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Grassland productivity and carbon sequestration in Mongolian grasslands: The underlying mechanisms and nomadic implications

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ABSTRACT

Background: Quantifying carbon (*C*) dioxide exchanges between ecosystems and the atmosphere and the underlying mechanism of biophysical regulations under similar environmental conditions is critical for an accurate understanding of *C* budgets and ecosystem functions.

Methods: For the first time, a cluster of four eddy covariance towers were set up to answer how *C* fluxes shift among four dominant ecosystems in Mongolia – meadow steppe (MDW), typical steppe (TPL), dry typical steppe (DRT) and shrubland (SHB) during two growing seasons (2014 and 2015).

Results: Large variations were observed for the annual net ecosystem exchange (NEE) from 59 to 193 g C m^{-2}, though all four sites acted as a *C* source. During the two growing seasons, MDW acted as a *C* sink, TPL and DRT were *C* neutral, while SHB acted as a *C* source. MDW to SHB and TPL conversions resulted in a 2.6- and 2.2-fold increase in *C* release, respectively, whereas the TPL to SHB conversion resulted in a 1.1-fold increase at the annual scale. *C* assimilation was higher at MDW than those at the other three ecosystems due to its greater *C* assimilation ability and longer *C* assimilation times during the day and growing period. On the other hand, *C* release was highest at SHB due to significantly lower photosynthetic production and relatively higher ecosystem respiration (ER). A stepwise multiple regression analysis showed that the seasonal variations in NEE, ER and gross ecosystem production (GEP) were controlled by air temperature at MDW, while they were controlled mainly by soil moisture at TPL, DRT and SHB. When air temperature increased, the NEE at MDW and TPL changed more dramatically than at DRT and SHB, suggesting not only a stronger *C* release ability but also a higher temperature sensitivity at MDW and TPL.

Conclusions: The ongoing and predicted global changes in Mongolia likely impact the *C* exchange at MDW and TPL more than at DRT and SHB in Mongolia. Our results suggest that, with increasing drought and vegetation type succession, a clear trend for greater CO_2 emissions may result in further global warming in the future. This study implies that diverse grassland ecosystems will respond differently to climate change in the future and can be seen as nature-based solutions (NBS) supporting climate change adaptation and mitigation strategies.

1. Introduction

Promoted by the European Union (EU), the concept of nature-based solutions (NBS) is becoming the dominant school of thought in planning and managing socioecological systems (SES) toward sustainability (European Commission, 2010; Maes and Jacobs, 2015). It advances conventional ecosystem management by focusing on society and human wellbeing. Eggermont et al. (2015) stated that NBS "refer to the sustainable management and use of nature for tackling societal challenges". While the primary target of the EU's mission was human-dominated systems (e.g., urban areas, European Commission, 2010), the NBS concept seems readily applicable for rural ecosystems. One of the best examples are the dryland regions, where herders are highly dependent on nature for their nomadic practices to sustain the livestock

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(Dangal et al., 2016; John et al., 2016), which in turn determines the stability of the herders' societal and individual wellbeing. Herders migrate with their livestock across the landscape based on grassland quantity (e.g., cover type and area) and quality (e.g., productivity). From a scientific perspective, a mechanistic understanding and accurate prediction of productivity in dominant grasslands would be a first step in assisting with the herders' management activities (Dangal et al., 2016). Unfortunately, our current capability in predicting the spatiotemporal changes of grasslands on drylands lag significantly behind other biomes (e.g., forests), and are mostly based on model predictions and/or remote sensing products (Yuan et al., 2007; Hilker et al., 2014; Zhang et al., 2014; Dangal et al., 2016). For example, in situ direct measurements of gross ecosystem productivity (GEP) using flux towers in drylands remain scarce across the globe (Kato and Tang, 2008; Li et al., 2013; Xiao et al., 2013; Ahlström et al., 2015), regardless of their high sensitivity to the changing climate and human disturbances (Chen et al., 2013).

Vast grasslands account for ~ 60% of the Mongolian Plateau, with a total area of ~1.56 million km^2; however, approximately 3 million people live there. Because Mongolia is land locked, there exists a much tighter relationship between its people and nature. This is especially true for the nomadic herders who have traditionally roamed based on grassland productivity, water, etc. (Fernández-Giménez et al., 2012; Chen et al., 2015b). Intense human activities and rapid change in climate over recent decades have produced serious ecological (IPCC, 2014; Liu et al., 2014; Shao et al., 2014; Shao et al., 2017) and socioeconomic (Groisman and Soja, 2009; Qi et al., 2012, 2017; Chen et al., 2015a) consequences at both local and regional scales, such as the higher-than-average global warming rate on the plateau (John et al., 2009; Lu et al., 2009), a decreased trend in summer precipitation and an increased trend in spatial variability (John et al., 2016), and increased livestock density (Chen et al., 2015b). Worse yet, the IPCC (2014) has predicted that this water-limited region will experience a warming trend that is higher than the global mean, which would further alter summer and winter precipitation patterns and increase the frequency of extreme climatic events (Qu et al., 2016). Scientists and policy makers are becoming increasingly interested in the spatiotemporal changes of grassland productivity and/or *C* sequestration strength (Xie et al., 2014; Abraha et al., 2016; Lafortezza and Chen, 2016; Luo and Wu, 2016). However, direct measurements of *C* sequestration in Mongolia have received little attention, with most literature based on model predictions (including remote sensing modeling). To our knowledge, literature reports only a one-year eddy covariance (EC) measurement (i.e., Li et al., 2005) for this vast landscape.

