Agricultural and Forest Meteorology 248 (2018) 177–184

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Research paper

A comparative analysis of the spatio-temporal variation in the phenologies of two herbaceous species and associated climatic driving factors on the Tibetan Plateau

Wenquan Zhu[a,b,c,*,1], Zhoutao Zheng[a,b,c,*,1], Nan Jiang[a,b,c], Donghai Zhang[a,b,c]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, 100875, China
[b] Joint Center for Global Change Studies (JCGCS), Beijing, 100875, China
[c] Beijing Engineering Research Center for Global Land Remote Sensing Products, Institute of Remote Sensing Science and Engineering, Faculty of Geographical Science, Beijing Normal University, Beijing, 100875, China

ARTICLE INFO

Keywords:
Climate change
Phenology
Plantago asiatica
Taraxacum mongolicum
Tibetan plateau

ABSTRACT

Studying the differences in phenology among plant species is important for understanding their physiological and reproductive responses to climate change and complex inter-species interactions. This study conducted a comparative analysis of the spatio-temporal variation in the phenologies of two herbaceous species (*Plantago asiatica* and *Taraxacum mongolicum*) and associated climatic driving factors on the Tibetan Plateau (TP) based on ground-observed phenology data during 2000–2012. The results indicated that both spring and autumn phenology of the two species showed strong dependences on altitude, latitude and longitude, although the magnitudes of the variation with geographical factors were different among species. Change in altitude contributed the most to the spatial variation in phenology for both species. In addition, strong dependences on altitude were also observed for the phenological differences between the two species. With the increase of altitude, the same phenophases of the two species tended to occur synchronously at first and then the chronological order of the same phenophases between the two species changed. Spring and autumn phenophases showed significant negative correlations with the growing degree-days (GDD) and the cold degree-days (CDD) ($p < 0.001$), respectively. Moreover, the phenophases of *T. mongolicum* were more sensitive than those of *P. asiatica* in response to GDD or CDD, which explained the spatial variation in the phenological difference between the two species. The divergent phenological responses to climate change and the spatial variation in phenological differences between *P. asiatica* and *T. mongolicum* may alter the inter-species interactions between the two species.

1. Introduction

Plant phenology is the study of the timing of recurring biological events of plant developmental stages caused by biotic and abiotic factors, including the occurrence of leafing, flowering and fruiting (Lieth, 1974; Morisette et al., 2009). Plant phenology is sensitive to changes in climate and the natural environment (Cong et al., 2012; Morisette et al., 2009). Moreover, it plays a crucial role in regulating the exchange of the fluxes of water, CO_2 and energy between the biosphere and atmosphere (Keenan et al., 2012; Richardson et al., 2012; Richardson et al., 2013). Shifts in phenology can reflect the adjustments and responses of the biosphere to climate change (Penuelas and Filella, 2001). Therefore, plant phenology has received extensive attention in the field of global change in recent years (Menzel, 2002).

Global warming has altered plant phenology in recent decades (Menzel et al., 2006; Parmesan and Yohe, 2003; Root et al., 2003). Many studies have reported advanced spring phenology and delayed autumn phenology worldwide, which has resulted in an extended growing season (Jeong et al., 2011; Menzel, 2000; Piao et al., 2006; Zhu et al., 2012). However, the phenological shifts vary in response to climate change at different locations, even for the same species (Primack et al., 2009; Schwartz and Hanes, 2010), and different species within the same community may also show distinct responses (Cleland et al., 2006; Crimmins et al., 2010; Diez et al., 2012; Fitter and Fitter, 2002; Miller-Rushing and Primack, 2008). Moreover, different changes in phenology among species could lead to alterations in inter-species relationships (Stenseth and Mysterud, 2002; Visser and Both, 2005), potentially altering the community structure and function (Richardson

---

* Corresponding authors at: Institute of Remote Sensing Science and Engineering, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China.
E-mail addresses: zhuwq75@bnu.edu.cn (W. Zhu), zhengzt90@mail.bnu.edu.cn (Z. Zheng).

[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.agrformet.2017.09.021
Received 11 January 2017; Received in revised form 25 September 2017; Accepted 27 September 2017
0168-1923/

et al., 2013). For example, Fitter and Fitter (2002) found that due to the different responses in flowering of 6 pairs of species that can form natural hybrids in the vicinity of a single locality in south-central England, 4 pairs of species were more likely to flower synchronously than they were formerly, increasing the probability of hybridization, and 2 were less likely to, reducing the probability of hybridization.

Plant phenology is much more sensitive to climate change on the Tibetan Plateau (TP) due to its harsh physical environment; this region is commonly known as Earth's "third pole". The unique geographical and environmental backgrounds make the TP an ideal region to explore the potential changes in plant communities under climate change by studying inter-species differences in phenological responses. Through experimental warming in a typical alpine meadow on the TP during 2014–2015, Zhu et al. (2016) found that warming caused the convergence of the flowering events of early- and late-flowering species and increased the overlap period of flowering among species, which could alter the competitive relationships among species. However, existing studies about inter-species differences in phenological responses to climate change on the TP to date have mainly focused on a single site with a few years' records, and a comparative analysis of the spatio-temporal variation in phenology based on multi-site and multi-year phenological records is therefore lacking.

