



# Elevation-influenced variation in canopy and stem phenology of Qinghai spruce, central Qilian Mountains, northeastern Tibetan Plateau

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Received: 14 August 2018 / Accepted: 3 January 2019 / Published online: 7 January 2019  
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## Abstract

**Key message** Canopy and stem phenology of Qinghai spruce, central Qilian Mountains, respond to different environmental factors depending on season and elevation.

**Abstract** To understand vegetation species response to climate change, much research has been devoted to changes in forest phenology. Results of such studies are not only of scientific interest; they are potentially of great use in forest management. This study focuses on variations in canopy and stem phenology as affected by climate and elevation. We collected data on canopy phenology (as recorded in the Normalized Differential Vegetation Index) and stem phenology [using the Vaganov–Shashkin (V–S) model] in Qinghai spruce (*Picea crassifolia*) growing at two sites in the central Qilian Mountains, Northeast Tibetan Plateau. One site was at a higher elevation, near the local alpine tree-line, and the other was near the local lower tree-line. At both sites, a significant correlation was found between canopy and stem spring phenology. This would seem to be mainly due to spring temperatures. No such correlation was found between canopy and stem autumn phenology. The study suggests that the main factors affecting stem growth after the beginning of growing season would be temperature and soil moisture, and that these have different effects depending on elevation. At the lower elevation, soil moisture seems to be the main factor limiting growth. At the higher elevation, temperature was the determining factor. Climate change will have different effects depending on elevation.

**Keywords** Spring phenology · *Picea crassifolia* · Stem radial growth · Forest management

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Communicated by E. Liang.

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Xiaomei Peng and Jun Du Co-first author.

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**Electronic supplementary material** The online version of this article (<https://doi.org/10.1007/s00468-019-01810-z>) contains supplementary material, which is available to authorized users.

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## Introduction

Phenology is attracting much research interest of late. Temporal changes in phenology reflect on-going climate change (Parmesan and Yohe 2003; Peñuelas et al. 2013). Climate change is having, and will have, profound impacts on species ranges, primary productivity, and the vegetation carbon cycle (Settele et al. 2014). It is particularly important to understand the phenology of forests, as climate change has already caused extensive tree mortality and widespread forest die-back in many regions [e.g. (Allen et al. 2010; Carnicer and Mooney 2011; Anderegg et al. 2013; Liu et al. 2013)].

Many studies of forest phenology have focused on canopy phenology. Researchers have noted changes in bud burst, flowering, and leaf defoliation (Chmielewski and Rötzer 2001; Ahl et al. 2006). They have used canopy phenology to assess species ability to adapt to local environmental conditions (Du et al. 2014; Jones et al. 2014) and to predict

growing-season changes under global climate change. Canopy phenology studies have been based to a large extent on data from deciduous broadleaf forests (Kross et al. 2011; Schwartz et al. 2002); much less interest has been shown in coniferous forests.

Tree stem phenology research has also gained attention in recent years, as it is central to dendroclimatology and dendroecology studies (Deslauriers et al. 2008; Rossi et al. 2008; Li et al. 2013; Yang et al. 2017). Plant stems constitute good records of apical and radial growth (which depend on the net photosynthetic product of leaves) (Deslauriers et al. 2017); long-lived species can record environmental variation over long time scales. Conifers have been a major source of data for dendroclimatology and dendroecology studies (George 2014).

Some researchers have looked at both stem and canopy phenology (Rossi et al. 2009; Cuny et al. 2012; Antonucci et al. 2015; Perrin et al. 2017). It is important to know how each type of phenology responds to environmental variation. Comparison of these responses can help to understand the relationship between apical and lateral meristems, and thus tree physiology in general. If stem and canopy studies are to be combined, then a good starting point would be conifers, and in particular, the Qinghai spruce (*Picea crassifolia*). This is one of the conifer species that has been the target of both canopy phenology and dendrochronological studies (Du et al. 2014; Liu et al. 2016).

The Qilian Mountains are located in the northeastern area of the Qinghai-Tibet Plateau. They are home to several long-lived tree species, which have been the subject of a large number of dendrochronology studies (Yang et al. 2014; Zhang et al. 2015; Liang et al. 2016). Qinghai spruce is one of those long-lived species; it is also one of the dominant species in the Qilian forests, accounting for more than half of the total forest area (Cheng et al. 2014; Zhu et al. 2017). These forests have been noticeably affected by global climate change. Starting in the 1960s, the average temperature has risen by 0.26 °C per decade in this region (Du et al. 2014). One would expect changes in Qinghai spruce phenology and physiology, and indeed, those changes have been observed and studied (Chen et al. 2011; Chang et al. 2014; Tian et al. 2017).

The current study builds on previous scientific work in the Qilian region. We have collected both tree-ring width records and canopy phenology data in an effort to elucidate the long-term relationship between the stem and canopy phenology of the Qinghai spruce. It should be noted that there are no long-term, large-scale field observations of bud and stem cambial activity in this area. For the stem phenology data, we used a Vaganov–Shashkin (V–S) model (Anchukaitis et al. 2006; Evans et al. 2006; Vaganov et al. 2006). We relied upon remote sensing data for a long-term record of canopy phenology (Du et al. 2014).

The specific objectives of this study were to detect the temporal relationship between the stem and canopy phenology in virgin Qinghai spruce stands in two elevations in the central Qilian Mountains and to determine how both have been affected by climate change. Phenology reflects the adaptation of plants to their environment, hence it is of great importance to learn their response to climate in different elevations. The results are also of great potential assistance to scientific forest management.

