Agricultural and Forest Meteorology 240–241 (2017) 1–9

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Aboveground net primary productivity and carbon balance remain stable under extreme precipitation events in a semiarid steppe ecosystem

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ARTICLE INFO

Article history:
Received 5 March 2017
Accepted 11 March 2017
Available online 1 April 2017

Keywords:
Climate change
Extreme large precipitation events
Grassland
Aboveground productivity
Ecosystem C exchange

ABSTRACT

Global climate change is projected to increase both the intensity and frequency of extreme precipitation events (EPEs), which are considered to have stronger impacts on ecosystem functions than gradual changes in mean precipitation conditions. In this study, a consecutive 20-day extreme precipitation event (282 mm) was applied during the mid- and late-growing season periods in a semiarid steppe for three years to investigate the effects of extreme large precipitation events on aboveground net primary productivity (ANPP) and ecosystem carbon dioxide (CO_2) fluxes, including net ecosystem carbon absorption (NEE), gross primary productivity (GPP) and ecosystem respiration (Re). Although soil moisture was significantly increased by extreme precipitation, and even exceeded field capacity during the treatment periods, ANPP remained stable across all the treatments. There was also little change in mean growing season ecosystem CO_2 fluxes under the two precipitation treatments, despite GPP rates decreased by 34.4 and 26.3%, and NEE rates were suppressed by 77 and 68% during the mid- and late-season treatment periods, respectively. The stable CO_2 fluxes could be attributed to the recovery of GPP and NEE in 7 and 12 days after the end of EPEs. Our study demonstrated that both ANPP and CO_2 fluxes in this semiarid steppe were very stable in the face of extreme large precipitation events, regardless of the timing of events occur. Nevertheless, future, long-term studies need to investigate the potential tipping points or thresholds for ecosystem function shifts, as an increasing occurrence of EPEs has been forecasted in future climate change scenarios.

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1. Introduction

As a result of global climate change, climate extremes such as extreme precipitation events (EPEs) are projected and also observed to increase in both frequency and intensity over most regions of the world (Easterling et al., 2000; IPCC, 2014; Knapp et al., 2015). Such EPEs can be characterized as suddenly precipitation events with statistically rare large water inputs, which may cause stressful conditions (i.e. water logging and topsoil erosion) to terrestrial ecosystems. As a consequence, EPEs may have the potential to push ecosystems beyond the thresholds of dynamic equilibrium and result in greater impacts on ecosystem structure and function than chronic changes in precipitation conditions (Jentsch et al., 2007; Reyer et al., 2013; Kreyling et al., 2014). Therefore, incorporating EPEs into climate change experiments is crucial for understanding and (Kreyling et al., 2014) predicting potential changes in key ecosystem function such as ecosystem carbon (C) exchange and productivity in response to ongoing climate change.

Grassland ecosystems account for 1/5 of the earth's land surface and store at least 10% of global C stocks (Eswaran et al., 1993). The productivity of those located in arid and semiarid regions is highly dependent on the availability of water (Weltzin et al., 2003). There is a strong correlation between mean annual precipitation (PT) and

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http://dx.doi.org/10.1016/j.agrformet.2017.03.006
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aboveground net primary productivity (ANPP) (Bai et al., 2004; Lehouerou et al., 1988; Sala et al., 1988). The positive linear ANPP-PT relationship was built from long-term observed data in almost all grassland ecosystems (Estiarte et al., 2016; Knapp et al., 2016). In contrast, the response of ANPP to experimentally increased extreme PT and to experimentally impose extreme drought shown a nonlinear relationship (Wilcox et al., 2016), which predicts ANPP responses to PT will saturate in extreme wet conditions (Flombaum et al., 2017). However, these extreme precipitation events were episodically distributed to the entire experimental periods, the effect of extreme precipitation events with long-duration period on ANPP remains still unknown, despite the occurrence of EPEs becomes more frequent in the future.

In arid and semiarid grasslands, net ecosystem CO_2 exchange (NEE), the balance between ecosystem photosynthetic activity by plants (i.e. gross primary productivity, GPP) and ecosystem respiration (Re), is also closely related to the intensity and timing of precipitation (Hao et al., 2010; Huxman et al., 2004b). It was similar with ANPP, CO_2 exchange is also controlled by variation in water availability. However, the value and direction of change of CO_2 exchange would be determined by the discrepant sensitivity of GPP and RE to the variation in PT (Li et al., 2016, 2017). Generally, the increased precipitation may cause a great degree of augment of GPP than Re, ecosystem will become net carbon uptake (Guo et al., 2016). Furthermore, the period of net carbon uptake following precipitation events increases with the size of the precipitation events (Chen et al., 2009). In contrast, if the precipitation event is too large, excess water in the soil reduces root respiration (Amthor, 2000; Blom and Voesenek, 1996) and limits gas exchange at the leaf level by inducing stomatal closure (Chen et al., 2005; Fernandez, 2006). Therefore, it was necessary to understand that how the variation in patterns of precipitation, especially extreme precipitation event, affect carbon exchange of ecosystems in the context of extreme climate events. Unfortunately, there has been little research into how EPEs impact CO_2 exchange at the ecosystem level (Jentsch, 2006). In addition to the size of the precipitation events, it is becoming increasingly clear that the ecosystem C exchange can be greatly affected by precipitation seasonality (Chou et al., 2008; Hao et al., 2010; Peng et al., 2013). The impact of an extreme event also depends on its occurrence timing, in relation to the sensitivity of plant during its growth stage. Yet, the effects of the altered distribution of EPEs on ecosystem CO_2 fluxes remain largely unknown.

