Environmental Research 144 (2016) 39–48

Contents lists available at ScienceDirect

Environmental Research

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

Heat waves reduce ecosystem carbon sink strength in a Eurasian meadow steppe

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ARTICLE INFO

Article history:
Received 7 May 2015
Received in revised form
25 August 2015
Accepted 4 September 2015
Available online 29 September 2015

Keywords:
Extreme climate
Global change
Eddy covariance
Grassland
Carbon flux
Temperature

ABSTRACT

Background: As a consequence of global change, intensity and frequency of extreme events such as heat waves (HW) have been increasing worldwide.
Methods: By using a combination of continuous 60-year meteorological and 6-year tower-based carbon dioxide (CO_2) flux measurements, we constructed a clear picture of a HWs effect on the dynamics of carbon, water, and vegetation on the Eurasian Songnen meadow steppe.
Results: The number of HWs in the Songnen meadow steppe began increasing since the 1980s and the rate of occurrence has advanced since the 2010s to higher than ever before. HWs can reduce the grassland carbon flux, while net ecosystem carbon exchange (NEE) will regularly fluctuate for 4–5 days during the HW before decreasing. However, ecosystem respiration (Re) and gross ecosystem production (GEP) decline from the beginning of the HW until the end, where Re and GEP will decrease 30% and 50%, respectively. When HWs last five days, water-use efficiency (WUE) will decrease by 26%, soil water content (SWC) by 30% and soil water potential (SWP) will increase by 38%. In addition, the soil temperature will still remain high after the HW although the air temperature will recover to its previous state.
Conclusions: HWs, as an extreme weather event, have increased during the last two decades in the Songnen meadow steppe. HWs will reduce the carbon flux of the steppe and will cause a sustained impact. Drought may be the main reason why HWs decrease carbon flux. At the later stages of or after a HW, the ecosystem usually lacks water and the soil becomes so hot and dry that it prevents roots from absorbing enough water to maintain their metabolism. This is the main reason why this grassland carbon exchange decreases during and after HWs.

1. Introduction

An increasing number of studies have shown that human activities and climate change have regulated ecosystems simultaneously, with human disturbances producing much stronger impacts than climate change (Chen et al., 2015a, 2015b). The fifth report of IPCC (2013) confirmed human activities contribute to extreme climate, such as heat waves (HWs) (Stocker et al., 2013). Compared to global warming, HWs have always done more damage to human societies and natural ecosystems, counteracting the global ecosystem and leading to more drastic climate changes (Ameye et al., 2012; Bauweraerts et al., 2013; Schubert et al., 2014). Therefore, HWs can be treated as a beginning of an ecosystem's vicious cycle. When we study this cycle, it is important to determine the impact of HWs on ecosystems.

The intensity and frequency of extreme climatic events such as HWs are increasing worldwide (Meehl and Tebaldi, 2004; Stocker et al., 2013). HWs are characterized by rapid heating for several days, having a much stronger influence on plants than gradual warming (Bauweraerts et al., 2013; Ciais et al., 2005; De Boeck et al., 2011; Meehl and Tebaldi, 2004). Unlike chronic warming,

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http://dx.doi.org/10.1016/j.envres.2015.09.004
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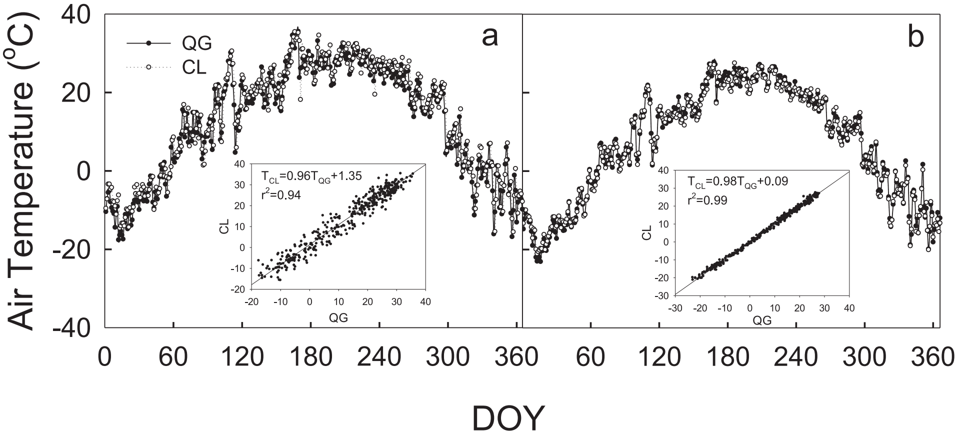

Fig. 1. Comparison of air temperature between Qianguo (QG) and Changling (CL) in a Eurasian meadow steppe in 2008. a, Daily maximum air temperature, and b, Daily mean air temperature at 2 m aboveground.

