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Underestimation of soil respiration in a desert ecosystem

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ABSTRACT

Soil respiration (R_s), conventionally considered as net soil CO_2 flux, is an important link in the terrestrial carbon cycle. However, existing estimates of R_s in drylands may be erroneous, because of the abiotic soil CO_2 flux. This may seriously hamper our understanding of the carbon cycle of desert ecosystems. In this study, we monitored CO_2 flux of natural and sterilized soils, and obtained the net and abiotic soil CO_2 flux in a desert ecosystem in Ningxia, China, and then computed R_s by using these data. Daily R_s was much larger than the net soil CO_2 flux both in the growing and non-growing season. Further analysis indicated that R_s was controlled by soil temperature (T_s) over the annual cycle, and an exponential model could provide a good prediction of R_s. During the growing season, R_s increased significantly with rising soil water content (*VWC*) ($P < 0.05$). A bivariate (T_s and *VWC*) exponential–power model had a better performance for predicting R_s in the growing season than a T_s-only model. However, during the non-growing season, this model failed to simulate R_s. Our results suggest that R_s is greatly underestimated, and the exponential model is more applicable for annual R_s prediction.

1. Introduction

The carbon cycle is the most important biogeochemical cycle on Earth, and its changes profoundly affect human survival (Schindler, 1999; Fang et al., 2001). Soil is the largest terrestrial surface carbon pool (Schlesinger and Andrews, 2000), and it releases a huge amount of carbon (> 10 times the amount of fossil fuel combustion (Chen et al., 2014)). It is generally considered that soil CO_2 emission is mainly caused by soil respiration (R_s) (Flanagan and Johnson, 2005). Therefore, any shift in processes that affect soil CO_2 input or output could greatly influence the terrestrial carbon cycle (DeLuca and Boisvenue, 2012).

R_s is defined as a biotic process that releases CO_2 from the soil via root respiration, the microbial decomposition of litter and soil organic matter, and fauna respiration (Luo and Zhou, 2006). Conventionally, its rate is evaluated by directly measuring the net soil CO_2 flux (F_{net}) (Maestre and Cortina, 2003; Khomik et al., 2006; Jia et al., 2013; Wang et al., 2014). Field-based R_s measurements in forest ecosystems, grasslands, and farmland ecosystems demonstrate that R_s is modulated by multiple factors (such as soil temperature (T_s), microbial dynamics, plant phenology and photosynthesis, and soil moisture and soil porosity) (Epron et al., 1999; Davidson et al., 2000; Liu et al., 2002; Yuste et al., 2003; Jia et al., 2016). Among these factors, T_s has been considered as a generally reliable predictor of R_s (Gaumont-Guay et al., 2006; Riveros-Iregui et al., 2007).

Drylands cover approximately 41% of the Earth's terrestrial surface, and their extent may increase in response to climate change (Delgado-Baquerizo et al., 2013). As a result, R_s in drylands is an important link in the terrestrial carbon cycle. However, recent reports have described significant abiotic soil CO_2 flux (after eliminating all soil biotic processes) ($F_{abiotic}$) in drylands across the world, including the Mojave Desert (Jasoni et al., 2005; Wohlfahrt et al., 2008; Soper et al., 2016), the Great Basin Desert (Yates et al., 2013) and the Chihuahuan Desert (Hamerlynck et al., 2003) in North America, the Gurbantunggut Desert (Xie et al., 2009; Ma et al., 2013), the Taklamakan Desert (Li et al., 2015), and the Mu Us Desert (Fa et al., 2015; Liu et al., 2015) in Asia, and the McMurdo Dry Valleys (Ball et al., 2009) in Antarctica. The observation of $F_{abiotic}$ indicates that the previously reported rates of R_s in drylands may be inaccurate, because the directly measured soil CO_2 flux (F_{net}) includes both biotic and abiotic components, rather than only biotic flux (R_s). Moreover, because of the inaccurate evaluation of R_s, estimates of R_s through soil temperature become uncertain as well. As a result, the misestimating of R_s resulting from $F_{abiotic}$ in drylands may seriously hamper our understanding of the terrestrial carbon cycle.

