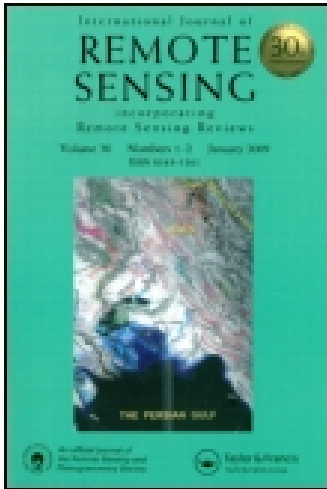


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## Detecting the effects of climate change on canopy phenology in coniferous forests in semi-arid mountain regions of China

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An increased understanding of the responses of forest phenology to climate on regional scales is critical to the evaluation of biochemical cycles (i.e. carbon, water, heat, and nutrient) under environmental changes. In this study, we aimed to identify climatic constraints on phenological events in an evergreen coniferous forest in semi-arid mountain regions of northern China. We quantified the start of season (SOS), end of season (EOS), and growing season length (GSL) based on satellite-derived data sets (normalized difference vegetation index (NDVI)) and investigated the relationships between these phenological events and climate factors. The results revealed discontinuous trends in phenological events throughout the study period, with neither an obvious extension nor decrement in GSL. We demonstrated that minimum temperatures controlled the dynamics of SOS and EOS, thus providing strong evidence for the need to include minimum temperature as a control on phenology in simulation models. Additionally, precipitation was coupled to the shift in maximum NDVI, as rainfall is a major climatic limitation to vegetation growth in semi-arid regions. It appears that selecting appropriate timescales to analyse the relationships between phenology and climate is critical. We illustrated that NDVI was an effective tool in an effort to gain greater understanding of the effects of environmental change on ecosystem functioning in this forest. Our results may be used as reference to track local changes in the evergreen coniferous forest dynamics under different climate change scenarios for semi-arid mountain regions.

### 1. Introduction

Significant recent changes in climate and land–atmosphere interactions may affect terrestrial ecosystems (IPCC 2007). The effects of climatic shifts on vegetation growth, including carbon storage and vegetation productivity are prominent (Braswell et al. 1997; Nemani et al. 2003; Brown, De Beurs, and Marshall 2012), and exerted by increasing temperatures, changing precipitation regimes, and shifting seasonal cycles. An enhanced understanding of the interactions between climate and vegetation is pivotal to predicting the impacts of climate change on ecosystems (Horion et al. 2013). However, the relationship between climate and vegetation is complex, regardless of geographic scale. The understanding of mechanisms is still far from complete, particularly in regions without sufficient resources to invest in climate-change research.

Considerable evidence indicates that temperate and boreal biomes may respond to temperature anomalies with greater biogeophysical effects than tropical zone (Bonan 2008; Heyder et al. 2011), including an increase in heat and drought stress in semi-arid

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ecosystems (Braswell et al. 1997). Similarly, for mountainous habitats, the variation of temperature as the most stressful growth limiting factor was a tremendous challenge to stability and resilience of plant growth (Carrer et al. 2012). Also, Zhang, Wang, and Wang (2010) analysed spatial patterns in biomass of Alpine ecosystems in the Qinghai–Tibet and showed that different ecosystems may exhibit distinct or even opposite responses to climate change. Thus, identifying environmental controls over vegetation dynamics and terrestrial carbon storage is a crucial step in the assessment of climate change impacts on vegetation (Horion et al. 2013).

Vegetation phenology, the science of recurring vegetation cycles and their connections to climate, is an important component of global change research (White, Thornton, and Running 1997). Several studies have shown that the phenology of various organisms is disturbed by climatic changes (Walther et al. 2002; Root et al. 2003). At northern high latitudes, global warming may alter canopy phenology of temperate and boreal forests, by affecting photosynthetic activities (Bunn, Scott, and Fiske 2005) and relating it to the growing season length (GSL) and seasonal amplitude of the normalized difference vegetation index (NDVI; Myneni et al. 1998; Zhou et al. 2001), resulting in affecting carbon balance, moisture exchange, and energy budgets (Ahl et al. 2006). Therefore, shifts in forest phenology can be used as indicators of climate variation (Kross et al. 2011).

Accurate estimates of canopy phenology are critical to quantifying carbon and water exchange between forests and the atmosphere, and canopy responses to climate change (Ahl et al. 2006). Remotely sensed data have long been used to evaluate vegetation phenology (Ashley, Dethier, and Rea 1973; Girard 1982; White, Thornton, and Running 1997; Zhang et al. 2004). The NDVI is an effective parameter in monitoring the spatial–temporal patterns of vegetation phenology because it is strongly related to the amount of green-leaf biomass (Lillesand and Keifer 2000). The NDVI is based on the differential reflectance of green vegetation in the infrared and near-infrared bands (Mangiarotti et al. 2012), which is related to the strength of plant activity, and it has been widely used in monitoring vegetation dynamics and vegetation phenology (Zhang et al. 2004; Mangiarotti et al. 2012), analysing the interactions between climate and vegetation (White, Thornton, and Running 1997), and forecasting vegetation growth and yield (Nemani et al. 2003). Distinct effects of climatic factors on biomass and phenological patterns of vegetation as assessed by NDVI have been documented for many tropical and temperate ecosystems (Brown, De Beurs, and Marshall 2012; Delbart et al. 2006) as have been the feedback effects of vegetation on local climate.

