Ecological Indicators 91 (2018) 562–569

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

The strongest EI Niño event stimulated ecosystem respiration, not evapotranspiration, over a humid alpine meadow on the Qinghai-Tibetan Plateau

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ARTICLE INFO

Keywords:
Gross primary production
Ecosystem respiration
Evapotranspiration
Eddy covariance technique
Extreme events
Alpine meadow

ABSTRACT

Frequent EI Niño events have worldwide impacts, but their effects on carbon and water budgets in alpine grasslands have been poorly explored. The responses of carbon and water vapor exchanges, monitored by the eddy covariance techniques, to the strongest EI Niño event in 2015/2016 were investigated over a humid alpine meadow on the Northeastern Qinghai-Tibetan Plateau. Monthly air temperature (T_a) in August could be considered as a clear indicator of this event and was elevated by 44% (by 4.0 °C) in 2016, mainly due to a 204% (5.2 °C) increase in daily minimum T_a. On a diurnal scale, a paired-samples T-test between the EI Niño duration (August in 2016) and the reference period (August in 2014 and 2015) revealed that the EI Niño-induced increase in gross primary production (*GPP*, 0.078 gC·m^{-2}·h^{-1}) was lower than the growth in ecosystem respiration (*RES*, 0.12 gC·m^{-2}·h^{-1}), resulting in an increase in net ecosystem CO_2 exchange (*NEE*, 0.079 gC·m^{-2}·h^{-1}). Diurnal evapotranspiration (*ET*) was significantly increased, by 8.6%, at a rate of 0.011 mm·h^{-1}. On a monthly scale, this ecosystem fixed less carbon by 58.7 g C·m^{-2}·month^{-1} while *ET* water losses increased by only 6.2 mm·month^{-1} in August. The alpine meadow thus acted as a carbon sink with a 36.2 g C·m^{-2}·year^{-1} influx in 2015, but switched to a carbon source with a 21.6 g C·m^{-2}·year^{-1} efflux in 2016, mainly due to a 78.7 g C·m^{-2}·year^{-1} increase in *RES*. Annual *ET* increased by less 3%. The divergent responses of CO_2 and H_2O fluxes were mostly attributed to a great increase only in nocturnal T_a, which instantaneously stimulated *RES* but not *ET*. Our findings revealed that extreme nocturnal warming led to greater carbon losses and weaker compensatory carbon gains, highlighting the inconsistent response of carbon dynamics to gradual warming and to exceptional warmth in humid alpine meadows.

1. Introduction

Alpine grasslands play an indicative role in terrestrial biochemical and hydrological cycles, and their carbon and water budgets are tightly coupled with climate variations (Beer et al., 2010; Zhao and Running, 2010; Li et al., 2016). Climate extremes induced by global change have become frequent and severe (IPCC, 2013), consequently creating more stressful conditions for terrestrial ecosystems than those would be caused by gradual warming (Teuling et al., 2010; Frank et al., 2015). The strong EI Niño events have substantially impacted temperate grassland carbon and water dynamics through atmospheric teleconnections (Behrenfeld et al., 2001; Mcphaden et al., 2006; Kogan and Guo, 2017), but the direction and magnitude of the effects on alpine grasslands are poorly quantified (De Boeck et al., 2015; Zhang and Cao, 2017). Therefore, quantifying the EI Niño-induced effects on alpine grasslands is crucial for understanding potential changes of carbon and water dynamics in response to ongoing climate change, given that these ecosystems are generally referred as water towers for lowlands, and

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https://doi.org/10.1016/j.ecolind.2018.04.039
Received 8 August 2017; Received in revised form 14 April 2018; Accepted 16 April 2018
Available online 24 April 2018
1470-160X/

have been experiencing the "more-than-average" climate warming (Holmgren et al., 2001; Moriyama et al., 2013; Chai et al., 2017).

Although short-statured alpine plants have evolved phenological strategies for adapting to the cold environment, these species are generally temperature-limited and most sensitive to warmer conditions (Körner, 1999; Brilli et al., 2011; Budge et al., 2011). Hence, manipulation experiments and long-term *in situ* observations have both reported that warmer scenarios have enhanced the plant photosynthesis rate (Li et al., 2014; Fu et al., 2015), carbon sequestration capacity (Kato et al., 2006; Li et al., 2016), plant production (Wang et al., 2012; Li et al., 2015a,b), and ecosystem evapotranspiration (Brilli et al., 2011; Zhang et al., 2017). However, the strength of these changes could be mediated by soil moisture availability and vegetation types (Moriyama et al., 2013; De Boeck et al., 2015; Chen et al., 2016). More importantly, current knowledge of the effects on alpine ecosystems of strong warm EI Niño events is still poor (Brilli et al., 2011) and cannot easily be improved based on observations related to gradual warming because strong events may push ecosystems beyond the thresholds of dynamic equilibrium (Holmgren et al., 2001; Ciais et al., 2005). Exceptional warmth could alleviate cold constraints and favor alpine flora performance by increasing leaf length and number (Walker et al., 1995), photosynthetic activity (Zhang and Cao, 2017) and seed generations (Orsenigo et al., 2015). Nevertheless, extreme warming and consequent soil drought may threaten soil moisture availability and plant fitness, in turn leading to a decrease in water holding capacity and carbon sequestration in terrestrial ecosystems (Mcphaden et al., 2006; Beer et al., 2010; Zhao and Running, 2010). Limited by the unpredictability of naturally occurring extreme events, the response manners of carbon and water dynamics to strong EI Niño events in alpine grasslands still remain largely unknown.

