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The effects of grazing and watering on ecosystem CO_2 fluxes vary by community phenology

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A B S T R A C T

Grazing profoundly influences vegetation and the subsequent carbon fluxes in various ecosystems. However, little effort has been made to explore the underlying mechanisms for phenological changes and their consequences on carbon fluxes at ecosystem level, especially under the coupled influences of human disturbances and climate change. Here, a manipulative experiment (2012–2013) was conducted to examine both the independent and interactive effects of grazing and watering on carbon fluxes across phenological phases in a desert steppe. Grazing advanced or delayed phenological timing, leading to a shortened green-up phase (GrP: 23.60 days) in 2013 and browning phase (BrP: 12.48 days) in 2012 from high grazing, and insignificant effects on the reproductive phase (ReP) in either year. High grazing significantly enhance carbon uptake, while light grazing reduce carbon uptake in ReP. Watering only delayed the browning time by 5.01 days in 2013, producing no significant effects on any phenophase. Watering promoted the net ecosystem exchange (NEE), ecosystem respiration (ER), and gross ecosystem productivity (GEP) only in the GrP. When calculating the yearly differences in phenophases and the corresponding carbon fluxes, we found that an extended GrP greatly enhanced NEE, but a prolonged ReP distinctly reduced it. The extended GrP also significantly promote GEP. Increases in growing season length appeared promoting ER, regardless of any phenophase. Additionally, the shifts in NEE appeared dependent of the variations in leaf area index (LAI).

1. Introduction

Human activities as disturbance events are increasingly reported as important drivers for ecosystem composition, structure, and function across the Earth's surface. In addition to their direct alterations of land cover type and vegetation/soil properties (de Vries et al., 2012; Liu et al., 2013; Matthews et al., 2004), indirect influences on microclimate, plant phenology, ecosystem processes (e.g., carbon uptake and emission, evapotranspiration, nutrient cycling), and functions (e.g., productivity, ecosystem diversity) are also widely recognized (Min et al., 2011; Petraglia et al., 2014; Root et al., 2005; Syvitski et al., 2005). Among many key lessons on disturbance–ecosystem relationships, the long-lasting effects (Cuddington, 2011) and interactive effects with other drivers (e.g., climate change) are still not well understood. For example, the effects of a disturbance on ecosystem processes may depend on phenology (DeForest et al., 2006; Migliavacca et al., 2015; Richardson et al., 2012), and these effects may also be coupled by the changes in climate and other natural disturbances. With an interest in plant phenology and ecosystem processes, we conducted a literature search with different sets of keywords via the Web of Science, revealing that human disturbance research (e.g., nutrient addition, land use change, grazing and heat island) had become growing concern in phenology (Fig. 1).

In the semiarid and arid regions of the Eurasian continent, grazing and water stress are among the most important drivers on ecosystem functions and dynamics (Chen et al., 2014; Hao et al., 2014; Pennington and Collins, 2007; Shao et al., 2013). For plant phenology, water is a critical agent in advancing the green-up timing (Shen et al., 2011), flowering (Crimmins et al., 2011; Prieto et al., 2008), and senescence (Han et al., 2015). However, water is not the sole limiting factor for phenological changes during the growing season (Ji and Peters, 2003); temperature and other climatic conditions can produce independent or interactive effects on

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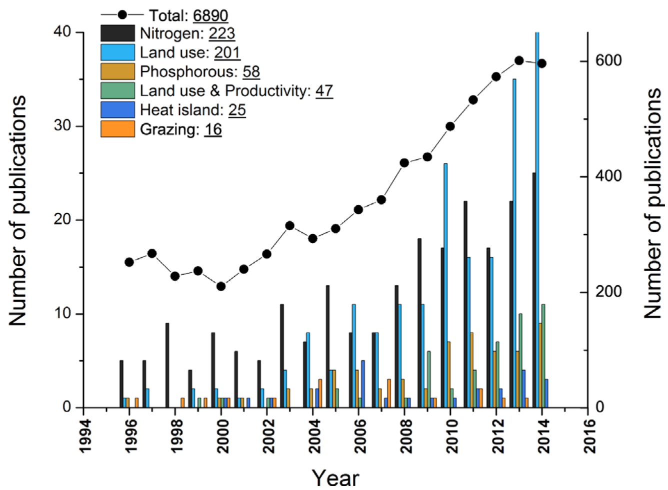

Fig. 1. Summary of publications (1996–2014) on the effects of human disturbances on plant phenology. The literature search was conducted by using the following keywords in "Web of Science (ISI)". Total: Title="phenolog*" OR "length of growing season" OR "flowering date" in Ecology related fields. Each human disturbance, such as "grazing" was run as Title=(phenolog* OR length of growing season OR flowering date) and Topic=(grazing), respectively. The underlined values are the number of publications. The left and right axes show the number of publication by year and in total, respectively.