Here, we focused on the mountainous area in a semi-arid inland river basin in northern China. The area experiences low rainfall and abundant evapotranspiration. Ecological processes here are closely coupled to both atmospheric influences and human activities and may be highly sensitive to climate change (He et al. 2012). Evergreen coniferous forest is the dominant plant community, affecting the annual water yield volume that enters several key inland rivers that are critical to local people's livelihood (He et al. 2012). During the past 50 years, the average temperature has risen by  $0.26^{\circ}\text{C decade}^{-1}$  in this region, higher than the national rate ( $0.14^{\circ}\text{C decade}^{-1}$ ). Moreover, anomalous climate events (e.g. severe drought and catastrophic rainstorm) occurred frequently (Yin et al. 2009). These semi-arid regions do not receive enough scientific attention because of lack of adequate funding. The majority of studies aimed at analysing forest phenology and its relationship to climate focused on the deciduous broadleaf forests (Schwartz, Reed, and White 2002; Kross et al. 2011; Ahl et al. 2006). By contrast, the information about that of

coniferous forest is lacking. Moreover, the effects of global warming on vegetation dynamics are likely to differ in coniferous and deciduous forests and in semi-arid mountain and other regions because of distinctive thermal and hydrological conditions in each forest type and region (Richards and Pocard 1998). For example, Tang and Bechage (2010) exported that projected global warming in twenty-first century is expected to result in the more extensive loss of boreal conifer forests than northern hardwood deciduous forests in New England.

In this study, we used Moderate Resolution Imaging Spectroradiometer (MODIS) – derived vegetation data (NDVI) to quantify the canopy phenology of evergreen coniferous forests and to assess the response to climate change of phenological events on a regional scale. Our study objectives were to (1) illustrate NDVI as a useful tool in efforts to gain characteristics of phenological events of *Picea crassifolia*, (2) evaluate the interannual relationship between climate and forest phenology, and (3) identify the climatic constraints on phenological events (e.g. the timing of forest green-up and dormancy). A greater understanding of the interactions between canopy phenology and climate will increase prediction accuracy of vegetation dynamics under future climate change scenarios.

## 2. Materials and methods

### 2.1. Study site

The study site, which is part of the Chinese Ecosystem Research Network (<http://www.cern.ac.cn/0index/index.asp>), is located in a temperate evergreen coniferous forest (centre Lon: 99° 32' 29.3" E; centre Lat: 38° 50' 27.4" N) in Water Resource Conservation Forest Protection Zone of the Qilian Mountains, upstream of the Heihe River basin in northern China (Figure 1). The climate is typical of temperate continental plateau, with annual rainfall between 450 and 650 mm (Figure 2), concentrated in July to August. Evapotranspiration is greater than 1000 mm year<sup>-1</sup>. Mean air temperature was -4.4°C in 2011 and has been gradually increasing during the past decade (Figure 2). In general, the snow season at this site lasts from October to mid-May.

The forest area is limited to north-facing or east-facing slopes at elevations ranging from 2500 to 3900 m above sea level (a.s.l.) and covers 1018 km<sup>2</sup>. *P. crassifolia* (Figure 3), a secondary conifer, is the dominant species and is vulnerable to the impacts of climate change and human activities (e.g. overgrazing and deforestation) (He et al. 2012). The mean height of the tree canopy ranges from 5 to 11 m, and the average density of timbers is about 2400 stems ha<sup>-1</sup>. In most cases, the understory is poorly developed, only moss covered on forest floor. The leaf area index (LAI) of the site is approximately 2.0, with the canopy mostly closed.

### 2.2. Data processing

#### 2.2.1. NDVI time series

In this study, we used a MODIS reflectance data set originally produced by the Land Processes Distributed Active Archive Center (LPDAAC), which is located at the US Geological Survey Earth Resources Observation and Science Center (USGS-EROS, <http://LPDAAC.usgs.gov>). The 8 day composite reflectance data (MOD09Q1) with a ground resolution of 250 m were further processed and released by the Atmosphere Archive and Distribution System (<http://ladsweb.nascom.nasa.gov/>). Each reflectance pixel was

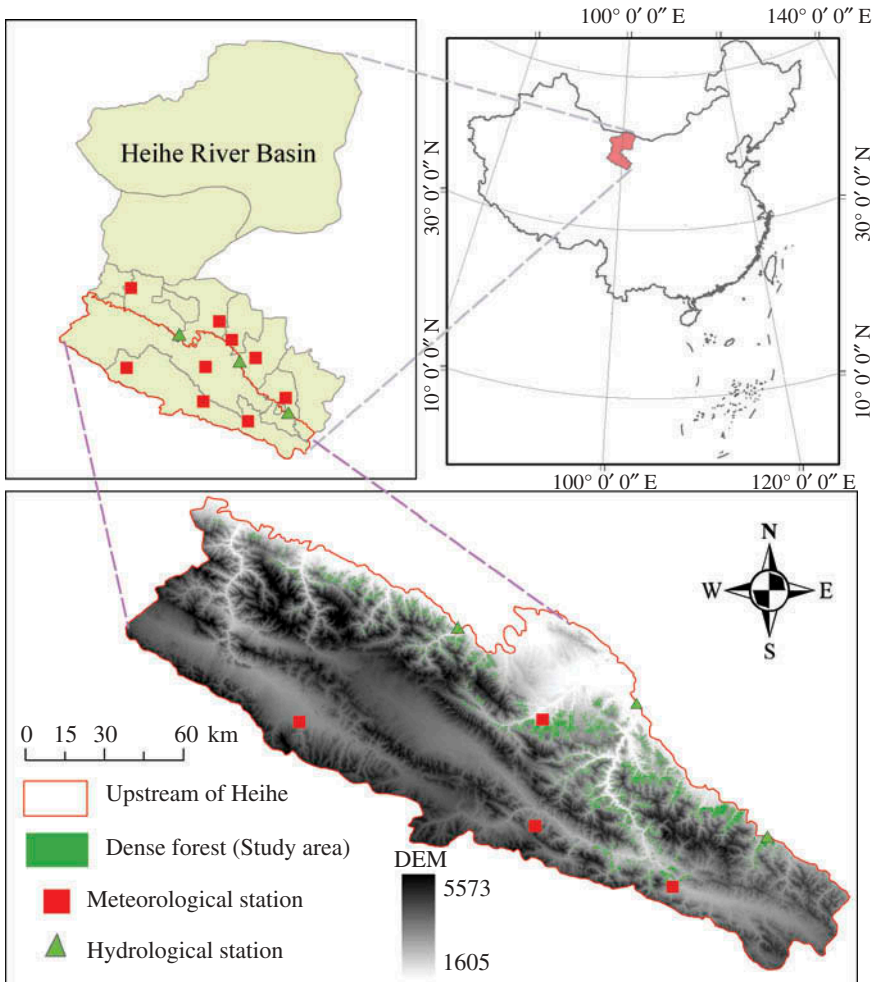


Figure 1. Location of the study area.