Located in arid and semiarid regions, the temperate steppe in northern China is a representative component of the Eurasian steppes. The ecosystem C cycling of this steppe has been proved to be highly sensitive to precipitation variation, varying from sizes of individual rainfall pulses to precipitation amount, seasonality and frequency (Niu et al., 2008; Chen et al., 2009; Hao et al., 2013; Peng et al., 2013; Li et al., 2017). However, little research has focused on discrete EPEs based on realistic extremes. As precipitation data in these regions show an increasing trend of extreme precipitation events during past 50-year, which have been delivering an increasing proportion of precipitation (Liu et al., 2005; Fu et al., 2013), direct experimental evidence on the response of ecosystem C exchange to EPEs is urgently needed.

We conducted a 3-year field experiment of extreme precipitation events to investigate the potential influence of EPEs on ANPP and ecosystem carbon fluxes during two plant growth stages in a semiarid temperate steppe in Inner Mongolia, China. The specific objectives of this study were to address the following two questions: (1) how ANPP respond to the temporal distribution of EPEs; (2) how the EPEs and their temporal distribution affect ecosystem CO_2 exchange?

2. Materials and methods

2.1. Site description

The study was undertaken at the Inner Mongolia Grassland Ecosystem Research Station in the Xilin River watershed, a semi-arid area located in Inner Mongolia (43°32′N, 116°40′E, 1200 m a.s.l.), China. The study site has been fenced off since 1979 and is located on a smooth wide plain with low hills. Mean annual temperature was −0.48 °C, varying from −21 °C in January to 18 °C in July. Long-term mean annual precipitation was 318 mm, 89% of which concentrated from May to September (Hao et al., 2012). The growing season usually lasted for 150-180 days from May to September, and the biomass reached its peak in late August. The soil type was classified as dark chestnut (Mollisol) with a depth of 100–150 cm. The soil texture was 21% clay, 60% sand and 19% silt on average. Bulk density was 1.32 g cm^{-3}, average soil pH was about 7.56, and field capacity was 25%. There were 86 plant species at this site, with the xeric rhizomatous grass *Leymus chinensis* as the dominant species. Other common species included *Agropyron cristatum*, *Cleistogenes squarrosa* and *Carex duriuscula*.

2.2. Experimental design

We studied the effects of simulated extreme precipitation on ANPP and CO_2 fluxes in different periods of growing season. Long-term daily precipitation data were obtained from the climate database of a local meteorological station (XilinGol League Meteorological Administration) for 1953–2010 (longest available historical data). In our study, only ecologically effective precipitation (daily precipitation >3 mm) was included in the analyses (Hao et al., 2012). A statistical extreme precipitation event was defined as a total of 282 mm precipitation over 20 days (14.1 mm day^{-1}) in the growing season. During the growing seasons of 2012, 2013 and 2014, we conducted a random block design experiment with four replicates to simulate extreme precipitation events, which was applied during two separate periods: the mid-season (17 June– 6 July, Pm) and the late-season (20 August–8 September, Ps). Ambient condition plots without treatment were used as controls. Each plot was 2.0 m × 2.0 m and all data were collected from the central square meter of each plot to avoid edge effects. Soil water content (SWC) at 5 cm and 20 cm depth was monitored weekly using a time domain reflectrometry (Model TDR300, Spectrum Technologies, Inc., USA).

During the treatment periods, steel framed rainout shelters (3 m × 3 m) were constructed and covered with clear 0.8 mm thick fiberglass reinforced polyester roofs (90% light transmission) to prevent natural rainfall The shelter was designed with a dual span (2.1 m and 1.8 m maximum and minimum heights, respectively) and the sides were kept open to minimize greenhouse effects. The results showed that there were no significant differences in measured temperature (HMP45C temperature probe, VAISALA, Woburn, MA, USA) and photosynthetic active radiation (PAR) (LI-190SB quantum sensor, LI-COR, Lincoln, NE, USA) between inside and outside the rainout shelters (unpublished data). Each plot was surrounded by metal flashing that extended 40 cm below and 10 cm above the ground surface to prevent root and rhizome penetration, and water flow into or out of the plot. The shelters were removed after the finish of treatment to assure winter precipitation (predominantly snow) was not affected in our plots.

2.3. Aboveground net primary productivity (ANPP)

Aboveground net primary productivity was estimated from the dry biomass of the aboveground living parts. Samples were taken at the end of each experimental year (first week in September)

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