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Biophysical regulation of net ecosystem carbon dioxide exchange over a temperate desert steppe in Inner Mongolia, China

Fulin Yang[a,c], Guangsheng Zhou[b,a,*], John E. Hunt[d], Feng Zhang[a]

[a] State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, 20 Nanxincun, Xiangshan, Haidian District, Beijing 100093, China
[b] Chinese Academy of Meteorological Sciences, 46 Nandajie, Zhongguancun, Haidian District, Beijing 100081, China
[c] Graduate University of the Chinese Academy of Sciences, 19A Yuquan Road, Shijingshan District, Beijing 100049, China
[d] Landcare Research, P.O. Box 40, Gerald Street, Lincoln 7640, New Zealand

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ABSTRACT

Measurements of net ecosystem carbon dioxide (CO_2) exchange (NEE) were made, using eddy covariance, to investigate the biophysical regulation of a temperate desert steppe characterized drought in Inner Mongolia, China during 2008. The half-hourly maximum and minimum NEE were −3.07 and 0.85 μmol CO_2 m^{-2} s^{-1} (negative values denoting net carbon uptake). The maximum daily NEE was −6.0 g CO_2 m^{-2} day^{-1}. On an annual basis, integrated NEE was −7.2 g C m^{-2} y^{-1}, indicating a weak carbon sink. The light response curves of NEE showed a rather low apparent quantum yield (α) and saturation value of NEE (NEE_{sat}). Moreover, α and NEE_{sat} varied with canopy development, soil water content (SWC), air temperature (T_a), and vapor pressure deficit (VPD). Piecewise regression results suggested that the optimal SWC, T_a, and VPD for half-hourly daytime NEE were 12.6%, 24.3 °C, and 1.7 kPa, respectively. The apparent temperature sensitivity of ecosystem respiration was 1.6 for the entire growing season, and it was significantly controlled by soil moisture. During the growing season, leaf area index explained about 26% of the variation in daily NEE. Overall, NEE was strongly suppressed by water stress and this was the dominant biophysical regulator in the desert steppe.

1. Introduction

Grasslands store approximately 34% of the global stock of carbon in terrestrial ecosystems (White et al., 2000), and play an important role in regional and global carbon storage and cycling. Accurate measurements and predictions of CO_2 exchange between grassland ecosystems and the atmosphere are particularly important for global carbon cycle research. Micrometeorological measurements of CO_2 flux are commonly used to determine environmental drivers of carbon cycling in grassland ecosystems (Baldocchi et al., 2001; Yu et al., 2006), with the aim of developing or improving ecosystem models. These models can then be used to assess the effects of changing climate on land surface processes (Friend et al., 2007). The response of CO_2 exchange to climatic variation has been found to vary on a temporal scale and across ecosystems. Consequently, uncertainty in these models limits the ability to accurately predict CO_2 exchange (Polley et al., 2010). Therefore, validation and improved ecosystem models are required to understand the regulation of CO_2 exchange at multiple temporal scales and by diverse ecosystems.

Net ecosystem CO_2 exchange (NEE) is a result of gross ecosystem production (GEP), i.e. photosynthetic assimilation, and autotrophic (R_a) and heterotrophic (R_h) respirations. Photosynthesis and respirations may respond at different rates to environmental variabilities. Wang and Zhou (2008) suggested that single-factor response functions of carbon budget components had limited values in arid and semiarid ecosystems, due to the combination of drought and high temperatures. Drought can substantially modify the seasonal development of leaf area and change plant physiology, and therefore impact on both the timing and magnitude of maximal CO_2 uptake (Hunt et al., 2002). Canopy development and other biological processes that regulate photosynthesis and respiration, in turn, are affected by seasonal or annual amounts of precipitation (PPT) (Polley et al., 2010). Depending on timing and amount of precipitation, more or less carbon uptake can occur in grassland ecosystems. At the ecosystem level, grasslands can be either net carbon sources or sinks (Meyers, 2001; Flanagan et al., 2002; Xu and Baldocchi, 2004). Scott et al. (2009) reported severe cool season drought could lead to the greatest annual net carbon loss. In one dry tussock

* Corresponding author at: State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, 20 Nanxincun, Xiangshan, Haidian District, Beijing 100093, China. Tel.: +86 10 62836268; fax: +86 10 82595962.
E-mail address: gszhou@ibcas.ac.cn (G. Zhou).