selected on the basis of low-view zenith angle from MODO9QA product using the MODIS Reprojection Tool. While preliminarily atmospheric correction has been done in the MOD09Q1 generating process, the anisotropic characteristics of the mountainous surface reflectance, usually characterized by the Bidirectional Reflectance Distribution Function (BRDF), should be considered to attain a radiometric rectified product free from distortion. Therefore, the linear kernel-driven BRDF model (Roujean, Leroy, and Deschamps 1992; Schaaf et al. 2002), an algorithm for correcting MODIS bidirectional reflectance, was applied to the images. In this work, a set of spectral reflectance data of the *P. crassifolia* over multi-observational zenith angles measured by Song et al. (2008) was used for model construction, and the performance of the correlation was evaluated with a single time series of parameters in 2008 to determine whether the directional effect limited the information content of NDVI.

We obtained the NDVI data of the forest using the following procedure. First, all the standard MODIS data in the HDF-EOS were converted to the geotiff format with the



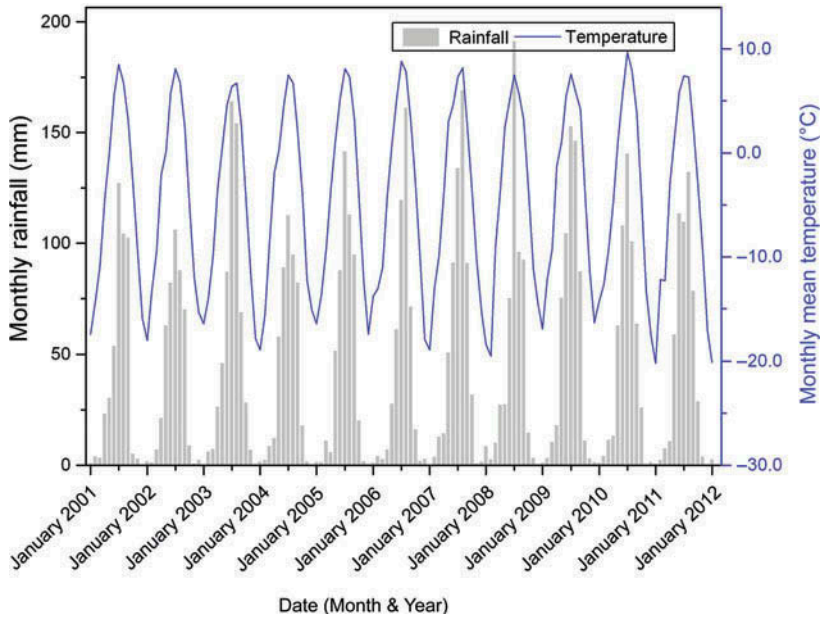


Figure 2. The seasonal cycle of monthly mean temperature and rainfall from upstream of the Heihe River basin.

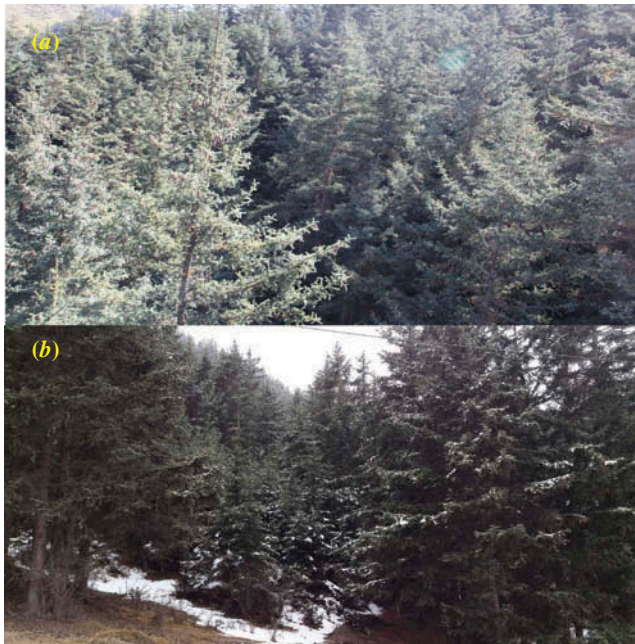


Figure 3. Photographs of targeted ecosystem (*P. crassifolia*) taken in different seasons of 2010 at Xishui Protection District. (a) An image of the canopy was captured from a monitoring tower during the end of summer (August); (b) A scene of snow covering was taken in early spring (April).

known geographic coordinate system (WGS\_1984\_UTM\_Zone\_47 N; sampling protocol: nearest neighbour). We removed data with band reflectance values  $>0.5$ , as disturbance noise whose values were considerably larger than those of the neighbourhood (Nagai et al. 2010). Then, the NDVI was calculated from the MOD09Q1 data using the following equations:

$$\text{NDVI}_{\text{MODIS}} = (B_2 - B_1)/(B_2 + B_1) \quad (1)$$

where  $B_1$  and  $B_2$  are the surface reflectance of red (620–670 nm) and near-infrared (841–876 nm) band wavelengths, respectively. Finally, to minimize the edge effect, we created a 100 m buffer within the forest boundary, extracted the core space, and eliminated the patches with remnant area less than 6.25 ha (one pixel of MODIS data). We extracted each sampled NDVI data using this forest map mask.

