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Water availability is more important than temperature in driving the carbon fluxes of an alpine meadow on the Tibetan Plateau

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ABSTRACT

Temperature is conventionally considered as the dominant factor regulating carbon fluxes of the alpine meadow on the Tibetan Plateau, while contribution from water availability is composed of large uncertainty. In this study, eddy covariance (EC) data were used to assess the relative contribution of temperature and water availability to carbon fluxes of the alpine meadow ecosystem. The results showed that soil water content (SWC) was the most important factor controlling carbon fluxes – Net Ecosystem Productivity (NEP), Gross Primary Productivity (GPP) and Ecosystem Respiration (Re). The GPP and Re increased with strengthened SWC under any temperature conditions, indicating the dominant control of water availability on carbon fluxes. In addition, water availability regulated the response size of ecosystem to temperature, and could alleviate the stress caused by low temperature. The photosynthesis capacity of alpine plants at noon was depressed by water stress rather than by high temperature. The structural equation modeling (SEM) analysis further confirmed the dominance of SWC on the carbon fluxes. This study implies that effects of climatic change on this alpine ecosystem might be more induced by changes in water pattern than increased temperature, which provides new insights into the climate controls of carbon fluxes over alpine meadow, and adds to our understanding on climate change impacts on carbon cycling on the Tibetan Plateau.

1. Introduction

Temperature and moisture are the two key factors regulating plant distribution and productivity (Epstein et al., 1997; Yu et al., 2013). Compared to increasing temperature, the precipitation trend varied strongly at temporal scales and spatial dimension on the Tibetan Plateau (Wang et al., 2008). The alpine ecosystems on the Tibetan Plateau are suggested to be highly sensitive to climatic change (Gao et al., 2009), but relative contribution from precipitation and temperature still involves much uncertainty (Craine et al., 2012). Disentangling their relative contribution to the carbon fluxes is the basis for understanding climatic variability impacts on the alpine ecosystems on the Tibetan Plateau.

Temperature affects plant growth and distribution (Sage and Kubien, 2007) via influencing physiological activities such as photosynthesis (Ganjurjav et al., 2015) and respiration (Hu et al., 2016). It is generally assumed that warming accelerates both photosynthesis and respiration (Wu et al., 2011). However, the acceleration magnitude varies in different ecosystems (Craine et al., 2012; Davi et al., 2007; Oberbauer et al., 2007). Also warming effects are adjusted by water availability (Wu et al., 2011; Yu et al., 2013). An ecosystem could shift from carbon source to sink when warming occurs along with increased precipitation (Harper et al., 2005). When warming occurs along with decreased precipitation, warming-induced soil drought could shift ecosystem from carbon sink to source (Ciais et al., 2005; Saleska et al., 2003).

Ecosystem productivity in cold environments is more responsive to warming than to cooling (Rustad et al., 2001), but carbon emission can also increase with warming owing to a greater sensitivity of respiration to warming (Lu et al., 2013). Altered precipitation has been suggested to exert larger impacts on semiarid ecosystems than on mesic ecosystems (Mooney et al., 1996). For example, the semiarid ecosystem productivity increased but that of the mesic one decreased under a similar annual precipitation of 380 mm (Sala et al., 2015).

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Regardless the critical role of water availability on ecosystem functions (Harper et al., 2005; Piao et al., 2007), most of previous studies have been focused on temperature effects on carbon fluxes of alpine meadow (Fu et al., 2009; Fu et al., 2006), whereas water availability played an even more important role in some cases (Wang et al., 2017a; Burke et al., 1997; Yang et al., 2009).

The alpine *Kobresia* meadow on the Tibetan Plateau is one of the highest-elevation vegetation types in the world (Wang et al., 2008), covering over 7×10^5 km^2 and approximately 35% of the plateau. It is an extremely fragile system and highly sensitive to climatic change. Research findings for this system can be used as pre-warning for other low elevation ones (Zhang et al., 2013). Related knowledge is also critical for improving our prediction of global carbon cycle.

Alpine ecosystem is sensitive to both warming and cooling (Hu et al., 2016), but warming can cause no significant effects on GPP and aboveground biomass or its effect is regulated by water availability (Fu et al., 2013). Precipitation can change both photosynthesis and respiration (Angert et al., 2005; Breshears et al., 2005), but its net effects on carbon storage are still uncertain for the alpine ecosystem on the Tibetan Plateau (Zhang et al., 2016). To this end, eddy covariance and micrometeorological data were integrated to examine how carbon fluxes responded to climates. This work aimed at addressing the following questions: (1) How do climatic factors affect ecosystem carbon fluxes (GPP, Re and NEP)? (2) Are there interactions between temperature and water availability on carbon fluxes? (3) Between temperature and water availability, which one plays the dominant role?

2. Data and methods

2.1. Study site

The experimental site is located at 31.64°N, 92.01°E, 4598 m above sea level, in the hinderland of the Tibetan Plateau. The climate features the plateau subfrigid monsoon climate. The annual temperature averages −1.9 °C, with an active vegetation period length of 60–70 days. The annual precipitation is 380 mm, mainly concentrated in June–September and with large inter-annual variations. The annual average sunlight exceeds 2886 h. The soil is the meadow soil with sandy loam. The vegetation is typical alpine meadow, dominated by *Kobresia pygmaea*, accompanied by *Potentilla bifurca, Potentilla saundersiana, Leontopodium pusillum,* and *Carex moorcroftii*.

