Precipitation as a control of vegetation phenology for temperate steppes in China

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ABSTRACT

Using the NDVI ratio method, the authors extracted phenological parameters from NOAA-AVHRR NDVI time-series data (1982–2008). The start of the growing season (SOS) and the date of maximum NDVI (Peak$t$) correlated significantly with the mean annual precipitation along regional gradients of the steppes. Along the south transect (located at a lower latitude with a higher annual mean temperature) there was a positive correlation between the end of the growing season (EOS) and the mean annual precipitation along precipitation gradients ($R^2 = 0.709, p < 0.0001$). However, along the north transect (located at higher latitude with lower annual mean temperature), the EOS was slightly negatively related with the mean annual precipitation ($R^2 = 0.179, p < 0.1$). There was positive correlation between the length of the growing season and the annual precipitation along two transects ($R^2 = 0.876, p < 0.0001$ for the south transect; $R^2 = 0.290, p < 0.01$ for the north transect). Thus, for the Inner Mongolian steppe, it is precipitation rather than temperature that determines the date of the SOS.

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1. Introduction

Climate change over the last several decades has substantially altered the arrival of biological spring and winter (Brown and de Beurs 2010). The changes in the annual cycles of plants and the lengthening of the growing season have had considerable influence on natural and social systems (Morisette et al. 2009). Moreover, shifts in vegetative phenology have, in turn, feed back to climate change through vegetation–atmosphere interactions (Finzi et al. 2011). Vegetative phenology, therefore, is an important dimension of ecological research for understanding future global change (Cong et al. 2012).

On regional and global scales, temperature and precipitation have been widely documented as major factors influencing vegetative phenology (Morisette et al. 2009). Previous research has focused on the effects of temperature on vegetative phenology, and temperature is widely considered to be a dominant control over phenology. However, more research is needed into the effects of other important factors on vegetative phenology, especially precipitation in arid and semi-arid regions (Cleland et al. 2006). So far, we have very limited understanding of the influence that complex environmental factors have on shifts in key vegetative phenological parameters. This limited understanding has hindered simulations and predictions of future changes in vegetative phenology (Richardson et al. 2012). As a result, spatial heterogeneity of shifting vegetation phenology and its key drivers are so far poorly understood.

Steppes in arid and semi-arid regions are more sensitive to climate variations, especially precipitation shifts, than many other terrestrial ecosystems (Knapp and Smith 2001). Precipitation is considered as the dominant factor that determines the emergence of green leaves, the duration of the vegetation growing season, and the primary production in arid and semi-arid areas (Soudani et al. 2012). Therefore, investigating the effects of precipitation...
falls during the summer (June–September), coinciding with peak high temperatures. Severe drought frequently occurs in spring and early summer. In the two study areas (the north transect and the south transect), the main plant species include *Stipa grandis*, *Stipa krylovii*, *Leymus chinensis*, *Agropyron cristatum*, *Artemisia frigida*, *Cleistogenes squarrosa*, *Koeleria cristata*, *Poa sphondylodes*, and *Carex duriuscula*. The topsoil in the two study areas is chestnut soil. The dominant plant species in the part of the two study areas close to Daxing'an Mountains include *Stipa baicalensis*, *Carex pediformis*, and *Spiraea salici olia*; and in the part of the two study areas close to desertified steppe they include *S. krylovii*, *Allium polyrhizum*, and *Allium mongolicum*. Detailed information about the study area is available in Lee et al. (2002) and Yu et al. (2003).