For our study, we acquired 11 years of NDVI time series (Figures 4 and 5) (i.e. 506 images), from 1 January 2001 to 27 November 2011. All gridded NDVI values were used to estimate forest phenology and mean values were calculated during the growing season for the determinations of relationships with climate.

We used two data sets of Landsat 5 Thematic Mapper (TM) images from June and August 2010, respectively, to determine whether the NDVI of *P. crassifolia* expressed seasonal variation or a nearly-constant value and to compare with  $\text{NDVI}_{\text{MODIS}}$  (Table 2). The TM data were downloaded from Global Land Cover Facility website (<http://www.landcover.org/data/>). Each data set comprised of four Landsat scenes (path 133, rows 033–034 and paths 134–135, row 033), and covered the entire forest region. In the seven spectral bands of the TM image, we only used bands 3 (red) and 4 (near-infrared), with a spatial resolution of  $30 \times 30$  m, to calculate NDVI using:

$$\text{NDVI}_{\text{TM}} = (B_4 - B_3)/(B_4 + B_3) \quad (2)$$

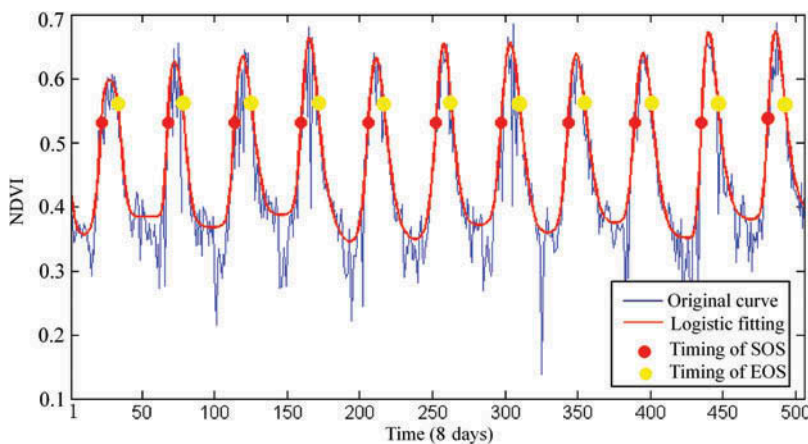


Figure 4. A profile of NDVI (blue line) obtained for a random pixel ( $i, j$ ). The double logistic function was used to fit the data (red line); the green-up (red circles) and dormancy points (yellow circles) were determined. Values in the time series that sufficiently differed from the left and right-hand neighbours were classified as snow/cloud-contaminated values or outlier points.



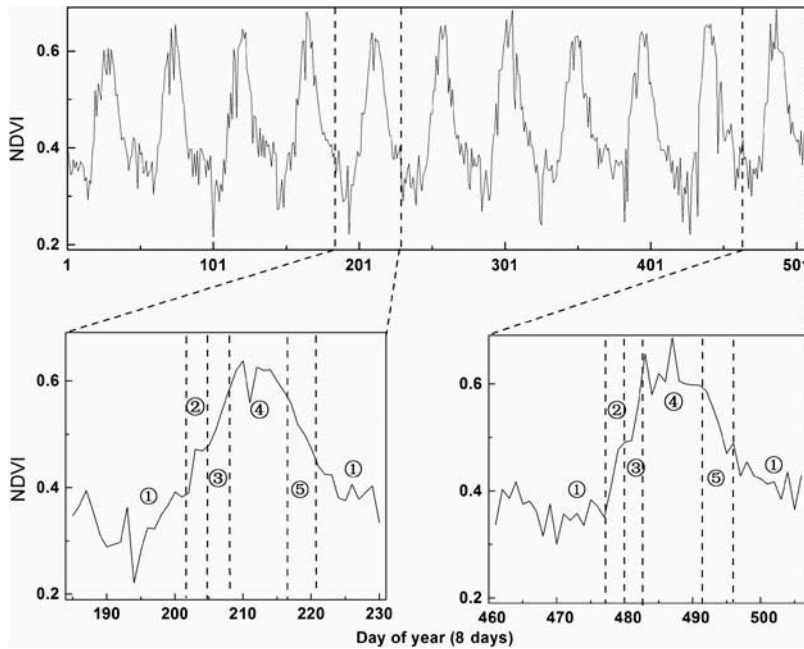


Figure 5. Seasonal patterns in annual NDVI values for a random pixel ( $i, j$ ): (a) the profile of 11 years from 2001 to 2011; (b) NDVI profile of 2005; (c) NDVI profile of 2011. Phase ① corresponds to snow-cover period, phase ② matches the snowmelt stage, phase ③ parallels the timing of rapid growth, phase ④ reflects the equilibrium period of growth, and phase ⑤ is the beginning of tree dormancy.

where  $B_3$  and  $B_4$  are the surface reflectance of red (630–690 nm) and near-infrared (760–900 nm) band wavelengths, respectively. To correct for the geometry and radiation distortion, the data set had to be georeferenced with subpixel accuracy using the orbital geometry, ephemeris data, and ground control points (Kross et al. 2011). For extracting NDVI data of the forest region, the same method was used as for the MODIS data set.

### 2.2.2. Phenology data and in situ observation

To characterize the intraannual variation of the growing season parameters, we applied the methodology of Jönsson and Eklundh (2004) to detect the start of season (SOS), end of season (EOS), and GSL (Figure 4). We smoothed the time series of NDVI using the double logistic function-fitting approach based on the least-squares fitting to the upper envelope of NDVI data (Jönsson and Eklundh 2004). This approach is suitable for handling irregular data (e.g. multi-day NDVI composites) (Ahl et al. 2006) and for correcting for disturbance from clouds and snow (Kross et al. 2011). We used the TIMESAT program (<http://www.nateko.lu.se/TIMESAT/timesat.asp?cat=4>) to analyse time series of satellite sensor data (Jönsson and Eklundh 2004) and applied the median filter method to possible outliers, which may influence subsequent fitting.