## Materials and methods

### Study area and study species

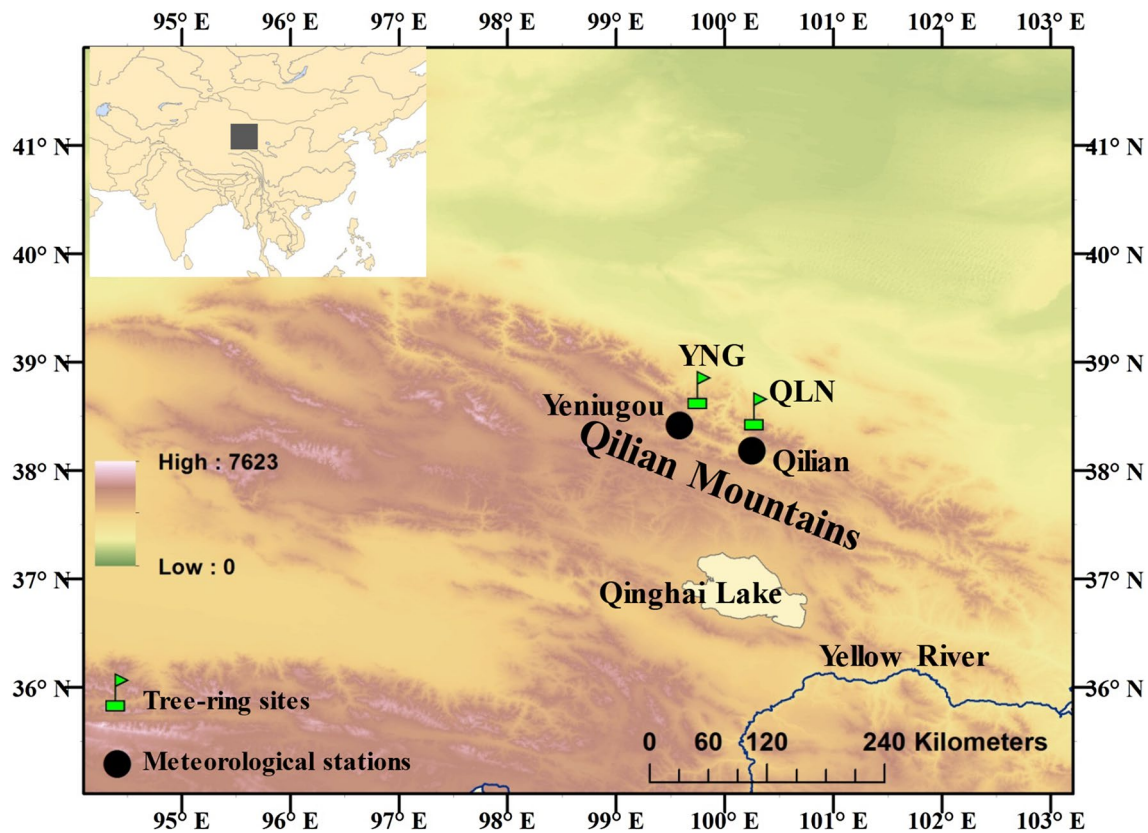
The study was conducted at two sites in the central Qilian Mountains (Fig. 1). One site, QLN, is located close to the Qilian meteorological station (elevation 2787 m). The other site, YNG, is close to the Yeniugou meteorological station (elevation 3320 m). Both the study sites lie in a forested region with a temperate continental climate. Annual rainfall is concentrated in a five-month period, from May to September. Over the period 1960–2014, the mean annual air temperature as measured at the Qilian meteorological station was 0.2 °C. During the same period, the Yeniugou meteorological station showed a mean annual temperature of –0.9 °C. The maximum and minimum mean daily air temperatures were 22.2 °C max and –25.5 °C min for Qilian, and 20.6 °C max and –26.2 °C min for Yeniugou. Mean annual precipitation was 409 mm for Qilian and 419 mm for Yeniugou.

Qinghai spruce is found at elevations ranging from about 2500 to 3400 m a.s.l. The mean height of the mature spruce ranges from 5 to 11 m; the average stand density is about 2400 stems ha<sup>-1</sup>. The leaf area index (LAI) of canopies averages approximately 2.0 (Du et al. 2014).

### Tree-ring chronology and modeling

Following standard dendrochronological methods, tree-ring samples were collected from site QLN (Fig. 1b) in May 2015 and from site YNG in 2007 and 2016. Increment cores (one or two cores) were extracted at breast height from presumably old and healthy trees, which were growing in virgin stands. Trees sampled grew from 2700 to 2900 m at the QLN site (near the local lower tree-line), and from 2900 to 3100 m at the YNG site (near the local alpine tree-line).

The cores were mounted, air-dried, and sanded to make the vessels and rings visible. Ring widths were measured using a Lintab tree-ring measuring system (<http://www.rinntech.de>) with a precision of 0.001 mm. The quality of the cross-dating was confirmed using COFECHA software (Grissino-Mayer 2001). No missing rings were found. The



**Fig. 1** Tree ring sampling sites and meteorological stations

ring-width chronologies were constructed using RCSsig-Free\_v45 software (Melvin and Briffa 2008) (<http://www.ideo.columbia.edu/tree-ring-laboratory/resources/software>). Age-related growth trends were removed for all samples, using a cubic spline curve. We used an expressed-population signal greater than 0.85 (Wigley et al. 1984; Briffa and Jones 1990) to identify the reliable parts of each ring-width chronology. We collected several descriptive statistics to characterize the chronology: the mean segment lengths of the cores, mean sensitivity, and mean correlation between series.