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To improve the understanding of R_s in desert ecosystems, we measured F_{net} and $F_{abiotic}$ (by using a soil-sterilization technique) in the desert soil of the Mu Us Desert of northern China. The specific objectives of this study were to accurately determine the precise R_s rate and ascertain whether R_s was overestimated or underestimated, reveal the response of R_s to both T_s and soil water content (*VWC*) and find out the fitted model for predicting R_s.

2. Materials and methods

2.1. Site description

The study area is located on the southwestern fringe of the Mu Us Desert, Yanchi County, Ningxia province (37°42′ N, 107°13′ E, and 1509 m above sea level, 20 km^2), and belongs to a typical semi-arid ecosystem. It has a temperate continental monsoon climate with mean annual precipitation of 275 mm (1954–2013) occurring mainly in August–September. The average relative humidity is 51% and the potential annual evaporation is 2100–2500 mm. The frost-free period lasts 128 days. The mean annual temperature is 7.6 °C and the annual solar radiation is 1.4×10^5 J cm^{-2}. Generally, the growing season starts from April to October, and the non-growing season starts from January to March and November to December. The soil is classified as Aripsamment (United States soil classification criteria) with pH values of 8.6–9.2. Vegetation covers < 40% of the ground and is dominated by *Artemisia ordosica*, *Hedysarum mongolicum*, and *Hedysarum scoparium*.

2.2. Field measurements

2.2.1. Soil CO_2 flux measurements

Soil CO_2 flux was measured continuously using a LI-COR 8100 automated soil CO_2 flux measurement system (LI-COR Environmental, Nebraska, USA) with four LI-8100-104 long-term chambers connected to a LI-8150 multiplexer (LI-COR Environmental, Nebraska, USA). In the first place, seven steel soil collars were made (21.34-cm outer diameter, 20.3-cm inner diameter, 20-cm high). Subsequently, one collar was placed randomly and continuously measured the soil CO_2 flux of unsterilized soil (F_{net}), surrounded by six other collars within a 5-m radius used to measure the soil CO_2 flux of sterilized soil ($F_{abiotic}$). The six collars were divided into two groups and paired 1-m apart. We use the method of sterilization (sterilized the soils in the collars) to measure $F_{abiotic}$ (Xie et al., 2009): inserted the collars of group one into soil, and excavated them with intact soils inside (at 9 o'clock, the first day). The bottoms were sealed immediately with steel sheets to prevent soil leaking. The intact soil samples were then taken to the laboratory to sterilize in a pressure steam sterilizer for 20 h at 130 °C. When sterilizing, each of the intact soil samples, as well as the collars, was placed into a gauze sack and towels were placed on the sack to minimize the water infiltrating into the soil. After that, every collar with the sealed bottom was placed in the original position with a filter paper covering the topside of the collar to prevent microbial invasion (at 9 o'clock, the next day), and installed the chamber. The sterilized soils were then allowed to equilibrate with the surroundings for 9 h before measurement started. Then started the measurement and logged data for 24 h. During $F_{abiotic}$ measurement of the group one, sterilized the group two with the same way. Subsequently measured $F_{abiotic}$ of the group two and sterilized the group one. The two groups were sterilized and measured $F_{abiotic}$ in rotation. To make the comparison valid, the collar containing the unsterilized soil was also sealed at the bottom. The flux values of all collars were logged every hour from January to December 2012.

2.2.2. T_s and VWC measurements

T_s and *VWC* were measured at a depth of 10 cm using the EC_{H_2O} System (LI-COR Environmental, Nebraska, USA) with four Em50R sensors. Three of the Em50R sensors were placed nearby the abiotic soil CO_2 flux measuring chambers and the fourth Em50R sensor was place nearby the net soil CO_2 flux measuring chamber. The data were logged every hour.