Two transition dates (SOS and EOS) that characterize key phenological phases were determined by the relative threshold method (Delbart et al. 2006; Schwartz, Reed, and White 2002); briefly, the dates of SOS or EOS were defined as the times at which NDVI

values increased (SOS) or decreased (EOS) to a value of the seasonal amplitude in the left or the right edge of the annual curve. However, the lowest part of the curve may be affected by disturbances, influencing the amplitude (Kross et al. 2011). For this reason, we used specific NDVI values instead of the amplitude; we assumed that phenological events occurred when these values were reached from both sides of the curve. The method is globally applicable for trend analysis of time series (White et al. 2009), although the fixed values may be sensitive to the maximum NDVI of a pixel.

Our field observations of phenological events from the site located in the Xishui Protection District (100° 17' 9.6" E, 38° 33' 21.6" N) were conducted for two years (2011–2012), and revealed that, on average, SOS occurred in June and EOS in September. The records were taken as representative of the study area, because of the elevation of the site (from 2660 to 3780 m a.s.l.) involved almost all of the altitude extent. To match actual dates with these phenological events, we defined the date of onset as the date at which the NDVI reached its absolute value of 0.53 calculated by the annual average NDVI during June; similarly, the date of offset corresponded to the absolute NDVI value of 0.56 calculated by annual average NDVI in September.

### 2.2.3. Meteorological data

Climate data were obtained from nine meteorological stations (four inside of the study area and five outside, but near the boundary), made possible through the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn>) (Figure 1). Four variables were acquired: maximum, mean, and minimum temperatures and rainfall for each month. We adopted the methods of Hadano et al. (2013) to interpolate the temperature across the forest area; first, we converted the station data to equivalent temperature at sea level, then we interpolated the equivalent data at all sites based on regularized splines with tension, and finally, we converted the interpolated map of equivalent data to actual values (for a detailed description, see Hadano et al. (2013)). For rainfall, we used the Kriging method to interpolate values. The results were projected onto a 250 × 250 m grid. Data from three hydrological stations for the years 2000 and 2004 were used to verify the interpolation results (Figure 1).

### 2.3. Statistical analysis

We used average values instead of pixel values for the forest area to investigate the relationship between phenological metrics and climate variables; this was necessary because temporal variation in canopy phenology reflects vegetation response to climate change more prominently than does its spatial pattern (Zhao, Zhou, and Fang 2012). To choose appropriate timescales for climate variables, we selected three periods for analysis each year: June (during which onset of green-up occurred), from July to August (corresponding to the primary growing period), and September (when trees entered dormancy). Given that vegetation response to climate may exhibit delayed effects (Chhin et al. 2008), we also considered the climatic variables of May and August, one month earlier than SOS and EOS, respectively. Correlation coefficients and significance levels were used to estimate the importance of interactions during the different phases. Additionally, the interannual variation of phenological parameters was assessed by fitting temporal trend.

### 3. Results

Results of BRDF correction revealed that the reflectance time series demonstrated an inconspicuous change when compared to original data, with a slight noise that was about 0.010 in the red band and 0.004 in the near infrared (RMSE = 0.014 and 0.010, respectively). The resulting NDVI in average deviation between pre- and post-correlation was 0.007 (RMSE = 0.019), much less than the variation triggered by physiological property of leaves or snowmelt during an 8 day interval (0.048 in mean value). Additionally, the lack of observational data in other years will generate additional noise when the BRDF model established by using the data of 2008 is applied to the whole time series of 11 years. For example, the increase of leaf area due to the growth of trees may affect the model parameters to be calculated. Therefore, the original data were applied in the following analysis.

#### 3.1. Seasonal patterns in NDVI

The seasonal pattern in NDVI of *P. crassifolia* unambiguously exhibited the dynamics of phenological events and the effects of cloud contamination and snowmelting. The NDVI time series indicated that forest growth exhibited a unimodal form on an annual basis (Figures 4 and 5). We divided the seasonal patterns for each year into five phases based on the pattern of change in NDVI and the growth characteristics of *P. crassifolia* (Lei, Zhang, and Fan 2012).

Phase 1: Beginning in October of the previous year, the NDVI was relatively low (0.30–0.40) until May of the following year. During this period, the LAI of the forest canopy was at the minimum of the year due to the presence of snow in the canopy (Figure 3(b)).

Phase 2: NDVI increased rapidly for two weeks because of an increase in temperature to above 0 (approximately 1.1°C during May), resulting in snowmelt and gradual leaf expansion. At the end of May, the NDVI values reached between 0.45 and 0.50 (e.g. 0.47 in 2005 and 0.49 in 2007). This stage was generally characterized by the fastest increase for NDVI, which showed a steep ascending curve in Figure 5.

Phase 3: After an initial steep increase and a subsequent relative stabilization for about one week, NDVI then increased gradually and monotonically until early July, and the increment lasted about one month. We called this period the rapid growth stage, and it included the onset of green-up. According to our field observation, more than 90% area of the region had no snow covering during this period.

Phase 4: Values of NDVI ranged from 0.60 to 0.69, the maximum values for the year, in July and August. This corresponded to an equilibrium period of forest growth.

Phase 5: NDVI gradually decreased to below 0.50 in September, as temperatures decreased. After this period (i.e. decline in growth), the forest became dormant.