Spatiotemporal changes of the dominant vegetation types on the Mongolian Plateau (e.g., meadow, dry steppe, and shrubland) have occurred at quite an alarming rate and scale and are expected to significantly increase in upcoming decades (Lioubimtseva and Henebry, 2009; Chen et al., 2015b; Kelley et al., 2015), magnifying the challenges in predicting the spatiotemporal distribution of grassland productivity. For example, total grassland area increased from 33% in 2001 to 42% in 2009 (Chen et al., 2013). John et al. (2009) reported that the sparsely vegetated area increased by 151% from 1992 to 2004, resulting in significant changes in species distribution and vegetation productivity. Our recent analyses based on MCD12Q1 between 2001 and 2012 further confirmed a 77% increase in shrublands for the East Asian dryland (Chen et al., 2013). These changes in vegetation types and distributions would result in direct feedbacks to the regional climate, livestock management, and nomadic cavities on the plateau.

To address the above pressing issues in Mongolia and fill the data gaps, a field experiment was designed for the first time in which a cluster of four EC systems was deployed to directly quantify ecosystem productivity of the dominant ecosystems, including a meadow steppe (MDW), a typical steppe (TPL), a dry typical steppe (DRT), and a shrubland (SHB) (Table 1), so that future upscaling to the region will have a solid foundation. While our long term goal is to develop the capacity to predict grassland productivity for herders upon which they can schedule their nomadic activities, the specific objectives of this study were to: (1) explore the daily, monthly, and seasonal variations in *C* fluxes: GEP, ER and NEE (net ecosystem CO_2 exchange) of the four ecosystems; (2) quantify the biophysical regulations of GEP, ER and NEE within and among the four ecosystems; and (3) diagnose the effect of vegetation change on the GEP, ER and NEE. We hypothesized that GEP would be higher at MDW than at other grassland types because of greater NEE (i.e., more *C* assimilation or less *C* release) than ER. We also predicted that the MDW and TPL are more resistant, or less sensitive, to the changing climate than the DRT and SHB. Lessons learned from this study may provide the first palpable data for nomadic societies to use when developing future management strategies and tactics.

2. Materials and methods

2.1. Study area

The four sites are located in the Ulaanbaatar and TOV provinces of Mongolia (Fig. 1). The region lies in a temperate zone and has a distinct continental climate with an average annual air temperature and precipitation of 1.2 °C and 196 mm, respectively. The growing season from June through September is warm and relatively wet registering an annual precipitation of about 88%, while the remaining months (October-May) are cold and dry. Mean daily temperatures for January and July are −22.9 and 21.4 °C, respectively. Precipitation is quite irregular from one year to the next and shows strong seasonal variability. Frequent droughts are usually the limiting factor for plant growth in this region, which is also characterized by windy conditions. The longest distance among our four study sites is ~200 km between TPL and SHB.

MDW is a permafrost site dominated by *Leymus chinensis* meadow steppe. TPL is comprised of short-grass steppe with cool-season perennial C_3 grasses—*Stipa krylovii* and *Artemisia frigida* – as the dominant species. DRT is dominated by a perennial grass—*Achnatherum splendens*, a widely distributed cover type with overgrazing, while SHB is dominated by *Caragana stenophylla* shrub (Table 1). All four sites are flat with relatively homogenous vegetation, of which the dominant species contributes > 80% of the cover. The soil is classified as chestnut soil (FAO) with a sand loamy texture.

2.2. Flux and micrometeorological measurements

Four open-path EC systems, each consisting of an infrared gas analyzer (IRGA, LI-7500, LI-COR, Lincoln, NE) and a CSAT3 three-dimensional sonic anemometer (Campbell Scientific Inc. (CSI), Logan, UT), were deployed 2.0 m above ground to obtain NEE, latent heat (LE) and sensible heat (*H*) fluxes. The raw time series (TS) of three-dimensional wind velocities, sonic temperature, and CO_2 and H_2O concentrations were sampled at a 10 Hz frequency. The IRGA was calibrated before field setup and at the beginning of the growing season each year.

Micrometeorological measurements included photosynthetically active radiation (PAR) (LI-190, LI-COR), net radiation (R_n) (CNR4, Kipp & Zonen, Delft, Netherlands), relative humidity (RH) and air temperature (T_a) (HMP45C, CSI) 2.0 m above ground. Rainfall was measured with tipping bucket rain gauges (TE-525, CSI). Soil temperature (T_s) was measured at 0.05 and 0.10 m depths with eight CS107 probes (CSI). The top 0.30 m averaged volumetric soil water content (SWC) was measured using eight vertically inserted CS616 probes (CSI). Soil heat flux (*G*) was measured at twelve locations using heat flux plates (HFT3.1, CSI) placed 0.02 m below the ground surface. Instrument maintenance was performed biweekly, and the online-computed mean half-hourly scalar fluxes and micrometeorological

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