2.3. Data treatment and analysis

Because R_s was a biotic CO_2 flux according to the definition presented by Luo and Zhou (2006) and the directly measured CO_2 flux of unsterilized soil (F_{net}) was the total of abiotic and biotic components, R_s could be calculated as:

$$R_s = F_{net} - F_{abiotic}$$

where R_s is soil respiration, F_{net} is the directly measured CO_2 flux of unsterilized soil, and $F_{abiotic}$ is the measured CO_2 flux of sterilized soil.

Hourly values of soil CO_2 flux with an absolute deviation from the mean of more than five times the standard deviation were excluded for each month (Jia et al., 2013). Missing data due to instrument failure (caused by power failure) represented 9.5% of the dataset during the measurement period. Mean values from the four chambers were used for analysis. Daily mean values were the average of the hourly values over 24 h.

Short gaps of 1–2 h in the CO_2 flux data were filled by linear interpolation, generally following methods described by Savage et al. (2008). Nonlinear regression analysis was used to examine relationships between the variables. Regression significance was evaluated using the *F*-statistic at a significance level of 0.05. All statistical analyses were performed using the MATLAB software (version 7.12.0.635, The MathWorks, Natick, MA, USA).

3. Results

3.1. Seasonal and diel variations in F_{net}, $F_{abiotic}$ and R_s

At the seasonal scale, there was a remarkable difference between F_{net} and $F_{abiotic}$ (Fig. 1a). Daily mean values of F_{net} varied from − 0.06 (in the 1st day) to 1.22 (in the 211th day) μmol CO_2 m^{-2} s^{-1}. However, the seasonal variation of $F_{abiotic}$ showed the inverse variation tendency (Fig. 1a) and the mean value varied from − 0.31 (in the 303rd day) to − 0.003 (in the 341st day) μmol CO_2 m^{-2} s^{-1}.The daily R_s was lowest (0.02 μmo CO_2 m^{-2} s^{-1}) in the 8th day, and did not show any remarkable increase until the 114th day. It peaked in the 211th day (1.27 μmol CO_2 m^{-2} s^{-1}) and then decreased rapidly to 0.04 μmol CO_2 m^{-2} s^{-1} by the end of the year (Fig. 1a). T_s exhibited a typical seasonal pattern with a broad peak from the 157th day to the 247th day. On the other hand, pulse dynamics in *VWC* changed from the 107th day to the 304th day, ranging from 0.05 to 0.16 m^3 m^{-3}, with the highest values in the 245th day (Fig. 1a).

At the diel scale, during the growing season, $F_{abiotic}$ was positive (soil released CO_2) during the day, and was negative (soil absorbed CO_2) at night. In the non-growing season, $F_{abiotic}$ displayed mostly negative values during the entire diel cycle. F_{net} in growing season exhibited a remarkable fluctuation with a maximum of 1.33 ± 0.3 μmol CO_2 m^{-2} s^{-1} (at 13: 00) and a minimum of − 0.03 ± 0.09 μmol CO_2 m^{-2} s^{-1} (at 0: 00). In the non-growing season, the amplitude of fluctuation decreased, although daytime flux values remained positive and night time flux values were still negative. R_s also fluctuated, with a maximum of 1.0 ± 0.3 μmol CO_2 m^{-2} s^{-1} (at 14: 00) and a minimum of 0.29 ± 0.11 μmol CO_2 m^{-2} s^{-1} (at 1: 00) during the growing season. In the non-growing season, R_s showed no obvious fluctuation, and was close to zero (Fig. 1b). Fig. 1c shows that during the growing season the accumulated daytime $F_{abiotic}$ was positive, but accumulated the night time flux was negative. In the non-growing season, both daytime and night time accumulated $F_{abiotic}$ were negative.