#### 3.2. Dynamics of phenology

Figure 6 shows a seemingly opposite pattern between SOS and EOS. The growth of *P. crassifolia* commenced (SOS) on average on the date ranging from the 158th to 183th day of the year, with the earliest SOS in 2001 and the latest in 2004; these results corresponded to phase 3 (Figure 5). On the contrary, the earliest onset of dormancy occurred in 2004 (253th day), and the latest in 2001 (266th day), both within phase 5 (Figure 5). Previous studies have demonstrated a notable change of vegetation phenology pattern in

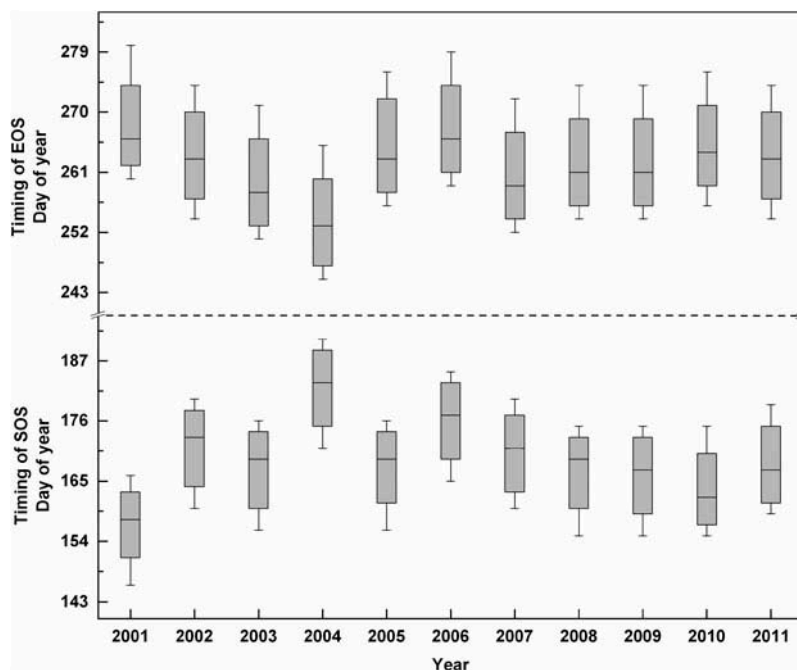


Figure 6. The dynamics of phenological events (i.e. SOS and EOS). The boundaries of the box indicate the 25th and 75th percentiles; a line within the box marks the mean. Error bars above and below the box indicate the 10th and 90th percentiles, respectively.

temperate regions of northern hemisphere. For example, Jeong et al. (2011) pointed that the SOS of temperate vegetation advanced 5.4 days during 1982 and 2008. In northeast China, which lies at roughly the same latitudes as our region, Guo et al. (2010) revealed a 3.9 days per decade increase of GSL in needle-leaf forests. However, our results showed that the phenology trends were not continuous throughout the 11 year period, with a transition point in 2004. The SOS trend indicated a delay in the first four years and an advance during the following seven years, while EOS experienced an earlier shift and then a postponement. As a whole, neither an obvious extension nor decrement in GSL was detected ( $r = 0.2$ ,  $p = 0.7$ ), which may be due to the short period investigated.

### 3.3. Relationships between phenology and climate

Differences in the patterns of annual phenology at the scale of a mountain zone (e.g. upstream of Heihe River basin, see Figure 1) occurred in relation to the differences in the course of climatic factors each year, because of patchy distribution of woody cover and the altitudinal gradient.

Comparisons between interpolated meteorological values and empirical data from our hydrological sites yielded a total precision of 92% for temperature and 78% for precipitation. Our results revealed that the annual date of SOS was associated with the pattern of minimum temperature in June (Figure 7), with high correlation coefficient ( $-0.87$ ) (Table 1), indicating a prominent shift to an earlier date of SOS with an increase in late spring minimum temperatures. Similarly, the timing of EOS displayed an analogical trend

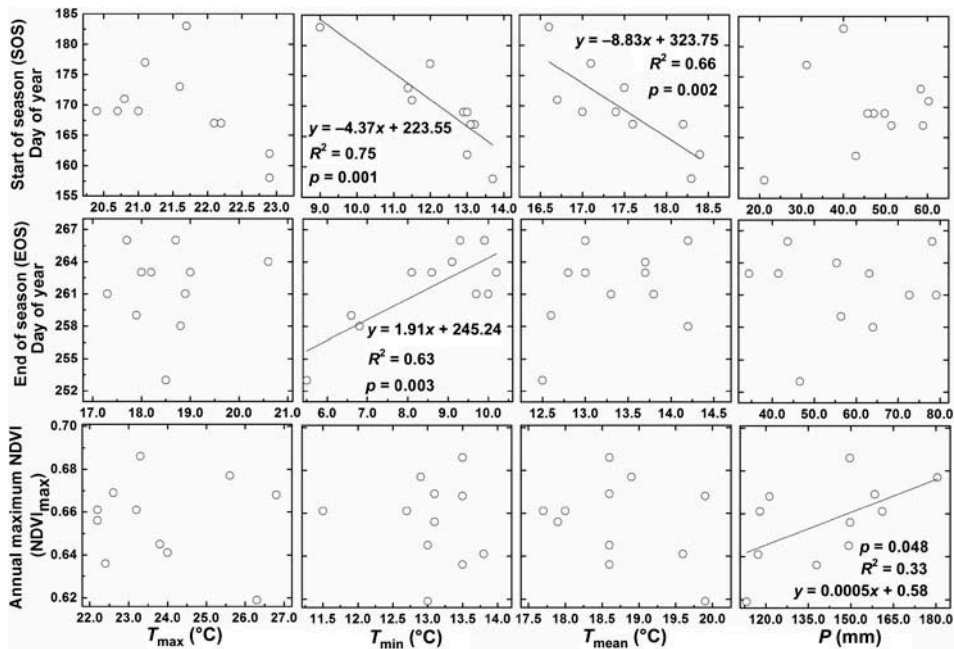


Figure 7. The scatterplots of relationships between phenological events and  $\text{NDVI}_{\max}$  and climate factors during 11 years from 2001 to 2011. The regression lines were calculated when those relationships were significant ( $p < 0.05$ ). The climatic parameters ( $T_{\max}$ ,  $T_{\min}$ ,  $T_{\text{mean}}$ , and  $P$ ) of June, July to August, and September correspond to SOS,  $\text{NDVI}_{\max}$ , and EOS, respectively.