We used the Vaganov–Shashkin (V–S) model (Anchukaitis et al. 2006; Evans et al. 2006; Vaganov et al. 2006) to establish a model of stem phenology time-series for the two research sites. 1960–2014 data from the Qilian and Yeniugou meteorological stations (records of climate, daily temperature, precipitation) were used as inputs. Even though these stations were not located at the research sites, they were close enough that climate conditions were similar. We attempted to partially correct temperature inputs for the elevation difference between the YNG tree-ring site and the Yeniugou meteorological station with an adiabatic correction of 5.6 °C/km (Chen et al. 2014). This suggested a temperature correction of 1.96 °C. No temperature correction

was applied to the data from site QLN; it is quite close to the same elevation as the Qilian meteorological station.

Modeled and actual tree-ring width chronologies were compared. The model was adjusted to attain the highest possible Pearson correlation coefficient. We also used data from a 1-year (2014) dendrometer-detected tree-ring growth study conducted by Tian et al. (2017) at the QLN site. Data for altitudes of 2700 and 2800 m a.s.l. were collected, which served as a useful reference when tuning model parameters. The stem phenology records thus obtained were used to determine seasonal transition dates: start and end of stem growth season (SOSs and EOSs). We could then investigate which major factors were influencing SOSs, EOSs, and the whole stem radial growth season.

### Canopy phenology using remote sensing data

We used remote-sensing data (GIMMS and MODIS NDVI) collected from 1982 to 2014 over the Qilian Mountains. The Normalized Differential Vegetation Index (NDVI) is based on the differential reflectance of green vegetation in the infrared and near-infrared bands. It is used as an indicator of plant canopy greenness and productivity, as it has been shown to be strongly correlated with the strength of

photosynthetic activity (Pettorelli et al. 2005; Jeong et al. 2011; Zhang et al. 2013). The time-series NDVI data did require some pre-processing before use. Snow coverage during the non-growing season and poor atmospheric conditions (e.g. clouds) add noise to the data and depress NDVI values. After noise elimination, the NDVI time series were fitted (using a double-logistic function based on non-linear least-squares method) to the upper envelope of NDVI data (Jönsson and Eklundh 2004). We extracted the pixels representing the locations of the meteorological stations from the satellite data for further analysis.

We used the inflection-point-based method to determine two transition dates: start of canopy growth season (SOSc) and the end of canopy growth season (EOSc). This method has been used to study a variety of biomes in different climatic zones and has been well-validated by many researchers [see, among others, (Schwartz et al. 2002; Yang et al. 2012; Du et al. 2014)]. It is based on the rate of change of the fitted NDVI curve, that is, the derivative of the curvature. We defined the dates of SOSc or EOSc as the dates on which RC values achieved local maxima on the left (SOSc) or the right (EOSc) edge of the annual curve.

## Statistical analysis

We analyzed the relationship between climate and tree stem radial growth for the period 1960–2014 through correlation analysis of ring-width chronology and the climatic data. We used DendroClim2002 software (Biondi and Waikul 2004). The meteorological data used: mean monthly temperature and monthly total precipitation. Statistical significance levels were estimated with two-tailed significance tests.

We used Pearson's correlation coefficient and multiple linear regression analysis to investigate the influence of climate factors that could be controlling SOSc and EOSc variation. As the V–S model works with three main factors, we investigated the effects of eighteen variables: six warmth-related (mean temperatures 10, 20, 30, 60, 90 and 120 days before mean SOSc and EOSc); six precipitation-related variables (total precipitation 10, 20, 30, 60, 90 and 120 days before mean SOSc and EOSc); and six sunlight-related variables (10, 20, 30, 60, 90 and 120 days of accumulated sunshine time before mean SOSc and EOSc).

A multiple linear regression model was used to identify the eighteen variables responsible for the shifts in SOSc and EOSc using R (R Development Core Team 2018). We used the R relainpo package to evaluate the relative importance of the variables. To eliminate the effects of multicollinearity, only three variables (one warmth-related, one precipitation-related, and one sunlight-related) were used in each separate analysis. Each variable was standardized before performing linear regression analysis. 216 models were built for each

SOSc and EOSc in each of the two sites, for a total of 864 models.

## Results

### Ring-width chronologies and response to climate

Table 1 summarizes the statistical characteristics of the ring width chronologies. The mean segment length of cores at site QLN was 84 years; for YNG it was 156 years. Mean sensitivity values were 0.30 and 0.16; inter-serial correlation values were 0.77 and 0.57. We have a reliable ring-width chronology for site QLN for the period 1894–2014. The chronology for site YNG runs from 1803 to 2016 (see Fig. 2 for both chronologies). Because we only had reliable instrumental climate records for the period 1960–2014, we have only used the ring-width records for the same period.

Correlation analysis showed that at site QLN radial growth was positively and significantly correlated with precipitation in May, June, and the previous September ( $P < 0.05$ ). No significant correlation with temperature was found (Fig. 3). At site YNG there was a significant correlation between radial growth and temperature in last autumn and from current May to July. There was also a significant correlation with precipitation in May ( $P < 0.05$ ) (see Fig. 3).