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grassland, the annual net CO_2 exchange was determined mostly by the timing and intensity of spring rainfall (Hunt et al., 2004). In Inner Mongolian typical steppe, the capacity to fix CO_2 was closely related to both timing and frequency of rainfall events (Hao et al., 2008).

Soil respiration involves a suite of complex processes contributing to CO_2 efflux from the surface of soils (Qi et al., 2002), and is usually expressed empirically as an exponential function of temperature. The temperature sensitivity of respiration is often expressed by a Q_{10} value, the factor by which respiration rate increases with every 10 °C increase in temperature. Q_{10} is treated commonly as a constant of 2 in many ecosystem models, such as CASA (Potter et al., 1993), TEM (Tian et al., 1999), and can be used to calculate soil or ecosystem respiration (R_{eco}) from local to global scales (Cox et al., 2000; Fang and Moncrieff, 2001). However, recent studies have shown that the value of Q_{10} may vary considerably in space and time across systems (Raich and Schlesinger, 1992; Kirschbaum, 2000; Aires et al., 2008), and a small change in Q_{10} in models can cause a significant bias in the estimate of soil respiration (Xu and Qi, 2001; Reichstein and Beer, 2008). Kutsch and Kappen (1997) compared a Q_{10}-adjustment model to a fixed model in agricultural ecosystems and found that the Q_{10}-fixed model overestimated soil respiration in the dry season and underestimated soil respiration in the other seasons. Recent studies showed that Q_{10} varied over the season with changes in soil moisture, temperature, phenology, and carbon inputs, and should be taken into account in modeling long-term ecosystem respiration (Xu and Baldocchi, 2004; Yuste et al., 2007). Davidson and Janssens (2006) suggested the environmental constraints, such as drought, that can also temporarily or indefinitely affect apparent temperature sensitivities. However, ecosystem models commonly do not explicitly consider the varying sensitivity of soil respiration rates to temperature and moisture (Qi et al., 2002). Therefore, accurately quantifying response of R_{eco} to soil temperature (T_s) and soil water content (SWC), especially drought, is critical for obtaining a reliable estimate of ecosystem carbon budget.

The desert steppes are the most arid grassland ecosystem type, distributing in the region with annual precipitation between 150 and 250 mm and continental climate (Sun, 2005). The 17.5 million ha of temperate desert steppe in China provided 0.066 Pg of carbon storage in the biomass (Fan et al., 2008). Inner Mongolian temperate desert steppe covering 8.8 million ha (Liao and Jia, 1996) is located in a transitional zone between steppe and desert, and is vulnerable to desertification due to climate change and increased human activity (Yang and Zhou, 2011). Severe drought conditions have the most significant effect on plant biomass in Inner Mongolia grasslands (Xiao et al., 1995). Recent studies have shown that the annual mean temperature has increased, while precipitation in spring and winter has decreased over the past 40 years (Li et al., 2002). Warming trend may intensify the hydrological cycle and lead to increased drought severity and duration. Severe drought could lead to a change in plant community structure, which, in turn, may alter the water and carbon dioxide cycling processes (Scott et al., 2010). Understanding how CO_2 exchange responds under current climate variability and drought is thus of critical importance to predict how the desert steppe ecosystem will respond to future climate change. Knowledge of the biophysical regulations of CO_2 exchange from this large area of water-limited grassland ecosystem, however, is still lacking.