phenological changes as well (Llorens and Penuelas, 2005). More importantly, grazing—the most dominant land-use practice in Eurasian pastoral lands—exerts substantial and extensive influences on phenology. It directly alters vegetation and soil properties that modify the microclimate (Yates et al., 2000). It also influences phenology indirectly due to altered biogeochemistry processes (Bremer et al., 2001), species composition and richness (Socher et al., 2013), forage quality (Rossignol et al., 2011), and interspecific competition (Medina-Roldan et al., 2012). Using green-up timing as an example, grazing via defoliation in the early growing season will yield a reduced litter layer, which is partially responsible for the increase in energy absorbed by the soil during the daytime (i.e., soil temperatures elevating in daytime; Van der Wal et al., 2001; Shao et al., 2014), and will thereby advance the green-up time. Similarly, a reduced litter layer would elevate water loss through soil evaporation (Miao et al., 2009), and possibly delaying the green-up time. While it is clear that these biotic and abiotic changes can directly or indirectly influence ecosystem processes such as carbon fluxes, phenology appears to be an integrative indicator in understanding the casual relationships between drivers and ecosystem processes. Here, we placed our focus on the variation of these biophysical regulations in different phenophases through a manipulative experiment of grazing and watering.

Scientific investigations on the roles of plant phenology in ecosystem functions, especially on productivity or carbon fluxes, have received increasing attention in recent years. For example, the length of a CO_2 uptake period or of a growing season (GSL) is suggested to have significant direct effects on vegetation dynamics, carbon gains and losses (Chen et al., 2014; Oberbauer et al., 1998; Piao et al., 2007; Richardson et al., 2009; Xia et al., 2015), and evapotranspiration (Liu et al., 2014). Both ground-based experimental and modeling approaches have been extensively used in these studies. Field observations tend to focus on *in situ* phenological timing or on reproductive successes at species level (Fitter and Fitter, 2002), while remote sensing modeling is more advantageous by delineating the beginning/ending of a growing season by tracking vegetation quantities (e.g., NDVI) at broader spatial scales (Fisher and Mustard, 2007). In comparison, little effort has been placed on understanding the mechanisms through controlled experiments at community level. This limits our understanding of the role of phenology in regulating the magnitude and dynamics of ecosystem processes such as CO_2 fluxes (Migliavacca et al., 2015).

In this study, we propose a "co-flowering ratio" method to connect phenology observations and ecosystem carbon fluxes by scaling the phenology from species to community level. These phenological measures then were related to the ecosystem carbon fluxes of a manipulative experiment. This method was not designed to better integrate phenological traits from species to community, rather it is designed as a simple approach for quantifying "community phenology" from species records, in hope that it can be widely applied in phenology-carbon fluxes research.

A two-year manipulative experiment in a Eurasian steppe was conducted to examine the independent and interactive effects of grazing and watering on CO_2 fluxes by phenophases. We address two fundamental questions: (i) How do grazing and watering affect phenological timing and duration both independently and interactively? (ii) Do the grazing- and watering-induced phenological shifts yield corresponding changes in CO_2 fluxes?

2. Materials and methods

2.1. Study area and the experiment

Our experiment was conducted in a desert steppe in Inner Mongolia (41°47′N, 111°53′E, 1450 m a.s.l.) during 2012–2013. This region has a temperate continental climate, with a mean temperature of 14.37 °C and 16.38 °C in the growing season of 2012 and 2013, respectively. The average annual precipitation was 230 mm in the past 10 years, while it was 360 mm and 236 mm in 2012 and 2013, respectively. In our reference plot, there were similar, lower, higher, and almost similar soil volumetric water (VWC) in 2012 (7.1%, 10.8%, 17.9%, 9.4%) than those in 2013 (7.9%, 13.2%, 14.5%, 9.7%) at a depth of 10 cm before the growing season, in greening up, reproductive, and browning phase, respectively.

A randomized block experiment with three grazing levels (CK, zero; LG, 0.93 sheep half year^{-1} ha^{-1}; and HG, 2.71 sheep half year^{-1} ha^{-1}), with three replications for each treatment, was installed since 2003 (Han et al., 2014). Base on this experiment, a nested design was applied with watering treatment embedded in this grazing platform (i.e., 12 blocks) in order to test the effects of grazing and watering treatment on CO_2 fluxes within different phenological phases during 2012–2013. Thus, prior to the growing season of 2012, we enclosed each block within an area of 9×9 m^2 to avoid grazing. In each enclosure, four 1×1 m^2 plots were randomly installed for fluxes measurements, four 1×2 m^2 plots for phenological observations, ten 1×1 m^2 plots for community characteristic measurements, including species height, cover, biomass, and leaf area index (LAI). Each block has an area of 4 ha. Half of the total sampling plots in each treatment were randomly partitioned to the watering treatments. A hand sprinkler was used to water amounts of 5 mm on a biweekly basis from March to August and amounts of 10 mm on a weekly basis from September to early October in both years, resulting in about 30% more precipitation than that of the 10-year average.

2.2. Vegetation sampling

Species cover, biomass, and LAI were collected monthly for each sampling plot. Aboveground vegetation was harvested by species in four quadrats (0.5×0.5 m^2) from each enclosure for the aboveground biomass (AGB) and green leaf area index (LAI). A frame with 100 grids was used for estimating the total cover of the dominant species.

Five individuals of each species, when available, in each