### Stem phenology and climate

Using the parameters listed in Table 2, we found highly significant ( $P < 0.01$ ) positive relationships between the actual tree ring width chronologies and the simulated ones. Correlation coefficients between actual and simulated chronologies were 0.61 for both Qilian and Yeniugou meteorological stations, from 1960 to 2014 (Fig. 2), demonstrating that confidence in our V–S model simulation was not misplaced.

Stem radial growth in site QLN seems to be mainly sensitive to the availability of water, although during time periods at the beginning of growing season, temperature can become an important factor. Radial growth begins close to or in May

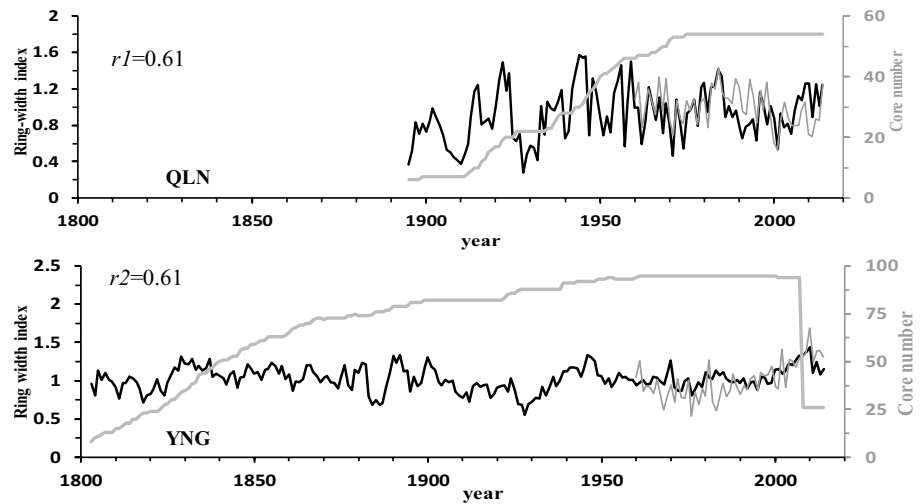
**Table 1** Tree-ring sampling sites and summary statistics of the stand chronologies

Site	Cores and trees cross-dated	ML (years)	Chronology period	MS	MC
QLN	62, 35	84	1894–2014	0.30	0.77
YNG	97, 61	156	1803–2016	0.16	0.57

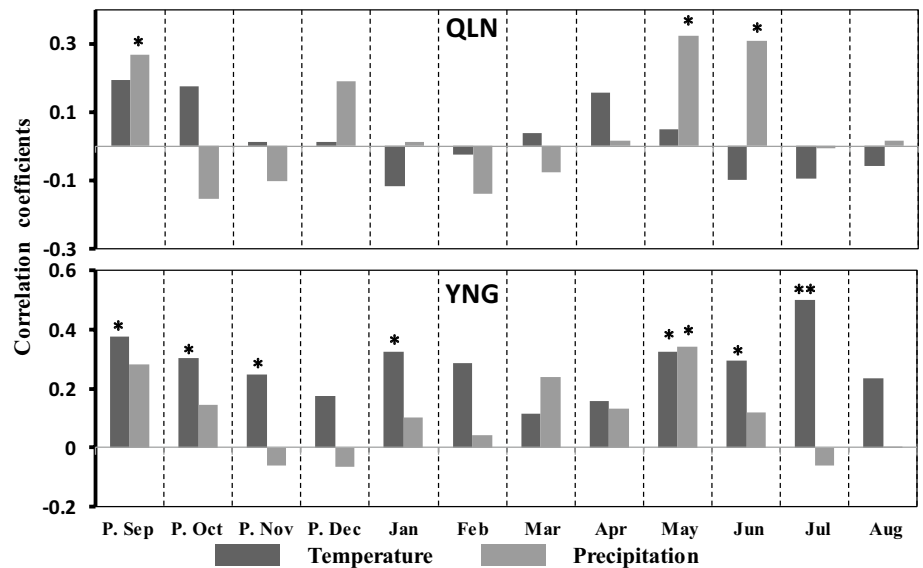
Figure 1 shows the location of the study sites

Mean segment length (ML), mean sensitivity (MS), and mean correlation (MC) between the series refer to the statistical characteristics of the raw ring-width series

**Fig. 2** Observed (solid black line) and simulated (dotted gray line) chronologies of tree-ring width.  $r_1$  and  $r_2$  are the Pearson correlation coefficients for observed/simulated chronologies for both study sites. Correlation between observed and simulated chronologies was significant at a  $P < 0.01$  level



**Fig. 3** Pearson correlation coefficients between observed tree-ring chronologies and observed monthly temperature (black bar) and total precipitation (gray bar) from previous September to current August. QLN is the study site close to the Qilian meteorological station; YNG is the study site close to Yeniugou station. Correlation significance levels (two-tailed test): \* $P < 0.05$ ; \*\* $P < 0.01$



for site QLN (Fig. 4). Growth remains high until the end of June, which we believe is due to net positive precipitation-evaporation in May and June. This is followed by a relatively dry period from June until the end of August, resulting in a drastic decrease in growth. Although there is again more available water in the fall, growth seems to be limited by temperature as the growing season draws to a close. 10 and 20 days before the EOSs in QLN, more than half of the days were temperature-limited. However, 30, 60, 90, and 120 days before the QNG EOSs, the majority of days were moisture-limited (Table 3). The SOSs in site QLN ranged from the middle April to early June; SOSs had a mean value of 142 ordinal days. The EOSs QLN ranged from 242 to 276 ordinal days. The mean value was 259 ordinal days.

