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Heavy mowing enhances the effects of heat waves on grassland carbon and water fluxes

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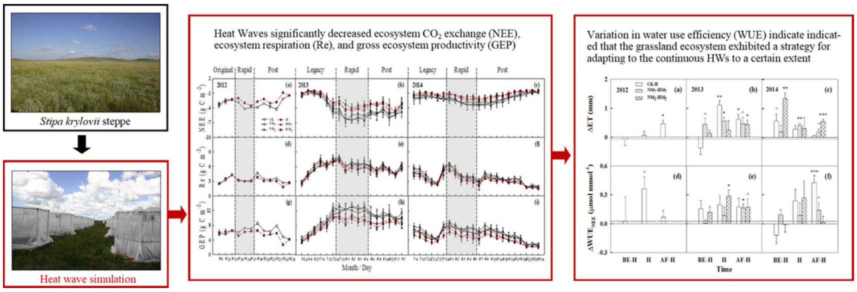
HIGHLIGHTS

- Heat waves (HWs) significantly decreased grassland NEE, Re, and GEP.
- The rapid, post, and legacy effects of HWs were defined and quantified.
- Continuous HWs over multiple years produced cumulative effects on reducing grassland NEE.
- Mowing increased the effects of HWs by extending the legacy effect.

GRAPHICAL ABSTRACT



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ABSTRACT

Heat waves (HWs) are a type of extreme weather event that is of growing concern in the scientific community. Yet field data based on sound experiment on the variation of ecosystem CO_2 levels under HWs remain rare. Additionally, ecosystems react to HWs and the coupled human activities (such as grazing in grasslands) are unknown. Thus, a 3-year field experiment was conducted to simulate HWs in conjunction with different mowing intensities that mimicking grazing in a *Stipa krylovii* steppe on the Mongolian Plateau. HWs significantly decreased ecosystem exchange (NEE) of CO_2, ecosystem respiration (Re) and gross ecosystem productivity (GEP) by 31%, 5% and 16%, respectively, over the three years. Continuous HWs over multiple years produced cumulative effects by reducing NEE at 20%, 34% and 40% in the first, second and third HW years, respectively. During three pre-defined three periods of HWs (during HW period, after HW period in the same year, and after HW period in the next year), variations in water use efficiency indicated that the grassland ecosystem exhibited a strategy for adapting to the continuous HWs to a certain extent, by adjusting community structure or increasing litter biomass. Finally, mowing increased the effects of HWs by extending the legacy effect, such that restoration of the grassland required a greater amount of time under the combination of HWs and mowing.

1. Introduction

Heat waves (HWs) represent a typical extreme weather event and are of growing concern in the scientific community because the sudden increase in temperature associated with HWs can cause ecosystem functions to shift dramatically and rapidly (De Boeck et al., 2010; Meehl and Tebaldi, 2004). The frequency and intensity of HWs have increased significantly, affecting >73% of the global terrestrial area since the mid-20th century (IPCC, 2013; Perkins-Kirkpatrick et al., 2016). Over the long term, extreme weather events such as HWs can act as important drivers of species evolution because they may lead to the

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elimination of individuals that are not suited for the environment (Gutschick and BassiriRad, 2003; Li et al., 2017; Zinta et al., 2014).

The sudden high temperatures associated with HWs have a greater impact on plants than gradual temperature increases (Sanz-Lázaro, 2016; Xia et al., 2009). Recent studies showed that HWs can significantly alter plant photosynthesis and respiration (Ameye et al., 2012) as well as aboveground and belowground biomass accumulation (Qu et al., 2016), reduce CO_2 sequestration strength (Tatarinov et al., 2016), and alter the reallocation of CO_2 and nitrogen within an ecosystem (Li et al., 2017). High temperatures also up-regulate leaf-cooling transpiration, resulting in excessive heat damage and greater evapotranspiration (ET), which may lead to the occurrence of drought (Duan et al., 2016). Previous studies have to some extent revealed the degree of the hazardous effects caused by HWs in ecosystems and the possible underlying mechanisms, but the results appear inconsistent and unilateral (Tatarinov et al., 2016). In most HW studies, the degree of the effects of HWs on the CO_2 flux has been examined at an interannual scale (Ciais et al., 2005; Lei et al., 2015; Qu et al., 2016; Reichstein et al., 2007). Because thermal and hydrological conditions vary both seasonally and annually, HWs with similar intensities may produce very different effects on ecosystems, as hydrological and thermal conditions and plant growth status differ over time, suggesting that the impacts of HWs can on the ecosystem CO_2 flux be easily overestimated or underestimated (Reichstein et al., 2007). Unfortunately, previous studies addressing HWs have been based on laboratory tests and have involved different definitions of HWs compared with naturally occurring HW events (Ameye et al., 2012; Bauweraerts et al., 2013; De Boeck et al., 2011). Furthermore, most of these previous studies were conducted on single plants, rather than entire ecosystem. Within a community, however, plants may reduce the impact of HWs through interactions among microorganisms or plants by adjusting the composition and structure of these organisms (Jentsch et al., 2007). Additionally, most HW experiments focus on a single HW event, and even though multiple HW simulation experiments can be conducted in a period no longer than a single growing season, there is a lack of long-term observational experiments (Fitzgerald et al., 2016; Sanz-Lázaro, 2016).

