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Earlier leaf-flushing suppressed ecosystem productivity by draining soil water in the Mongolian Plateau

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ABSTRACT

Recent earlier greening trends are believed to enhance terrestrial ecosystem productivity. However, advanced onset of growing season may also deplete soil water in early spring, leading to summer water stress for plant growth. In this study, we linked soil moisture with start of growing season (SGS, represented by day of year) to examine the responses of ecosystem productivity to water stress during 1982–2011 on the Mongolian Plateau. Results showed that, though not significant, earlier SGS has tendency to enhance spring productivity at north part of the study area. Nonetheless, we observed that suppressed summer photosynthesis due to phenology-induced water stress dramatically reduced annual carbon assimilation. Thus, phenology-associated changes in soil moisture have profound potential in regulating seasonal and annual productivity in arid and semi-arid ecosystems. The relationship between SGS and GPP was not observed in more mesic forest ecosystems ($R^2 = 0.04, p > 0.10$) nor in the agricultural area ($R^2 = 0.03, p > 0.10$) where practices like irrigation aim to alleviate summer water stress. Therefore, at the scale of the entire study area, earlier growing season did not translate to higher productivity ($R^2 = 0.006$). On the contrary, advanced SGS aggravated growing-season water stress, which in turn, supressed annual carbon assimilation in water limited area. This mechanism implies the advanced greening trends may not necessarily lead to more carbon uptake in terrestrial ecosystems but rather a carbon loss, especially in the arid and semi-arid regions.

1. Introduction

Shifts in plant phenology (e.g. leaf flushing, leaf fall) are seen as fingerprints of climate change and reflect the dynamics of carbon (C) exchange between the biosphere and the atmosphere (Yu et al., 2013; Jentsch et al., 2009). Phenological shifts affect ecosystem processes and services, and mediate feedbacks of global ecosystems to the climate system (Richardson et al., 2010; Schwartz, 1992). Changes in phenological events may potentially affect ecosystem productivity (Lucht et al., 2002), alter global biogeochemical cycles, change the duration of the pollination season, and affect the distribution of diseases (Schwartz and Reiter, 2000; White et al., 1999; Menzel, 2000). Phenology also controls many feedbacks of vegetation to the climate system by influencing the seasonality of albedo, surface roughness length, and canopy conductance (Richardson et al., 2013).

The majority of previous phenology-associated studies have suggested that earlier onset of the growing season would lead to more carbon uptake due to a longer growing season (Black et al., 2000; Richardson et al., 2009; Dragoni et al., 2011). Indeed, this is more likely to occur in areas where temperature is the major limiting factor because increased primary productivity can be expected from the prolonged periods when carbon assimilation is possible. For example, previous studies indicated a positive relationship between growing season length and ecosystem productivity in forests (Black et al., 2000; Baldocchi and Wilson, 2001; Churkina et al., 2005; Barr et al., 2009; Richardson et al., 2010). Nevertheless, advanced onset of growing season may also utilize more soil water in early spring and result into an ecosystem more susceptible to drought in the following summer. For example, Hu et al. (2010) reported lower carbon uptake in years with longer growing season because earlier onset triggered by shallow snowpack led to soil water reduction and drought in the growing season in a subalpine forest. Moreover, since plants have more intensive photosynthesis activity in summer than in spring, the "extra" carbon sequestrated during the early season may be offset by the suppressed summer photosynthesis due to phenology-induced water stress (Angert et al., 2005).

Several site-level and regional scale studies have reported

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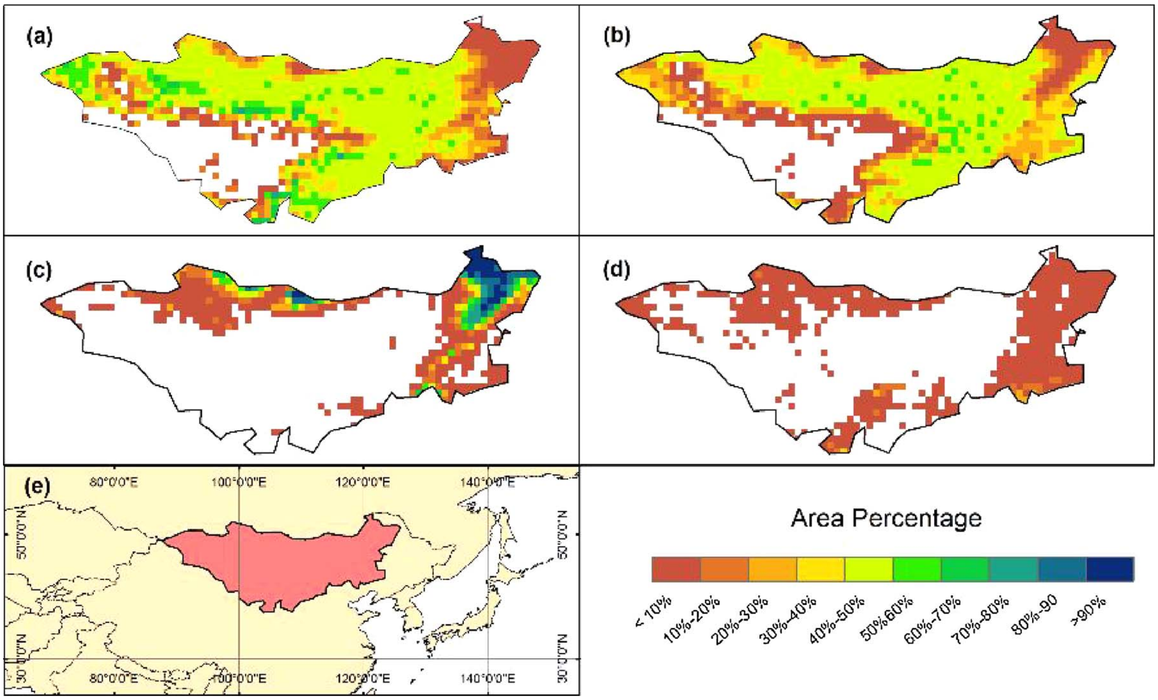