2.2. Instrumentation and measurements

The flux tower was located on a relatively flat open ground (< 3% slope in the primary wind direction). The open-path eddy covariance (OPEC) system, including a 3-D sonic anemometer (Model CSAT-3, Campbell Scientific Inc., Logan, UT, USA) to measure three-dimensional wind speed and temperature fluctuations, and an infrared gas analyzer (Model LI-7500A, Li-cor Inc., Lincoln, NE, USA) to measure carbon dioxide (CO_2) density, was used to measure carbon fluxes at 2.3 m above the ground. The flux data were collected at 10 Hz, then resampled to 30 min averages by a CR3000 datalogger (Model CR3000, Campbell Scientific).

The micrometeorological variables were measured near the OPEC system. Air temperature (Ta) and relative humidity (RH) were recorded at 1.8 m above ground by a temperature and humidity probe (Model HMP45C, Vaisala Inc., Helsinki, Finland), respectively. Photosynthetically active radiation (PAR) was measured at 1.5 m above the ground with a quantum sensor (LI190SB, Li-cor Inc.). Precipitation (PPT) was recorded at 1 m above ground level using a tipping bucket rain gauge (TE525MM-L, Campbell Scientific). Soil temperatures (Ts) and soil volumetric water contents (SWC) were measured at 0.05, 0.10, 0.20 and 0.50 m below the ground with thermometers (109-L, Campbell Scientific) and TDR probes (Model CS616-L, Campbell Scientific), respectively. The micrometeorological data were collected with a frequency of 1 Hz and then resampled to 30 min averages using a CR1000 datalogger (Model CR1000, Campbell Scientific).

2.3. Data processing

2.3.1. Eddy covariance data

The CO_2 flux data were processed using a data processing procedure for ChinaFLUX (Yu et al., 2006) implemented in Matlab R2010b software (MathWorks Inc., Natick, MA, USA). The flux data were first aligned with the coordinate system of mean wind direction using the three-dimensional rotation, to remove the effects of instrument tilt irregularity on the airflow (Wilczak et al., 2001). Then the WPL correction – the Webb, Pearman and Leuning density correction for effects of air density fluctuations on CO_2 fluxes – was used to adjust air density changes caused by heat and water vapor fluctuations (Webb et al., 1980). Missing or screened out data caused by power failures, instrumental malfunctions, and data filtering criteria such as the sonic temperature, water vapor density, CO_2 density values occurring outside reasonable bounds, rain, dew, hoarfrost, etc. were excluded from the analysis.

The CO_2 flux measured by the EC technique was the net ecosystem CO_2 exchange (NEE). There was a simple conversion of NEP = −NEE, then GPP could be estimated by GPP = NEP + Re, where Re is derived from the nighttime NEE (Reichstein et al., 2005). In order to eliminate the effects of poor turbulent mixing on nighttime CO_2 flux data, the data analyzed was restricted to the conditions when the friction velocity (u*) was greater than 0.14 m s$-^1$ (Saleska et al., 2003; Scott et al., 2006).

All flux and meteorological data collected were quality controlled. Data gaps were filled using the interpolation methods (Baldocchi, 2003) and the mean diurnal variation (MDV) method (Falge et al., 2001).

2.3.2. Data analysis

2.3.2.1. Vapor pressure deficit. The vapor pressure deficit (VPD) was calculated by the measurements of air temperature (Ta) and relative humidity (RH) (Howell and Dusek, 1995):

$$VPD = 0.611 \times e^{\frac{17.27 \times Ta}{Ta + 237.3}} \times \left(1 - \frac{RH}{100}\right) \tag{1}$$

2.3.2.2. Anomaly analysis. The anomaly was calculated as the difference between the specific value of a given day and the corresponding multi-year average of that day to identify the variations of climatic factors and carbon fluxes of each day:

$$A_{doy,y} = F_{doy,y} - \frac{1}{5}\sum_{n=2012}^{2016} F_{doy,n} \tag{2}$$

where, A is the anomaly, F are daily values of carbon fluxes or climatic factors, doy = 1–365, y = 2012–2016.

2.3.2.3. Multiple stepwise regression analysis. Six main climatic factors (photosynthetically active radiation (PAR), air temperature (Ta), soil temperature (Ts), precipitation (PPT), vapor pressure deficit (VPD) and soil water content (SWC)) were selected and the multiple stepwise regression analysis between carbon fluxes and climatic factors were conducted with SPSS statistics 19.0 software (IBM Corporation, Armonk, NY, USA), aiming to identify the key climatic factors linked to carbon fluxes. The minimum P-value for a variable to be included or excluded from the model was 0.05. The higher F-value represents a better fit.

2.3.2.4. Trend - fitting analysis. The OriginPro 9.2 software (OriginLab Corporation, Northampton, MA, USA) was used to fit the generalized linear regression, exponential or logarithmic model of carbon fluxes against climatic factors. The better-fit functions that possess a higher r-