Grassland ecosystems, which account for approximately 40% of the global land surface area (Imer et al., 2013; Jmo and Hall, 1998), play an essential role in global CO_2 cycling. For example, grassland soils hold large quantities of organic CO_2 and store approximately 28%–37% of global soil organic carbon (Lal, 2004). Grassland ecosystems are also more vulnerable to climate change than forest and cropland ecosystems (Reichstein et al., 2007; Imer et al., 2013). Unfortunately, reliable evidence regarding how grassland ecosystem CO_2 and water fluxes respond to HWs remains rare. Land-use change is another important factor that may fundamentally alter ecosystem CO_2 exchange and its response to climate change (Chen et al., 2015). For example, mowing and grazing are among the most prevalent land uses in global grassland landscapes (Shao et al., 2013) and have great potential to alter CO_2 fluxes and energy budgets by changing photosynthetic activity and stimulating compensatory growth (Han et al., 2014; Niu et al., 2013). Despite its importance, our knowledge of how grassland ecosystems respond to HWs in the face of these human disturbances based on sound experiments remains very limited.

A 3-year field experiment was conducted in this study to simulate HWs in conjunction with different mowing regimes to mimic human disturbance in a grassland ecosystem. Our study objectives were to: (1) quantify the independent and interactive contributions of multiple HWs and mowing treatments to net ecosystem CO_2 exchange (NEE), ecosystem respiration (Re) and gross ecosystem productivity (GEP); (2) explore the potential legacy effects of HWs under different mowing treatments; and (3) quantify the interactive effects of HWs and mowing on CO_2 and water fluxes and plant growth. We speculate that previous studies may have overvalued the effects of HWs on ecosystem CO_2 and water fluxes by neglecting the fact that ecosystem resistance and resilience to the HWs may be higher than individual plants. Additionally, we hypothesize that mowing may alleviate the effects of HWs because this activity could change the species composition and structure, which in turn will enhance the adaptability of the community through stimulating compensatory growth (e.g., more suitable to the hot and drought conditions).

2. Materials and methods

2.1. Study site

Our manipulative experiment was conducted in a semi-arid area in Duolun County (42°02′ N, 116°17′ E), Inner Mongolia, China. Mean annual precipitation is 385 mm in the region, while the average annual temperature is 2.1 °C, and the monthly mean temperatures ranges from −17.5 °C in January to 18.9 °C in July. The soils are classified as chestnut soils in the Chinese classification or Haplic Calcisols based on the FAO classification, containing 62.75 ± 0.04% sand, 20.30 ± 0.01% silt, and 16.95 ± 0.01% clay. The mean bulk density of the soils is 1.31 g cm^{-3}, and the pH is 7.12 ± 0.07. The plant community is dominated by perennial species, including *Stipa krylovii* Roshev, *Artemisia frigida* Willd., *Potentilla acaulis* L., *Cleistogenes squarrosa* (Trin.) Keng, *Allium bidentatum* Fisch. ex Prokh., and *Agropyron cristatum* (L.) Gaertn. The study site has been fenced to exclude grazing since 2001 (Shao et al., 2014). The 50-year historical records of nearby climatic data (1967–2016) from Duolun (Station#: 54208, 42°41′ N, 116°28′ E, 1245.4 m a.s.l.) were obtained from the China meteorological data-sharing service system (http://cdc.cma.gov.cn/) to determine the length and timing of HW treatment (Qu et al., 2016).

2.2. Experimental design

A full factorial experiment was designed with two factors: HW and mowing. The HW treatment included two levels: HW (H) or no HW (N). The mowing treatment included three levels: no mowing, light mowing (7 cm stubble, M_7) and heavy mowing (2 cm stubble, M_2). This experiment therefore yielded six treatments: CK (no heat + no mowing), H (heat + no mowing), NM_7 (no heat + 7 cm stubble), NM_2 (no heat + 2 cm stubble), HM_7 (heat + 7 cm stubble) and HM_2 (heat + 2 cm stubble). Each treatment was performed in four replicates, yielding a total of 24 plots (2 m × 2 m). We randomly allocated the treatments among the plots, which were laid out in total area of 308 m^2, with a 2-m buffer zone established between any two neighboring plots.

2.3. Heat wave treatment

Open-top chambers (OTCs) with a heater inside were constructed to simulate the effects of HWs (Fig. 1). The OTCs were octagonal in shape, with a diameter of 2.0 m and a height of 1.5 m, and were constructed using 6-inch steel tubes. During the HW treatment, the OTCs were covered with transparent PVC film. The light transmittance of the film was >90% based on measurements of photosynthetically active radiation (PAR) inside and outside the covered OCTs. A heater (20 cm × 15 cm × 15 cm) was hung inside each OTC at a height of 1.5 m and was powered at 3500 W. The OTCs were left open during the 5:00–6:00 h daily so that the internal and external environments of the OCTs remained consistent. Non-heated plots were also covered with a similar chamber to ensure comparable conditions.

According to the historical climate data for Duolun County, HWs usually occur in summers (Qu et al., 2016). Therefore, we started our heat simulation experiment during the same period. Dry sunny days were selected as heating periods following the natural occurrence of HWs. The experimental periods, intensity and duration of the simulated HWs also followed the changes in local historical conditions. The canopy temperature was increased by ~6–10 °C during the day and by ~4 °C at night. The HW treatments were carried out during three different