Table 1. The correlation coefficients between phenological events, NDVI, and climate factors during 11 years from 2001 to 2011.

	SOS	EOS	GSL	$\text{NDVI}_{\text{mean}}$	$\text{NDVI}_{\max}$
$T_{\max}$	-0.51	0.09	0.52	-0.13	-0.11
$T_{\min}$	-0.87**	0.80**	0.18	0.24	-0.09
$T_{\text{mean}}$	-0.81**	0.35	0.59*	-0.17	-0.33
$P$	0.17	0.05	0.06	0.01	0.57*
AT	-0.11	0.38	0.23	0.09	-0.30
AP	-0.17	-0.22	0.03	-0.02	0.17

Notes: AT, annual average temperature; AP, annual cumulative precipitation. The climatic parameters ( $T_{\max}$ ,  $T_{\min}$ ,  $T_{\text{mean}}$ , and  $P$ ) of June and September correspond to SOS and EOS, respectively, and those from July to August matching with GSL,  $\text{NDVI}_{\text{mean}}$ , and  $\text{NDVI}_{\max}$ . Asterisk indicates significance of correlation: \*\* $p < 0.01$ ; \* $p < 0.05$  (Pearson's correlation test).

to the minimum temperature of September (Figure 7), and significantly positive relationship was found between them ( $r = 0.80$ ) (Table 1); this possibly implied that the higher the minimum air temperature in autumn, the greater the delay in the onset of dormancy. However, there was no clear correlation between GSL and minimum temperature during the growing season (i.e. from July to August). Additionally, the mean temperature of June was also negatively related with SOS ( $r = -0.81$ ). When we associated SOS and temperature in May, no significant relationship was found, as did EOS and temperature in August, with low correlation coefficient (all at  $r < 0.5$  and  $p > 0.1$ , data not shown).

The high sensitivity of forest growth to moisture in semi-arid regions during the growing season suggested that precipitation limited maximum photosynthetic efficiency of canopy, as indicated by the high degree of correlation (0.57) between NDVI<sub>max</sub> and precipitation. We also observed a weak negative relationship between NDVI<sub>max</sub> and mean temperature. Further, when considering climatic parameters on an annual basis, NDVI and both SOS and EOS exhibited a lack of distinct relationships with climate (Table 1).

## 4. Discussion

### 4.1. Using NDVI to detect phenology of an evergreen forest

Satellite-derived NDVI is considered useful for monitoring the dynamics of phenology in many biomes (Zhang et al. 2004; Xiao et al. 2005). However, research conducted in Japanese cedar forests indicated that the information provided by NDVI about seasonal changes in photosynthetic capacity was limited (Nagai et al. 2010, 2012) and showed almost constant values throughout the year.

This study clearly demonstrated a bell-shaped seasonal pattern in NDVI (Figures 4 and 5). The comparison between MODIS-derived and TM-based NDVI of the forest in our study site (Table 2) showed that the amplitudes of NDVI were comparable; existing differences in NDVI values were probably due to the discrepancy in wavelengths of red and near-infrared bands between the two sensors. The annual pattern of NDVI not only reflects the outcomes of effective light absorption in leaves during photosynthesis but also indicates the effect of snowmelt on NDVI in early spring. If the timing of snowmelt overlapped with that of SOS, we could not determine whether the signal was triggered by the growth of the forest. However, the course of snowmelt has been accomplished before the onset of SOS, with no clear correlation between both. In the Qilian Mountains, only less than 35% of the annual rainfall, averaged 150–200 mm year<sup>-1</sup>, is distributed in other three seasons except summer (He et al. 2013). Generally, as temperature increases to above zero during May, the thin snow deposition begins thawing quickly, and the snowmelt persists for a short period of time, often not more than half a month. Therefore, the time lags between snowmelt and the onset of SOS lasted approximately from one to two weeks (Figure 5). Chen and Cihlar (1996) pointed out that satellite-observed radiance was also affected by the forest floor in sparse coniferous forests. However, the influence of moss in the nearly closed forest is slight, almost negligible (Bernier et al. 2011).

The discrepancy between the results of Nagai et al. (2012) and those from our study is likely due to the differences in species composition, which create the disparity between photosynthetic and structural characteristics (Nasahara et al. 2008). As testified by the

Table 2. Summary of the NDVI derived from TM data at 30 m scale and MODIS data with 250 m scale in the forest.

Date	NDVI <sub>TM</sub>				NDVI <sub>MODIS</sub>			
	Mean	SD	25th	75th	Mean	SD	25th	75th
August 2010	0.44	0.07	0.40	0.49	0.66	0.08	0.62	0.71
June 2010	0.25	0.10	0.18	0.33	0.54	0.09	0.47	0.58
AM	0.19		0.22	0.16	0.12		0.15	0.13

Note: SD, standard deviation; AM, amplitude modulation; *i*th indicates the *i*th percentile of the distributions.



research of Zhao, Shen, and Peng (2009), the NDVI in *P. crassifolia* forest has a significant positive relationship with LAI. The seasonality of LAI, probably due to the partial loss of reddish-green needles caused by wind disturbance in winter, can also cause the change of spectral radiance characteristics (Nasahara et al. 2008), triggering the seasonal pattern of NDVI. In this work, we used the original reflectance instead of BRDF corrected data, because we found no obvious distortion in resulting NDVI time series (see Section 3) and the comparable results of MODIS<sub>NDVI</sub> and TM<sub>NDVI</sub> (Table 2). This may be related to the less extent of sensor zenith angle (16°) and canopy characteristics (e.g. approximate 30° of mean leaf angle, regular leaf distribution, and more than 0.7 of crown density). Indeed, as the directional signatures are similar in the red and near-infrared bands, most indices based on their ratios (e.g. NDVI) are less sensitive to directional effect compared to individual reflectance (Bréon and Vermote 2012). Moreover, previous studies about the influence of view geometry on vegetation index variation using models of BRDF revealed a small or even negligible effect (Asrar, Myneni, and Choudhury 1992; Wardley 1984).