At site YNG, tree-ring formation seems to be limited by temperature throughout the course of the growing season. However, water availability (from spring melt) seems to have

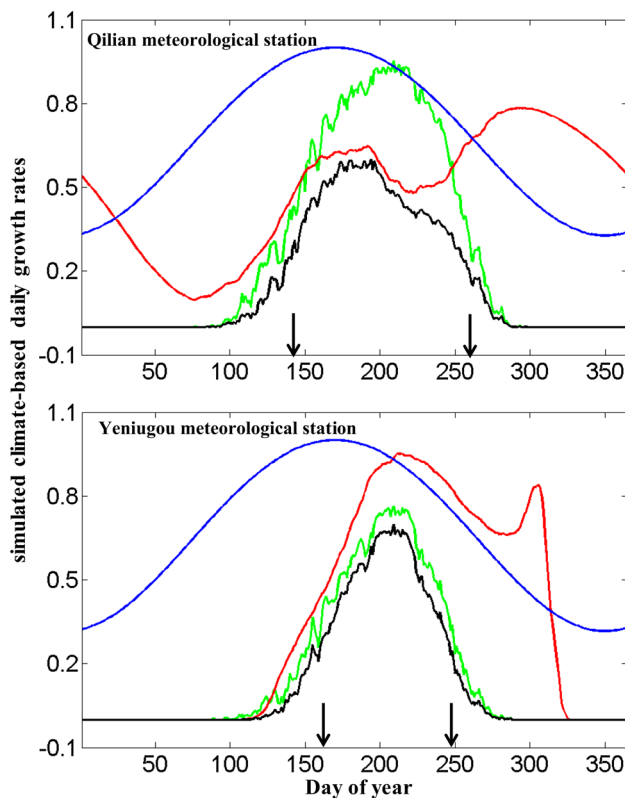
some influence in early May (Fig. 4). 10, 20, 30, 60, 90, and 120 days before EOSs, more than 70% of the days were temperature-limited. Temperature seems to be the major factor influencing SOSs for both sites. 10, 20, 30, 60, 90, and 120 days before the date of SOSs, more than 50% of the days that were temperature-limited (Table 3). The average stem-growth season at site QLN is 117 days; at site YNG it is shorter, at 85 days. Average SOSs for YNG was 163 ordinal days. Average EOSs for YNG was 248 ordinal days.

### Canopy phenology and climate

At site YNG, SOSc ranged from ordinal days 141 to 177. The earliest date was in 2004; the latest was in 1992. The earliest onset of canopy dormancy occurred in 1991 (day 258), and the latest in 1993 (day 287) (see Fig. 5). At site

**Table 2** Parameters used in designing a Vaganov–Shashkin (V–S) tree-ring formation model

Parameter	Description (units)	Value	
		QLN	YNG
$T_{\min}$	Minimum temperature for growth	5.5	5.5
$T_{\text{opt1}}$	Lower optimal temperature	13	14
$T_{\text{opt2}}$	Upper optimal temperature	22	22
$T_{\max}$	Maximum temperature for growth	28	28
$W_{\min}$	Minimum soil moisture for growth	0.08	0.05
$W_{\text{opt1}}$	Lower optimal soil moisture	0.14	0.18
$W_{\text{opt2}}$	Upper optimal soil moisture	0.24	0.24
$W_{\max}$	Maximum soil moisture for growth	0.4	0.4
$T_{\text{beg}}$	Sum of temperature for begin of growth	10	10
$D_{\text{root}}$	The root/soil thaw depth (mm)	900	500
$P_{\max}$	Maximum rate of water infiltration into soil (mm/day)	5	5
$a(1)$	First coefficient of soil thaw	22.5	22
$a(2)$	Second coefficient of soil thaw	0.006	0.005
$T_m$	Sum of temperature for start of soil thaw	5	5
$W_{\min}$	Minimum soil moisture	0.04	0.04
$W_{\max}$	Maximum soil moisture	0.5	0.5
$k(1)$	Constant about the tree crown interception	0.45	0.45
$k(2)$	First coefficient transpiration calculation	0.21	0.11
$k(3)$	Second coefficient transpiration calculation	0.2	0.13

**Fig. 4** The simulated daily mean radial growth response to: **a** sunlight (blue line), temperature (green line), soil moisture (red line), **b** these three factors combined (black line). Mean V–S model based SOSs and EOSs are indicated by arrows

QLN, SOSc ranged from ordinal days 142–170. The EOSc at QLN ranged from ordinal days 263 to 289.

Figure 6 shows correlations between SOSc, EOSc, and the eighteen explanatory factors used in our analyses. It is apparent that warmth factors have higher correlation coefficients with both QLN and YNG SOSc than do the precipitation and sunlight variables. Mean temperature at 90 days before the SOSc ( $T_{90}$ ) seems to be the most influential factor at both sites (Table 4). Few of the eighteen variables showed any significant correlation with EOSc. The variance percentages correlated with those variables were low for both sites. Of the six sunlight variables, only two, when correlated with SOSc and EOSc, displayed  $P < 0.05$  levels of significance.

### Comparisons between stem and canopy phenology

Stem and canopy spring phenology showed similar patterns, as indicated by the significant correlation coefficients (0.46 and 0.56) between SOSs and SOSc at both QLN and YNG (Fig. 5). This may result from the same temperature impact factor ( $T_{90}$ ) of SOSs and SOSc at both sites (Tables 3, 4). Significantly ( $P < 0.05$ ) advancing trends were seen for the period 1982–2014 in SOSs at both sites. The significant earlier SOSc was seen at QLN. none of the linear trends in EOSc and EOSs at both sites were significant ( $P < 0.05$ ).