Thanks to the phenology network established by the China Meteorological Administration, a large number of continuous and long-term, ground-observed phenology records across the TP can be available. At present, 26 phenological stations are distributed on the TP, with 22 herbaceous plants and 10 woody plants observed (Zheng et al., 2016). However, only two perennial herbs, herba plantaginis (*Plantago asiatica*, Plantaginaceae family) and dandelion (*Taraxacum mongolicum*, Compositae family), were widely observed among all stations. Focusing on the two species, this study aims to reveal the inter-species differences in phenological responses to climate change and the associated climatic driving factors on the TP.

2. Data and methods

2.1. Phenological dataset

The phenological data for *P. asiatica* and *T. mongolicum* on the TP were collected from the nation-wide phenological observation network established by the China Meteorological Administration. The starting year for the phenological records of the two species differed among stations and species. For example, the phenology of *P. asiatica* began to be recorded in 1983 at Huangyuan and Zoige stations, while that of *T. mongolicum* only started to be recorded in 2002 at Shiqu station. On the other hand, phenological observations continued at all stations except Maqu station, at which the observations discontinued after 2009. The phenological data for the two species during 2000–2012 were selected in this study because they were generally almost available during this period at the corresponding stations. Moreover, the key phenological metrics of the first leaf date (FLD), first flowering date (FFD), common leaf coloring date (LCD) and length of the growing season (LOG) were selected. FLD is defined as the date when a few leaves are fully expanded, FFD is defined as the date when a few flowers are fully blooming, and LCD is defined as the date when more than 50% of the green leaves have turned yellow (China Meteorological Administration, 1993). The time between FLD and LCD is regarded as LOG. All the onset dates of FLD, FFD and LCD were converted to the Julian day of year (DOY).

Outliers were removed from the phenological data according to the 30-day rule as proposed by Schaber and Badeck (2002). For each phenological metric, only the time series with at least 10-years records existed during 2000–2012 were included in the analysis. Finally, 16 phenological stations were selected for this study (Fig. 1). The phenology of each species was observed at 13 stations individually. Meanwhile, there were 10 stations recording the phenologies of the two species concurrently. More details about the locations and the plant species observed at each station can be found in Table S1 in Supplement A.

2.2. Climate dataset

The meteorological data were obtained from the China Meteorological Data Service System (http://data.cma.cn/), including the daily mean air temperature and daily precipitation at 96 stations on the TP from 2000 to 2012. Because daily meteorological data were not available for Haiyan, Huangyuan, Huzhu and Gande stations, the ANUSPLIN 4.3 software (Hutchinson, 2004), combined with the Digital Elevation Model (DEM) data derived from the US Geological Survey, was used to interpolate the daily mean air temperature and daily precipitation into 1 km × 1 km grids over the study region. Thus, gridded daily mean air temperature and daily precipitation data at the 4 phenological stations without daily meteorological data were obtained.

2.3. Frequency statistics for the occurring time of phenophases

To depict the phenological metrics, the mean, median, minimum, maximum, 25th and 75th percentiles for each phenological metric (FLD, FFD, LCD and LOG) across all stations over 2000–2012 were calculated for each species and exhibited by the boxplots. Meanwhile, the distributions of the differences in FLD (ΔFLD), FFD (ΔFFD), LCD (ΔLCD) and LOG (ΔLOG) between *P. asiatica* and *T. mongolicum* across all stations with both species observed over 2000–2012 were also illustrated by the boxplots.

2.4. Analysis of the spatial and temporal variations in phenological metrics

To explore the effect of geographical factors and years on the spatial-temporal variations in the phenological metrics (FLD, FFD, LCD and LOG) and the phenological differences (ΔFLD, ΔFFD, ΔLCD and ΔLOG) between *P. asiatica* and *T. mongolicum*, the stepwise multiple linear regression model was performed with geographical factors (longitude, latitude and altitude) and year as independent variables. The variance inflation factor (VIF) was used to detect the multi-collinearity among variables in the models. Models were accepted only if the VIF of individual predictors was less than 3, which indicated no multi-collinearity (Zuur et al., 2010). The squared semi-partial correlation coefficients were used to quantify the relative contribution of each independent variable in a given model, which were determined as the reduction in R^2 with removing a given predictor from the set of independent variables (Watson et al., 2011).

2.5. Analysis of the relationships between climatic driving factors and phenology

The growing degree-days (GDD) has been widely used as a measure of heat accumulation to assess the effect of temperature on spring phenophases (Chuine, 2000; Fu et al., 2014; Shen et al., 2015). On the other hand, the cold degree-days (CDD), as a surrogate for cumulative heat deficit, has been adopted to explain the variation in autumn phenophases (Delpierre et al., 2009; Dragoni and Rahman, 2012; Richardson et al., 2006). GDD was calculated as the thermal sum of the difference between daily mean temperature (T_m) and the base temperature (T_b) between DOY$_1$ and DOY$_2$ (Eq. (1)).

$$GDD = \sum_{DOY_1}^{DOY_2} \begin{bmatrix} (T_m - T_b) & when & T_m > T_b \\ 0 & when & T_m \le T_b \end{bmatrix} \tag{1}$$

Here, T_b was set to be 0 °C; DOY$_1$ was set as 1st January. To analyze the correlation between phenology and GDD across different stations and years, the end dates of GDD should be set to fixed dates. Specifically, DOY$_2$ was set to 30th April and 30th June for FLD and FFD,