Fig. 1. Area percentage of different land cover types in the Mongolian Plateau. (a: shrubland; b: grassland; c: forestland; d: cropland; e: Mongolian Plateau boundary; Fig. a-d use the same legend.)

reductions in growing season productivity in years with shallow, snow melting-induced early springs in North America (Buermann et al., 2013; Trujillo et al., 2012). Similar studies are lacking from the Mongolian Plateau, which is covered by both agricultural and natural ecosystems with a distinct moisture gradient from humid east (forestland and cropland) to dry inland (grassland and shrubland). Both the agricultural and natural ecosystems provide numerous ecological, economic, and social benefits for the region (a combined region including the country of Mongolia and Inner Mongolia Autonomous Region of China, Fig. 1). For the country of Mongolia especially, nomadic pastoralism accounts for 80% of agricultural industry that provides the primary source of income for many Mongolians (Rao et al., 2015). Noticeably, increasing warming and associated water stress have posed great threats to these services in the region. A striking example is the 1999–2002 drought-related *dzuds* (a combination of severe winter climate condition that results in high mortality of livestock) in Mongolia (Rao et al., 2015), leading to the loss of about 10–20 million livestock and placing a massive strain on the human society including the migration of roughly 180,000 people to the capital city of Ulaanbaatar (Pederson et al., 2014; Sternberg, 2010). In comparison to extreme climatic events, a slow but consistent shift towards earlier spring in dry ecosystems may result in an ecosystem more vulnerable to soil water deficit in growing season caused by a lengthened evaporative period in spring (Buermann et al., 2013).

Thus, there are essential environmental and economic reasons to examine the phenology shift and its impacts on ecosystem services in the Mongolian Plateau. In this study, we used the GIMMS AVHRR Global NDVI datasets (NDVI3g), model tree ensemble (MTE, version May 12) product (Jung et al., 2011), and European Space Agency (ESA) soil moisture images, to detect the trends of ecosystem productivity and their relationships with phenology in Mongolian Plateau during the period of 1982–2011. This study aims to identify and quantify the phenological impacts on ecosystem productivity across different moisture gradients.

2. Materials and methods

2.1. Study area and data

This study focused on the arid-to-semi-arid ecosystems of the Mongolian Plateau that is covered by shrubland, grassland, forest, and cropland (Fig. 1). The land cover map used is Synergetic Land Cover Product (SYNMAP) obtained from ORNL DAAC at resolution of 0.5° × 0.5° (http://webmap.ornl.gov/). Shrubland and grassland coverages were high in the central area, while forest and cropland were sparsely distributed in the east and part of the north region (Fig. 1). The Gobi Desert, where annual rainfall is generally lower than 100 mm, makes up much of southwestern Mongolian Plateau (Yu et al., 2003). Shrubland and grassland distributed in the region with lower rainfall (267–286 mm yr^{-1}) and soil water content (~0.14 m^3/m^3), while forest and cropland distributed in cooler and wetter area with higher rainfall (295–334 mm yr^{-1}) and soil moisture (0.15–0.17 m^3/m^3, Fig. 2).

2.2. Phenology detection

A double-logistic approach was applied to smooth and reconstruct the NDVI time series dataset in Timesat software (v3.1) (Eklundh and Jönsson, 2012; Yu et al., 2013). The Mongolian biomes (e.g. grass, shrub) have distinct leaf-flush and leaf-fall phases, resulting in a characteristic change of photosynthetic intensity each year. At the ecosystem level, the trough-peak cycles of photosynthesis activity (i.e. phenology) are attributable to leaf physiology and fluctuations in water and radiation resources. Thus, the start of growing season at the ecosystem level refers to the initiation of the high-photosynthesis activity period in each year. In this study, spring season is the period from March to May, and summer is the period from June to August.

2.3. GPP, soil moisture, snow water, and aridity index data

Monthly gross primary productivity (GPP) data were obtained from Department of Biogeochemical Integration (BGI) of Max Planck