HWs may place plants beyond their acclimated range, requiring emergency physiological responses in order to avoid sudden death (Ameye et al., 2012; De Boeck et al., 2010; Tóth et al., 2011).

Studies on the effects of natural HWs on ecosystem functions and humans are challenging because the timing and magnitudes of HWs are unpredictable (e.g., Barnett et al., 2012; Schubert et al., 2014; Smith et al., 2013; Trenberth and Fasullo, 2012). Recent studies have been mostly based on simulated HWs (e.g., Ameye et al., 2012; Bauweraerts et al., 2013; De Boeck et al., 2011; Sentis et al., 2013) and focused on particular meteorological factors such as rapid warming, high air temperature, and drought. However, most elevated temperature studies applied a sustained high air temperature that differs from natural HWs (Ballester et al., 2010). In addition, the length of simulated HWs in these experiments varied among studies, ranging from 8 h (White et al., 2000), 7 days (Ameye et al., 2012), 7 days per month (Bauweraerts et al., 2013), to 10 days (De Boeck et al., 2011). These simulated HWs differed by ecosystem type and study objectives.

Previous studies have focused on how heat stress affects the physiology of individual plant or species, with few addressing the responses of the plant community as a whole. Plant communities are more complex than individual species. For example, a species-rich community may change its tolerance against the extreme climate change (Morison and Lawlor, 1999; Xu and Huang, 2000). Reichstein et al. (2007) reported that the European HWs reduced the net ecosystem exchange of carbon flux (NEE) at nine out of 14 stations, including 12 forests, one shrub and one grassland, primarily due to water stress rather than high temperature. They showed that grasslands are more vulnerable to extremes than other ecosystems. In another two-factorial experiment (i.e., investigating heat and drought), De Boeck et al. (2011) demonstrated that the interaction of heat and drought produced significantly greater effects than the independent factor. However, there remains a substantial lack of knowledge on how HWs affect carbon and water fluxes in natural ecosystems (Jentsch et al., 2007).

Here, we used a continuous 6-year dataset from an eddy-covariance (EC) tower and 60 years of meteorological data to analyze the effect of HWs on the dynamics of carbon, water, and vegetation on a Songnen meadow steppe. We hypothesize that HWs can affect carbon fluxes, but that they vary with the microclimatic conditions. The objective of this study was to answer three questions: (1) During HW events, what types of microclimatic characteristic changes would occur and to what degree? (2) How long must an HW last to affect grassland carbon exchange, and how large will the effect be? (3) If there are HW effects, how do they influence carbon flux and its variation over time?

2. Materials and methods

2.1. Study site

The study was conducted at the Songnen Grassland Ecology Field Station of the Northeast Normal University (NENU), in Changling (CL), Jilin Province, China (123°30′E, 44°35′N, 171 ma s l). The Songnen meadow steppe is located in transitional zone. The climatic data were obtained from the China meteorological data-sharing service system (http://cdc.cma.gov.cn/). We selected the data of Qianguo'erluosi (QG), which is the site nearest to the flux tower (Station number: 50949, 124°52′E, 45°05′N, 135.9 ma s l); both sites are situated in the southern Songnen Plain. This area has a temperate, semi-arid continental climate; characterized as cold with dry springs and warm, wet summers. Our study site is classified as a temperate meadow steppe and is dominated by perennial grasses of *Leymus chinensis* and *Phragmitis communis*. *L. chinensis* represents 80–90% of the total grassland biomass. The total vegetation cover is $>80\%$. *L. chinensis* is the most dominant species, with a density of 917 plants/m$^{2\cdot}$ The soil type is alkali-saline, with a pH of 9.6 and an organic matter content of 1.5%.

We compared the 2008 air temperature between CL and QG (Fig. 1) via linear regression. The correlation coefficient of determination (r^2) of the daily maximum air temperature was 0.94, and the r^2 of the daily mean temperature was 1.00. The maximum and mean temperatures of the two locations were not significantly different, with similar inter-annual variations of air temperature. Given the strong similarities in temperature between the two locations, we used the QG temperatures to estimate the long-term series of HWs from CL.

2.2. Flux and meteorological measurements

An open-path eddy covariance (EC) flux measurement tower was deployed in 2007 for a long-term monitoring project to measure CO_2, water vapor, energy, and meteorological variables. The fetch of the EC system exceeded 500×500 m^2. A footprint analysis using the flux source area model (Schmid, 1997) suggested a footprint in the prevalent wind direction (150–240°) extending approximately 6.5–77.8 m during unstable conditions (Monin-Obukhov length $L < 0$) and approximately 11.3–229.9 m