We calculated annual mean temperature and precipitation of all 52 weather stations in Inner Mongolia, and then generated gridded mean annual precipitation and mean annual temperature maps for the study region using the Kriging interpolation method over meteorological records (Figure 1). The annual mean temperatures along the south transect and along the north transect were 2.9–4.1 °C and 0–1.0 °C, respectively. The south transect, located in the Xilingol steppe, had an annual mean precipitation of 130–400 mm, while the annual mean precipitation along the north transect, located in the Hulunbeier steppe, ranged from 230 to 360 mm. Along each transect, the mean annual temperature had little spatial variation (0–1.0 °C for the north transect and 2.9–4.1 °C for the south transect), while the annual precipitation varied greatly (Figure 1(a)). This made it possible to analyze the effects of annual precipitation on vegetative phenology without the effects of temperature. Considering relatively homogeneous mean annual temperature within each of the two transects, we used data from 14 meteorological stations in the IMS, and vegetation pixels close to those weather stations (distance of less than 15 km), to examine the relationship between

**2. Data and methods**

**2.1. Study area**

We chose the temperate steppe (the east and center of Inner Mongolia Autonomous Region) in China as the study area. The majority of annual precipitation (100–400 mm)
the vegetation phenoological parameters and mean annual temperature.

2.2. Data

Long-term satellite records of vegetation greenness at a spatial resolution of 8 km × 8 km and a 15-day interval were acquired from the global inventory monitoring and modeling studies (GIMMS) group derived from the NOAA/AVHRR series satellites during 1982–2008. The GIMMS NDVI data have been corrected to remove some calibration errors caused by sensor degradation, clouds, and stratospheric aerosol loadings from volcanic eruptions (Tucker et al. 2001). Climate datasets came from the China Meteorological Administration, and included 27 years (1982–2008) of continuous records from 52 weather stations throughout Inner Mongolia Autonomous Region. The objective of the study is to examine the response of key vegetation pheno- logical parameters to annual precipitation and mean temperature, in order to identify controlling factors behind changing seasonality over the IMS.

2.3. Methods

Phenological analysis of a small area consisting of homogeneous vegetation can avoid the influence of mixed signals of natural vegetation, crop farming, urbanization, and forestation on the phenological measurements of vegetation. Previous studies on vegetative phenology based on remote sensing have used homogeneous subsets (4–9 pixels) of NDVI data in order to achieve better estimates of phenological parameters (de Beurs and Henebry 2005; Jia, Epstein, and Walker 2003; Jobbagy, Sala, and Paruelo 2002).

We selected our subset areas and discarded pixels occupied by forest, or that contained a high percentage of wetlands, water bodies, cities, farmlands or rock outcrops with finer resolution satellite data. We obtained average NDVI values from the two study areas along the two transect lines in Figure 1(a). The sampling area was 256 km².

In order to quantify changes in the vegetative phenology of the IMS along precipitation gradients, we obtained the mean annual precipitation values for each 8 km × 8 km pixel using available precipitation records and geographical interpolation models calibrated for the whole study region.

Various methods have been proposed for retrieving phenology parameters from the NDVI time series data. In our study, we used NDVI ratios because they are considered the simplest and most effective method for pheno- logical studies (White et al. 2009; Yu, Luedeling, and Xu 2010).

According to previous studies (Chen and Li 2009; Gu et al. 2012) and climate data (daily temperature and precipitation records during 1982–2008) for the IMS, we selected an NDVI ratio threshold of 0.2–0.4 for the SOS; and a drop in the NDVI ratio below 0.4–0.6 was interpreted to signify the EOS. An advantage to the NDVI ratio method is that a change, within a certain range, in the NDVI ratio threshold, has little influence on vegetative phenological season dates (White, Thornton, and Running 1997). Generally, the NDVI ratio threshold value was lower in the east than in the west along each transect. Using the NDVI thresholds, the SOS, EOS, Peak-t, and LOS were estimated for each sampling pixel of the study area for each year on record.

In sparsely vegetated areas, such as desert steppe, the SOS may not occur in years of low precipitation. If the SOS could not be detected before late August, the LOS was set as 0, and a randomly selected pseudo SOS (250 days) in autumn, was assigned to the specific pixels at the particular year for further analysis (Yu et al. 2003).

