growing season, which indicates that the ecosystem respiration of alpine peatlands in the eastern Qinghai–Tibet Plateau is more sensitive to temperature increases than "Northern peatlands", and those alpine peatlands may release more CO_2 in warm winter scenario. What is more, the Q_{10} value varied significantly when it was calculated at different periods, suggesting that Q_{10} comparing may be inappropriate when the Q_{10} values were calculated at different time scales. Soil water content is also a key factor affecting ecosystem respiration. Bubier et al. (2003a) reported that plant functional type could respond on short time scales to changes in soil moisture,

and the transition from sedges to shrubs could occur rapidly in peatlands under a drier and warmer climate. Through model simulation studies, Frolking et al. (2001) concluded that warmer and wetter climate conditions benefit the accumulation of peat. Our empirical model (Eq. 4) confirmed that the changes in soil water content strongly affect ecosystem respiration (Fig. 3) in some cases.

Temporal variability of peatland ecosystem respiration

The ecosystem respiration of the Hongyuan peatland displayed obvious seasonal variation pattern in growing season which is similar to the ecosystem respiration of the Caribou peatland (Comas et al. 2008) and the wetlands in the Sanjiang Plain (Song et al. 2011). Though the ecosystem and soil respiration of different ecosystems peaked at different times, they still showed an obvious diurnal variation pattern (Evrendilek et al. 2011; Jin et al. 2013; Chang et al. 2008). Studies from different ecosystems revealed that temperature variation is the dominant factor affecting CO_2 exchange fluxes between ecosystems and the atmosphere (Evrendilek et al. 2011; Jin et al. 2013; Bubier et al. 2003b). However, the mechanism of the manipulation of diurnal and seasonal CO_2 exchange variation patterns by temperature variation is still unclear. Using a scanning electron microscope (SEM) to conduct studies on the comparative anatomy of the vegetative organs of tracheophytes, Thomas et al. (1996) suggested that the diurnal fluctuations of greenhouse gas exchange in peat may be attributed to the opening and closing of the stomata of the vascular plants. However, plant-mediated transport is not the only pathway of greenhouse gas migration. Diffusion (Heyer et al. 2002) and bubbling (Tokida et al. 2007) are also important pathways of greenhouse gas release. Thus, future studies should consider the effects of environmental factors (e.g., soil temperature, soil moisture, and redox potentials) on the production and migration of greenhouse gases.

Conclusions

The ecosystem respiration of the Hongyuan peatland shows clear annual and diurnal variation patterns. The highest, lowest, and mean ecosystem respirations during our study were 10.43, 0.20, and 2.06 μmol CO_2/m^2/s, respectively. From late October 2013 to late April 2014,

the ecosystem respiration fluctuated between negligible and 1.0 μmol $CO_2/m^2/s$ and remained at a high flux level during the growing season. The respiration peak and valley appeared at approximately 14:00 and 10:00, respectively. The annual ecosystem respiratory flux of the Hongyuan peatland is 599.98 g C/m^2, and 78 % of the flux occurred during the growing season. Soil temperature at 10-cm depth was the dominant controlling factor of alpine peatland ecosystem respiration on both diurnal and annual time scales. The Q_{10} value was 3.9, which is much higher than the average Q_{10} value of terrestrial ecosystems, indicating that alpine peatlands on the eastern Qinghai–Tibet Plateau is sensitive to climate change and will emit significantly more greenhouse gases in a warming scenario.

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