Correlation coefficients between the EOSs and EOSc at both sites were low and did not reach a significant level ( $P < 0.05$ ). This could be attributed to the long interval

**Table 3** Percentage of days (%) limited by temperature, soil moisture and sunlight variables, as predicted by our V–S tree-ring formation model

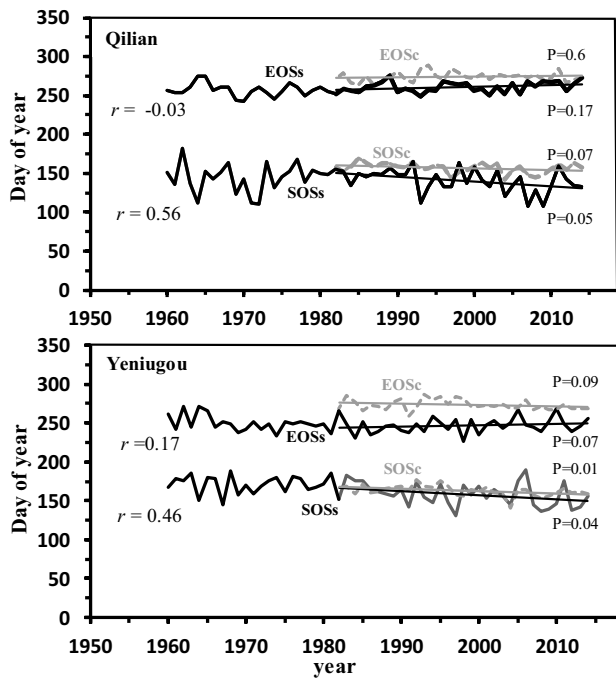
QLN SOSs			QLN EOSs		
Variables (%)			Variables (%)		
T_10 (52.2)	W_10 (47.6)	S_10 (0.1)	T_10 (66.0)	W_10 (32.9)	S_10 (1.1)
T_20 (57.8)	W_20 (42.1)	S_20 (0.1)	T_20 (54.5)	W_20 (44.1)	S_20 (1.4)
T_30 (63.4)	W_30 (36.5)	S_30 (0.1)	T_30 (42.5)	W_30 (56.4)	S_30 (1.1)
T_60 (77.3)	W_60 (11.3)	S_60 (11.3)	T_60 (26.3)	W_60 (72.4)	S_60 (1.2)
T_90 (73.4)	W_90 (18.7)	S_90 (8.0)	T_90 (25.6)	W_90 (73.4)	S_90 (1.1)
T_120 (86.8)	W_120 (12.3)	S_120 (0)	T_120 (30.7)	W_120 (68.5)	S_120 (0.8)
YNG SOSs			YNG EOSs		
Variables (%)			Variables (%)		
T_10 (60.4)	W_10 (39.6)	S_10 (0)	T_10 (83.8)	W_10 (6.5)	S_10 (9.6)
T_20 (63.5)	W_20 (36.5)	S_20 (0)	T_20 (84.5)	W_20 (4.7)	S_20 (10.7)
T_30 (65.4)	W_30 (34.6)	S_30 (0)	T_30 (80.4)	W_30 (6.4)	S_30 (13.2)
T_60 (73.1)	W_60 (26.9)	S_60 (0)	T_60 (77.3)	W_60 (11.3)	S_60 (11.4)
T_90 (81.5)	W_90 (18.5)	S_90 (0)	T_90 (73.4)	W_90 (18.7)	S_90 (8.0)
T_120 (86.1)	W_120 (13.9)	S_120 (0)	T_120 (72.3)	W_120 (21.7)	S_120 (6.0)

Variables included in model; days are days before the mean value of SOSs and EOSs

Mean temperatures at 10, 20, 30, 60, 90, and 120 days (T\_10, T\_20, T\_30, T\_60, T\_90, and T\_120)

Soil moisture at W\_10, W\_20, W\_30, W\_60, W\_90, and W\_120

Sunlight at S\_10, S\_20, S\_30, S\_60, S\_90, S\_120



**Fig. 5** Characteristics of the SOSs and EOSs derived from the V–S model (solid black line) and the SOSc and EOSc derived from remote sensing data (dotted gray line). Thin black lines show linear trends, 1982–2014. *r* is the Pearson correlation coefficient between the SOSs and SOSc, and between EOSs and EOSc. *P* is the significance of their linear trend

between EOSc and EOSs, and the different factors affecting EOSc and EOSs (Tables 3, 4). The interval EOSc–EOSs at QLN was 14.6 days on average. the interval EOSc–EOSs at YNG was 26.2 days on average. Temperature and moisture levels before EOSs had the greatest effect on the timing of EOSs at both sites. On the contrary, climate seems to play a little role in the variation of EOSc (Tables 3, 4). EOSc preceded EOSs at both sites.