Using eddy covariance measurements, the objectives of this study were to: (1) investigate the biophysical regulations on CO_2 fluxes; (2) quantify the magnitude of CO_2 exchange; (3) calculate the carbon balance in 2008 over the Inner Mongolian temperate desert steppe.

2. Material and methods

2.1. Study site

This study was conducted at the Inner Mongolian Temperate Desert Steppe Ecosystem Research Station (44°05′N, 113°34′E, 970 m a.s.l.), located north of the county of Sunitezuoqi, Inner Mongolia Autonomous Region, China, during 2008. The study region has an arid–semiarid, temperate continental climate. The annual mean air temperature is 3.2 °C, with monthly mean temperature ranging from −18.7 °C in January to 22.1 °C in July. The mean annual precipitation is 184 mm (40-year period from 1965 to 2004, Sunitezuoqi weather station), with most of precipitation (85%) occurring between May and September. The plant community is dominated by the bunch grass *Stipa klemenzii* and the herb *Allium polyrrhizum*. In mid-summer, the grass canopy is 0.20–0.35 m tall. The study site was fenced in August 2007 to prevent grazing and other disturbances. The soils are classified as brown calcic with an average bulk density of 1630 kg m^{-3}.

2.2. Eddy flux and micrometeorological measurements

An eddy covariance (EC) system was used to measure the fluxes of energy, water vapor and CO_2. The EC system was installed at a height of 2.0 m, and included a 3-D sonic anemometer–thermometer (CSAT-3, Campbell Scientific Inc., Logan, UT, USA) and an open path infrared gas (CO_2/H_2O) analyzer (LI-7500, LI-COR Inc., Lincoln, NE, USA). The raw signals were recorded at 10 Hz by a data logger (CR5000, Campbell Scientific Inc., Logan, UT, USA).

A meteorological tower was established near the eddy covariance tower to measure environmental variables. Photosynthetically active radiation (PAR) and net radiation (R_n) were measured at 2.4 m above the ground, using a quantum sensor (LI-190SB, LI-COR Inc., Lincoln, NE, USA) and a four-component net radiometer (CNR-1, Kipp & Zonen, Delft, Netherlands), respectively. Air temperature (T_a) and relative humidity (RH) were measured at 2.0 m (HMP45C, Vaisala, Helsinki, Finland). A horizontal wind speeds sensor (014A, Campbell Scientific Inc., Logan, UT, USA) was attached at 2.0 m to measure horizontal wind speed (W_s). Soil temperature (T_s) at 0.05 m was measured by a thermistor (107L, Campbell Scientific Inc., Logan, UT, USA). Soil water contents (SWC) at depths of 0.10, 0.20, 0.30, and 0.40 m were measured by time domain reflectometry probes (CS616, Campbell Scientific Inc., Logan, UT, USA). Soil heat flux (G) was measured using two soil heat plates (HFP01, Hukeflux Inc., Delft, Netherlands) in separate locations at 0.08 m below the soil surface. Precipitation above the canopy was measured with a tipping bucket rain gauge (Model 52203, RM Young Inc., Traverse City, MI, USA). All meteorological factors were measured every 2 s, and averaged half-hourly by a data logger (CR23X, Campbell Scientific Inc., Logan, UT, USA).

2.3. Above ground biomass and leaf area index measurements

Above ground biomass (AGB) was measured five times during the 2008 growing season (1 May–15 October) by clipping eight 1 m × 1 m quadrats. In each quadrat, all the plants were cut at the ground surface and oven dried at 65 °C to constant weight and the dominant species leaf area ratio (m^2 g^{-1}) was also measured. The total leaf area index (LAI, m^2 m^{-2}) was estimated as the product of total dry leaf biomass (g m^{-2}) and leaf area ratio (Wang and Zhou, 2008). All the above ground biomass dies over winter so we assumed LAI was set to zero on 1 May (DOY 122) and 15 October (DOY 289), corresponding to the beginning and end dates of growing season. Measurements of LAI were linearly interpolated to daily intervals (Li et al., 2005).