Cloud contamination is one of the most pervasive obstacles to quantifying phenology of evergreen coniferous forest in mountain regions with optical satellite remote sensing. In the Qilian Mountains, more than 40% of days each year are cloudy, the degree of cloudiness further increasing in the growing season (from June to September). Consequently, the temporal resolution of phenological observations is limited. Other studies documented that the composite-images method could be used to alleviate this limitation (Delbart et al. 2006; Kross et al. 2011). Our study revealed that the 8 day composite method for obtaining the best possible observation is suitable for mountain zones. Nagai et al. (2012) suggested a camera-based canopy surface index method to identify the phenology of evergreen coniferous forest. Although phenological observations using a digital camera facilitate ground-truthing on a daily time-step, this method is not practical over broad areas, especially in regions that contain various types of vegetation and complex topography.

#### 4.2. Climatic controls on phenology

The responses of vegetation to increased Earth surface temperature are of substantial concern for the scientific community (Pettorelli et al. 2005). The impacts of climatic change on vegetation are manifested not only as altered spatial distribution, productivity, and biodiversity but also as altered phenology (Kross et al. 2011). Yet, the interaction between climate and forest phenology has been explored in a few studies so far, generally for deciduous species.

Our results suggested that temperature determined the annual timing of phenology in *P. crassifolia*, especially the minimum temperature in late spring (for SOS) and early autumn (for EOS) (Figure 7 and Table 1). For temperate and boreal trees, all which overwinter as *P. crassifolia*, the SOS seems to be most frequently controlled by temperature (Delbart et al. 2006; Borchert et al. 2005; Cayan et al. 2001; Menzel and Fabian 1999), due to cambium development proceeding after a critical cumulative temperature is reached. Generally, warm springs with low precipitation contribute to an earlier snowmelt and soil warming, thus leading to an earlier start of the growing season (Chhin et al. 2008) (e.g. the highest  $T_{\min}$  in June 2001, with the earliest onset of SOS correspondingly). In the Qilian Mountains, the soil depth normally ranges from 30 to 100 cm (unpublished data). For most of the study area, there is a rough consistency between the surface and soil temperature ( $r = 0.96$ ,  $p < 0.001$ ), due to the tenuous layer. Therefore, the minimum air

temperature significantly affects soil thawing in spring and freezing in autumn leading to alterations in mineralization rates and nutrient availability, which, in turn, have an influence on both the start and the end of the growing season (Vanwijk et al. 2003). Indeed, changes in phenology in high altitude temperate forests may be more evident and direct as a result of global warming; for example, tree recruitment rate is anticipated to accelerate as a result of the increase in the mean minimum temperature in June and in winter (He et al. 2013). Our results provided an evidence for the minimum temperature control of some phenological events (i.e. SOS and EOS). This constitutes strong support for including minimum temperature in simulations in ecological models (Bondeau, Kicklighter, and Kaduk 1999). However, we found that GSL lacks sensitivity on the minimum temperature during the growing season, suggesting that the minimum temperature is no longer a limiting factor for tree growth if the degree of thermal requirement reached. Additionally, we did not detect the lag effect of climate on phenological events, perhaps indicating that phenology could be regarded as a direct response to climate change in our forests.

We showed that the rainfall conditions during the vegetative period are limiting forest growth in this forest. This was expected, as rainfall is a major climatic restriction to vegetation growth in semi-arid regions. In general, the likelihood of detecting a trend in  $NDVI_{max}$  dynamics is expected to be affected by the variability in cumulative precipitation (Svoray and Karnieli 2011; Ichii, Kawabata, and Yamaguchi 2002). In contrast, unusual warming may enhance water stress in semi-arid ecosystems (Braswell et al. 1997), consequently influencing growth of vegetation by increasing water consumption during transpiration; accordingly, the relationship between  $NDVI_{max}$  and temperature was negative in this study (Table 1).

Many attempts were made to predict the potential vulnerability of forests to future climatic change (Chhin et al. 2008; Bunn, Scott, and Fiske 2005). For example, given predicted changes in climate, Schrag, Bunn, and Graumlich (2008) reported an overall decrease of pine-dominated subalpine forests in the Greater Yellowstone Ecosystem. However, this influence on distribution may not be as direct and profound as that on phenology. Morin et al. (2010) investigated the response of different forest species to experimental climate change, revealing that warming caused a longer growing season by advancing the seedling's vegetative phenology and the date of leaf expansion. We found in this study that the minimum temperature may play an important role in controlling vegetation phenology. Further research may need to focus on the complexity of the response of vegetation phenology to climate change, such as effects of the combination of multiple climate variables on phenology, and dissimilarity and collinearity of responses to climate change for different species.

## 5. Conclusions

An accurate understanding of the response of forest phenology to climate on regional scales is critical to the evaluation of the biochemical cycles (i.e. carbon, water, energy, and nutrient) under recent environmental changes. Satellite-derived data have become a potential 'goldmine' for ecologists. Although the use of NDVI for monitoring phenological events in evergreen coniferous forests has some limitations, we illustrated that NDVI was a very useful tool in efforts to gain a better understanding of ecological effects of environmental change on ecosystem functioning in this forest type.

In this study, we demonstrated the primary role of minimum temperature in controlling the dynamics of SOS and EOS; additionally, precipitation was coupled to the shift in

maximum NDVI. Indeed, many other climate factors need to be taken into account in further analyses, such as potential changes in soil moisture and temperature, duration of insolation, effective solar radiation, and depth of soil freezing, among others. Moreover, identifying and quantifying climatic constraints on phenological dynamics in forests is a complex task that needs to be addressed at appropriate scales.

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