3. Results

3.1. SOS and annual precipitation

The SOS correlated significantly with the mean annual precipitation along the transects ($R^2 = 0.897, p < 0.0001$ for the south transect; $R^2 = 0.522, p < 0.0005$ for the north transect, Figure 2(a)). In other words, drier sites started their growing season later than wetter ones. The SOS date ranged widely from early May at wetter sites (meadow steppe) to early July at drier sites (desert steppe). The fitting functions were different between the two transects. The SOS date was spatially advanced by 24.9 days for the south transect and 10.4 days for the north transect, with an increase of 100 mm in annual precipitation. The different response of the SOS to precipitation might be explained by a difference in annual mean temperature, which caused a difference in the amount of evapotranspiration between the two transects with similar annual precipitation. Due to the relatively higher annual temperature and a severe lack of water in the winter and spring, precipitation would strongly determine the dates of the SOS along the south transect.

3.2. Peak-t and annual precipitation

There was negative correlation between the Peak-t and mean annual precipitation along annual precipitation gradients in both transects ($R^2 = 0.405, p < 0.0001$ for the south transect; $R^2 = 0.562, p < 0.0001$ for the north transect, Figure 2(b)). The Peak-t along the south transect advanced by 4.2 days per increase of 100 mm of precipitation, while the Peak-t along the north transect advanced by 5.7 days per increase of 100 mm of precipitation. The
of the EOS accompanied by an increase in precipitation (Figure 2(c)).

3.3. EOS and annual precipitation

Along the south transect, there was positive correlation between the date of the EOS and mean annual precipitation ($R^2 = 0.709$, $p < 0.0001$, Figure 2(c)). The EOS occurred in mid-October at wetter sites (meadow steppe), in late September at drier sites (desert steppe), and in early October in typical steppe (average wetness) that received moderate precipitation between wetter and drier sites. Along the south transect there was negative correlation between the date of the EOS and mean annual precipitation ($R^2 = 0.179$, $p < 0.1$, Figure 2(c)). Due to the higher latitude and cooler temperatures of the north transect, precipitation in late autumn could lead to lower soil temperatures during the late vegetation growing season (Piao et al. 2006), which may explain the earlier date of the EOS accompanied by an increase in precipitation (Figure 2(c)).

3.4. LOS and annual precipitation

There was positive correlation between the LOS and mean annual precipitation along both transects ($R^2 = 0.876$, $p < 0.0001$ for the south transect; $R^2 = 0.290$, $p < 0.05$ for north transect, Figure 2(d)). Along precipitation gradients, the LOS increased from 76 days at the driest end (desert steppe) to 162 days at the wettest end (meadow steppe). The average LOS in a typical steppe with moderate hydrothermal (water and heat) conditions was 120 days (Figure 2(d)). For every 100 mm increase in precipitation, the LOS extended by 34.1 days in the south transect and by 7.7 days in the north transect. There are two reasons that may explain why there were differences in the response of LOS to annual precipitation between the two transects. First, annual precipitation influenced the SOS along the south transect more than along the north transect. The negative correlation between the date of SOS and

![Figure 2. Relationship between the (a) SOS, (b) Peak-t, (c) EOS, (d) LOS9 and mean annual precipitation (solid squares denote the south transect and open circles denote the north transect).](image-url)
4. Discussion

The results supported our hypothesis that there would be negative correlation between the SOS date and annual precipitation. In other words, an increase in annual precipitation causes the advancement of the SOS date for the IMS. In the Patagonian steppe, however, the SOS date was found to be independent of the mean annual precipitation along precipitation gradients (Jobbagy, Sala, and Paruelo 2002). One possible cause of this difference is the effect of the temporal distribution of annual precipitation on vegetation activity. In the IMS, most of the annual precipitation falls during the summer, and severe water deficiencies frequently occur in the spring and early summer. During these months, precipitation becomes a major control over vegetation growth, influencing the SOS date by affecting water availability in the region. For the Patagonian steppe, more than 70% of the annual precipitation occurs during the fall and winter. As a result, during the spring, the soil has enough water to support vegetation growth. Thus, it is very likely that temperature, rather than precipitation, controls spring vegetation growth in the Patagonian steppe.