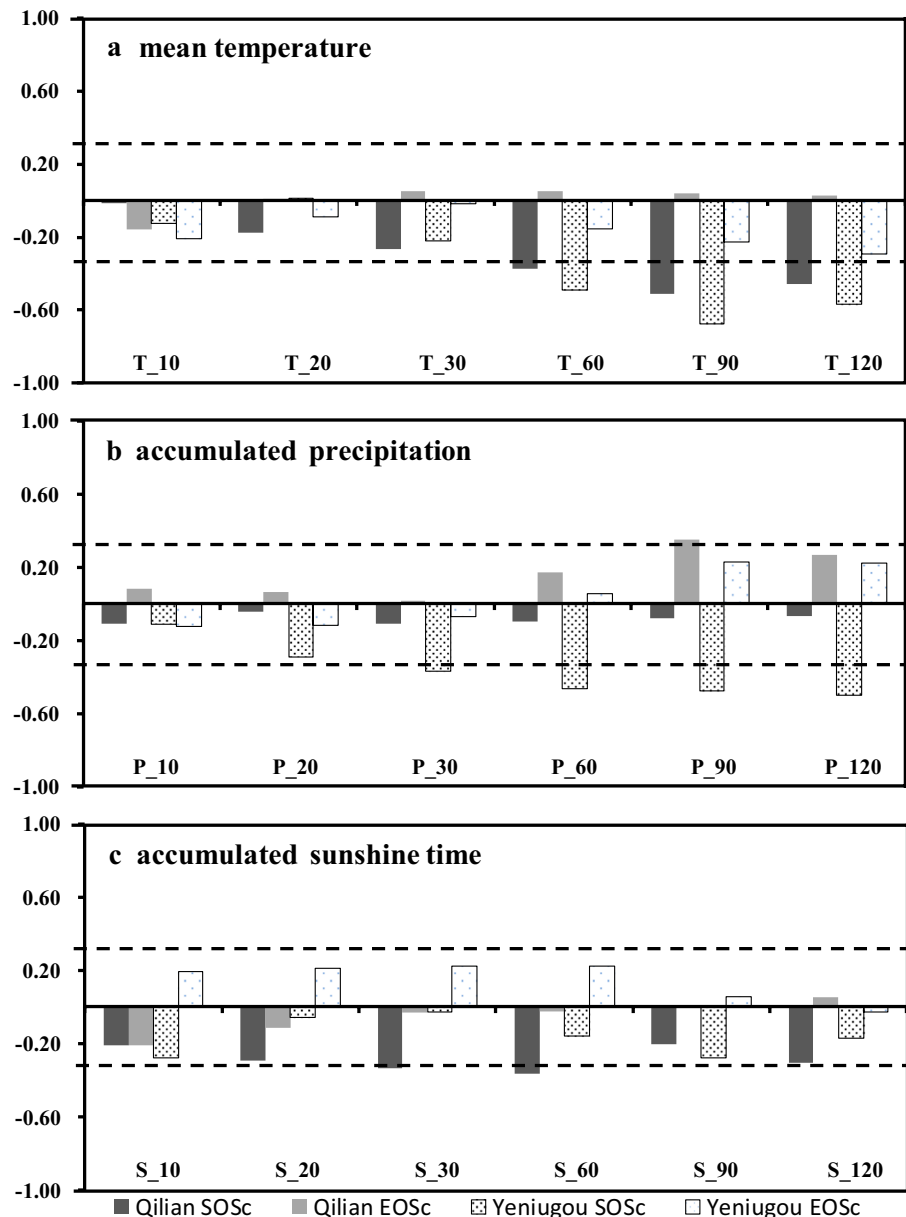
## Discussion

### Impact of climate on canopy and stem phenology

#### SOS

Our research indicated that there is a significant correlation between the start of the start of stem radial growth season and canopy growth season at sites QLN and YNG during the period 1982–2014 (Fig. 5). Another study of cold-region black spruce also showed synchronism between xylem and bud formation phenology (Perrin et al. 2017). As the mean spring temperature in two sites was increasing ( $P < 0.01$ , ESM\_1), SOSc and SOSs for two sites also increased ( $P < 0.05$ ). Recent observational and experimental studies in cold regions suggest that global warming has led to earlier SOS in the Northern Hemisphere

**Fig. 6** Pearson correlation coefficients ( $r$ ) between the remote sensing data based SOSc and EOSc and the eighteen variables. See Table 4 for an expansion of the abbreviations. See Fig. 1 for the locations of the two meteorological stations. Horizontal dotted lines indicate 95% confidence intervals of the correlation coefficients



(Settele et al. 2014). A recent study (Tian et al. 2017) near site QLN has suggested that warmer soil temperatures at the start of the growing season could favor root activity. This would allow for the transport of more water and nutrients for xylem cell growth. Moisture-related variables were the second-most important driver of stem phenology in the spring (Table 3). Drought stress may delay the onset of cambial cell division at drought-prone forest sites (Ren et al. 2018). This relationship has also been observed (using remote-sensing) for the Tibetan Plateau as a whole. Variations in available moisture strongly affect the spring vegetation green-up date (Piao et al. 2011; Ding et al. 2016).

## EOS

None of the three climatic variables (temperature, moisture, and sunlight) seem to have played important roles in variations in EOSc at either study site (Table 4). We infer that canopy growth may cease due to endogenous factors (Körner and Basler 2010; Cooke et al. 2012). Environmental influence on phenology may be marginal.