The present study investigated the effects of one of the three strongest EI Niño event (that of 2015/2016) (Kogan and Guo, 2017) on carbon and water vapor exchanges over a humid alpine *Kobresia* meadow on the Northeastern Qinghai-Tibetan Plateau (QTP). Our main research goal was to understand how the carbon and water vapor fluxes responded to this EI Niño event. The results would help to advance our understanding of the potential impacts of frequent extreme warming events in alpine regions.

2. Material and methods

2.1. Site description

The study was undertaken at the Haibei National Field Research Station of Alpine Grassland Ecosystem (hereafter Haibei Station, 37°37′ N, 101°19′ E, 3200 m a.s.l), which is situated in the Northeastern QTP. The Haibei station is one of the first 10 members of the Chinese Ecosystem Research Network since 1988, which have protocols for standard atmosphere environmental observation. Based on a 30-year time series of meteorological manual observations from 1981 to 2010, the mean annual air temperature (T_a) is −1.7 °C, varying from −15.0 °C in January to 10.1 °C in July. The annual precipitation (*Ppt*) averages 570 mm, 80% of which is concentrated in the plant growing season from May to September. The growing season sunshine duration and pan evaporation are 1061.7 h and 687.1 mm, respectively (Li et al., 2015a,b). The soil is a clay loam, with an average thickness of approximately 60 cm. The topsoil (0–10 cm) is high in moisture and organic matter and low in available nitrogen. The groundwater depth is about 4.2 m during the growing season.

The vegetation is classified as alpine meadow and, in the study area, comprised 51 plant species. *Kobresia humilis* is the dominant species, followed by *Elymus nutans*, *Stipa aliena*, *Taraxacum dissectum*, *Anaphalis lactea* and *Potentilla anserina*, which together represents nearly 70% of the surface area. The maximum canopy height and 80% root concentration depth is about 40 cm and 20 cm, respectively. The green leaf area index (*LAI*) and aboveground biomass (*AGB*) peaks in late July and late August, respectively. Tibetan sheep graze at a moderate density (3.75 sheep·ha^{-1}) in this area every winter (Li et al., 2014).

2.2. Measurements

Since May 2014, an open-path eddy covariance (EC) system has been in operation for flux measurements in the center of a flat (aspect < 5°), open (minimum 3 km distance from mountainous topography) and homogenous area (average canopy coverage is above 98% in July and August) covering about 12 km^2. The EC system consists of a three-dimensional ultrasonic anemometer (CSAT3, Campbell, USA) and an open-path infrared CO_2/H_2O gas analyzer (LI-7500A, LI-Cor, USA), both fixed at a height of 2.2 m above ground. The raw data (wind speed, sonic virtual temperature, and CO_2 and H_2O concentrations) were sampled at 10 Hz. The 30-min fluxes were calculated and logged with a SMARTFLUX system (LI-Cor, USA).

Micrometeorological variables were measured synchronously. Radiation (including incoming/outgoing long-wave, incoming/outgoing short-wave radiation) and photosynthetic photon flux density (*PPFD*) were measured with 4 radiometers (CNR4, Kipp & Zonen, Netherlands) and a quantum sensor (LI-190SB, LI-Cor, USA), respectively, at 1.5 m height. Precipitation (*Ppt*) was collected with a rain gauge (52203, RM Young, USA) positioned at 0.5 m above ground level. Soil temperature (T_s) and volumetric soil water content (*SWC*) were integratedly measured (Hydra probe II, Stevens, USA) at 5, 10, 15, 20, and 40 cm below ground. Soil heat flux (*G*) was measured with heat plates (HFT-3, Campbell, USA) buried at three nearby locations at 5 cm below the soil surface. The 30-min averages of meteorological data were recorded with a data logger (9210 XLITE, Sutron, USA).

2.3. Biotic factors and soil organic matters

From May to September, plant absolute coverage (*PAC*) and *AGB* were measured using the grid method with 5 cm × 5 cm (frame of 0.5 m × 0.5 m, total 100 points) and 10 random replicates at the end of each month. *PAC* (%) was defined by the total plant species occurrence within the 100 points, and the *AGB* (g·m^{-2}) of each species was obtained by the standard harvesting method in each quadrat. Meanwhile, four plant functional groups were also identified: sedges, graminoids, legumes, and forbs (Li et al., 2015a,b). Six soil cores at depths of 0–10, 10–20, 20–30 and 30–40 cm were extracted using a soil sampler with a diameter of 6 cm in the *AGB* quadrats. Soil organic matter contents (*SOM*, %) was measured using a TOC analyzer (TOC-5000, Shimadzu, Japan).

LAI was derived from an 8-day composite *LAI* product (MOD15A2). The spatial resolution was 1 km × 1 km and the selected area containing the flux tower was 1 km^2. *LAI* data were obtained from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC, http://daac.ornl.gov/MODIS/modis.html). Although *LAI* was not zero and was somewhat unreliable from November to April, these *LAI* data were retained for data integrity and not involved with any further statistical analysis. The satellite-*LAI* data for estimating green leaf quantity compared relatively favorably with the half-monthly *LAI* measured by LI-3000 portable leaf area meter (LI-Cor, USA) through standard harvesting methods (Li et al., 2016).

2.4. Data quality and gap filling

All flux data and quality flags were re-calculated by an open source software Eddypro 6.0 (LI-Cor, USA) with WPL (Webb-Pearman-Leuning) density correction (Webb et al., 1980), two-dimensional coordinate rotation, time lags compensation and storage item. We discarded the worst results, flagged as "2" (Foken et al., 2004). Data satisfying these quality controls represented over 80% of all records.

The 30-min CO_2 flux data (*NEE*) were removed when *Ppt* occurred or when the absolute value of *NEE* was above 0.3 mg C·m^{-2}·s^{-1}.