3.5. Phonological parameters and mean annual temperature

There was positive correlation between the SOS, Peak-$t$, and mean annual temperature in the IMS ($R^2 = 0.647, p < 0.001$ for SOS, Figure 3(a); $R^2 = 0.522, p < 0.005$ for Peak-$t$, Figure 3(b)). In other words, warmer sites started their growing season later than cooler ones. The SOS and Peak-$t$ occurred 8.6 and 3.1 days later with every 1 °C increase in mean annual temperature, respectively. In the IMS, however, there was negative correlation between the EOS, LOS, and mean annual temperature ($R^2 = 0.543, p < 0.5$ for EOS, Figure 3(c); $R^2 = 0.435, p < 0.05$ for LOS, Figure 3(d)). This meant that warmer sites ended their growing season earlier than cooler ones, and therefore had shorter LOS.

Figure 3. Relationship between the (a) SOS, (b) Peak-$t$, (c) EOS, (d) LOS and mean annual temperature.
The typical steppes along both transects in the present study had similar mean annual precipitation values but different mean annual temperatures (Figure 1). The north transect, located in a region of higher latitude, had a lower mean annual temperature, and thus had lower rates of evapotranspiration and more available water than the south transect. The SOS date for typical steppes occurred earlier along the north transect than along the south transect (Figure 2(a)), indicating that temperature plays a minor (or even negative) role in regulating plant growth in steppe ecosystems that receive less than 400 mm of annual precipitation (Epstein, Lauenroth, and Burke 1997; Figure 3(a)). If temperature has a determining (positive) role in steppe ecosystem SOS dates, the SOS date along the south transect would have occurred earlier than along the north transect, due to its location at a lower latitude with higher temperatures. Based on temporal analysis, Lee et al. (2002) suggested that the SOS date for a year of high precipitation and low temperatures in the central IMS occurred earlier in the year than it did during a year of low precipitation and high temperatures. Thus, for the IMS, it is precipitation rather than temperature that determines the timing of the SOS date. Based on spatial analysis, Shen et al. (2014) found a comparable pattern. The areas with a greater increase in pre-season temperature did not necessarily experience a stronger advance of green-up date. In contrast, the areas with increasing pre-season precipitation overlapped with the areas having an advancing SOS, while the areas with declining pre-season precipitation experienced a delayed SOS in the Qinghai–Tibetan Plateau.

There was positive correlation between the EOS date and mean annual precipitation along the south transect. This supported our hypothesis that the EOS date would be delayed as precipitation increases for this semi-arid biome. The occurrence of a delay in the EOS date due to an increase in precipitation did not occur along the north transect. Instead, the EOS date occurred earlier with increasing precipitation. The phenological patterns of the north transect concurred with the results of Gu et al. (2012), who analyzed phenological ground observations and climate data in the IMS and concluded that an increase in precipitation during autumn could advance the EOS date for meadows (located between steppe and forest). Due to the higher latitude and cooler environment along the north transect, temperature is the limiting factor for vegetation growth (Piao et al. 2006). An increase in precipitation (usually accompanied by an increase in cloud cover and a reduction in incoming solar radiation) can significantly reduce soil temperature, preventing the root system from absorbing water from near-frozen soil during the late vegetation growing season (Piao et al. 2006). Furthermore, low temperatures inhibit plant photosynthesis by reducing photosynthesis-related enzyme activity, causing structural damage to chloroplasts (organelles necessary for photosynthesis) and to the bio-membrane, resulting in metabolic disequilibrium of reactive oxygen in plants.

Disclosure statement

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