At both sites, the end of stem growth preceded the end of canopy growth. It is possible that, after the stem growth ended, the tree has to store sufficient photosynthetic products to sustain the plant over the winter and during the following spring. This hypothesis is supported by the fact that tree-ring width chronologies are significantly correlated with autumn



**Table 4** Percentage of variance in timing of SOSc and EOSc (% of  $R^2$ ) explained by the most significant multiple linear regression models of temperature, precipitation, and sunlight at selected times

QLN SOSc				QLN EOSc			
Variable name ( $R^2$ )		Model $R^2$		Variable name ( $R^2$ )		Model $R^2$	
T_120 (21.4)	P_20 (3.3)	S_60 (17.3)	42.0	T_10 (5.5)	P_90 (12.4)	S_10 (3.4)	21.3
T_60 (14.2)	P_10 (3.6)	S_30 (12.9)	30.6	T_120 (0.5)	P_90 (14.1)	S_90 (1.6)	16.2
T_90 (25.5)	P_10 (3.2)	S_30 (11.9)	40.7	T_90 (0.6)	P_90 (14.1)	S_90 (1.7)	16.3
YNG SOSc				YNG EOSc			
Variable name ( $R^2$ )		Model $R^2$		Variable name ( $R^2$ )		Model $R^2$	
T_120 (32.1)	P_30 (10.3)	S_90 (12.0)	54.4	T_10 (8.2)	P_90 (13.7)	S_30 (6.1)	28.0
T_60 (21.0)	P_30 (12.4)	S_90 (7.3)	40.7	T_120 (6.4)	P_90 (10.3)	S_60 (6.3)	22.9
T_90 (43.1)	P_20 (8.1)	S_90 (7.0)	58.2	T_20 (1.6)	P_90 (11.4)	S_60 (8.5)	21.5

All models included three variables: one of the six temperature-related; one of the six precipitation-related; one of the six sunlight-related variables. The variables shown in each table are those with the highest  $R^2$

climate conditions in the previous year (Fig. 3) (Liu et al. 2016).

Temperature was also a major factor in the timing of EOSs at site YNG (Table 3). This site is near the upper tree line. This result is in line with previous dendroclimatological studies of Qinghai spruce growing near the upper tree line (Liu et al. 2016). The major impact factors in the timing of EOSs in Qilian were alternatively temperature- or precipitation-related variables (Table 3). A similar result was found by Zhang et al. (2018), who studied *Juniperus przewalskii* growing on the southern slopes of the Qilian mountains: drought conditions seem to end xylem growth.

### Implications for the V–S model used for stem phenology research

Traditional linear statistical analyses alone are not useful in suggesting a physical or biological mechanism for variability or change in the relationship between climate and tree growth. The radial-growth V–S model provides a new and more useful approach to explain stem phenology data. Still it must be admitted that there are some areas of uncertainty in the process-model simulations used in this study. The first problem is uncertainty as to the quality and accuracy of local precipitation data. YNG ring-width models were developed with input from the Yeniugou meteorological station, which is ~300 m lower in elevation. There may have been differences in precipitation between the site and the station. Second, the model itself is a very simple depiction of tree growth. It does not take into account other important inputs into tree growth, such as nutrient and CO<sub>2</sub> availability. Tree-ring width is also influenced by tree age to some extent. These may be some of the reasons that variation in the V–S modeled SOSs and EOSs were much larger than those seen in remote sensing data for SOSc and EOSc (Fig. 5). It is to

be hoped that there will be further studies of radial growth in Qinghai spruce over a longer observation period. Such studies will improve our understanding of the ecological and physiological characteristics of the spruce and allow us to predict how this species might cope with changing climate conditions.

### Implications for forest growth

In recent decades the Chinese government has implemented several projects, such as the National Forest Conservation Program and the Grain for Green program, which have significantly increased vegetation coverage in the Qilian Mountains (Li 2004). Many semi-arid grasslands near the lower tree line have been converted to *P. crassifolia* plantation forests (Zhu et al. 2017). Our study has shown that rising spring temperatures (ESM\_1) could start the growing season earlier, which might increase tree growth. However, since the 1980s there has been no significant increase in annual precipitation in Qilian station (ESM\_1). Our V–S modeling results indicate that soil moisture is the most important factor limiting xylem cell differentiation during the June–August growing season at the lower-elevation QLN site (Fig. 4). (Note that according to Tian et al. (2017), major radial growth occurred in the June–July period.) Rising temperatures will likely increase water stress, which would complicate forest management (Yao et al. 2000; Lin et al. 2017).

### Conclusion

This study compiled and analyzed the stem and canopy phenology of Qinghai spruce and their correlation with climate; the study was conducted at two sites, at different elevations, in the central Qilian Mountains, Northeast Tibetan Plateau.

Both the NDVI-recorded canopy spring phenology and the V–S-modeled stem spring phenology are predominantly limited by temperature. These two events are linked; there were significant positive correlations between SOSC and SOSs at both sites. Canopy and stem autumn phenology are not correlated to the same degree. This may have been due to other factors that were not inputs to V–S model. The model did show its utility in its simulations of intra-seasonal radial-growth impact factors. Our results also showed that soil moisture is the major limiting factor for radial growth in the growing season at the lower elevation study site, QLN. The temperature is the major limiting factor for radial growth at the upper elevation study site, YNG. These results suggest that forest management must take elevation differences into account when facing the challenges of climate change.

**Author contribution statement** XP participated in the experiment design, sample collection, data analysis, manuscript draft and revision. JD participated in the experiment design, data analysis, and manuscript draft. BY and SX participated in the design of the study and manuscript draft. GL participated in the experiment design and sample collection.

**Acknowledgements** The study was jointly funded by the National Natural Science Foundation of China (nos. 41701050, 41601051, 41520104005, 41325008), the CAS Light of West China Program, and the Foundation for Excellent Youth Scholars of the Northwest Institute of Eco-Environment and Resources, CAS.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflicts of interest.

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