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Climate response of *Salix oritrepha* growth along a latitudinal gradient on the northeastern Tibetan Plateau

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Abstract: Shrubs are widespread at higher altitudes and latitudes. Dendrochronology of shrub growth has been intensively studied in the circumpolar Arctic, Mediterranean and Patagonia. However, relatively little is known about shrub growth responses to climate change on the Tibetan Plateau. Herein, we investigate climate sensitivity of *Salix oritrepha* growth along a north–south (35–39° N) latitudinal gradient on the northeastern Tibetan Plateau. Four *S. oritrepha* shrub sites were selected for dendrochronology study. Pearson and partial correlation analyses were used to estimate strength of the climate sensitivity of the growth time series at each site. We found that not all of the site chronologies show consistent variations. Despite of this, its radial growth was primarily limited by the July mean temperature across the latitudinal gradient, and warming summer climate tends to increase the growth of *S. oritrepha* on the northeastern Tibetan Plateau.

Keywords: shrub, radial growth, climate sensitivity, dendrochronology, summer temperature

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Introduction

Shrubland is a key plant community in treeless areas worldwide (Matthews, 1983). As shown by repeat photography, plot survey and dendroecology studies conducted in past decades, recent climate warming has already resulted in acceleration of shrub growth and shrub expansion in the Arctic tundra (Chapin et al., 2005; Forbes et al., 2010; Tape et al., 2012; Elmendorf et al., 2012; Myers-Smith et al., 2015). Such changes are highly relevant to nutrient cycling, surface albedo and biodiversity (Chapin et al., 2005; Wipf & Rixen, 2010; Bonfils et al., 2012). However, response of shrub growth to warming temperatures is likely to be heterogeneous under different local environment

conditions (Ropars et al., 2015; Myers-Smith et al., 2015). Thus, a better understanding on the response of shrub growth to warming temperatures is essential to evaluate spatial heterogeneity of shrub expansion and its influence on tundra and alpine ecosystems.

The climate sensitivity of erect and prostrate shrub growth across the circumpolar Arctic (Myers-Smith et al., 2015), Mediterranean (Gazol & Camarero, 2012) and alpine sites in Patagonia (Srur & Villalba, 2009) has been well established. As shown by a recent meta-analysis, the climate sensitivity of shrub growth was not uniform across the tundra biome, with more than half of the study sites exhibiting positive or negative relationships between growth and summer temperatures (Myers-Smith et al., 2015). Species

interactions were considered to be important factors to mediate growth responses of shrubs to regional climate in the Mediterranean region (Gazol & Camarero, 2012). Abundant winter precipitation, warmer spring and autumn temperatures tended to enhance the shrub growth in the Patagonia steppe (Sruar & Villalba, 2009). In alpine regions, most studies focused on moist sites (e.g. Bär et al., 2007; Liang & Eckstein, 2009; Hallinger et al., 2010; Li et al., 2013; Shetti et al., 2018; Weijers et al., 2018), while climate drivers of shrub growth at dry and cold alpine sites are less explored (e.g. Liang et al., 2012; Pellizzari et al., 2017).

The Tibetan Plateau with an average elevation surpassing 4000 m above the sea level (a.s.l.) provides adequate settings to investigate how alpine shrub growth responds to climate change. *Salix oritrepha* is an ubiquitous shrub species found throughout alpine area on the northeastern Tibetan Plateau (Fang et al., 2011). Summer temperature is a dominant factor limiting *S. oritrepha* growth above the juniper treeline (Lu et al., 2016). Given its wide distribution range and well-defined annual growth ring, *S. oritrepha* is an ideal alpine species to quantify climate-growth relationships at the regional scale.

The objective of this study is to investigate climate-growth relationships of *S. oritrepha* along a latitudinal gradient on the northeastern Tibetan Plateau. We expect to detect spatial differences in climate responses of *S. oritrepha* growth. This research will provide important clue to evaluate effects of climate change on alpine ecosystem of the Tibetan Plateau.

Methods

Study area and climate

S. oritrepha is a tall deciduous and multi-stemmed shrub species, widespread at high altitudes on the northeastern Tibetan Plateau (Fang et al., 2011). It

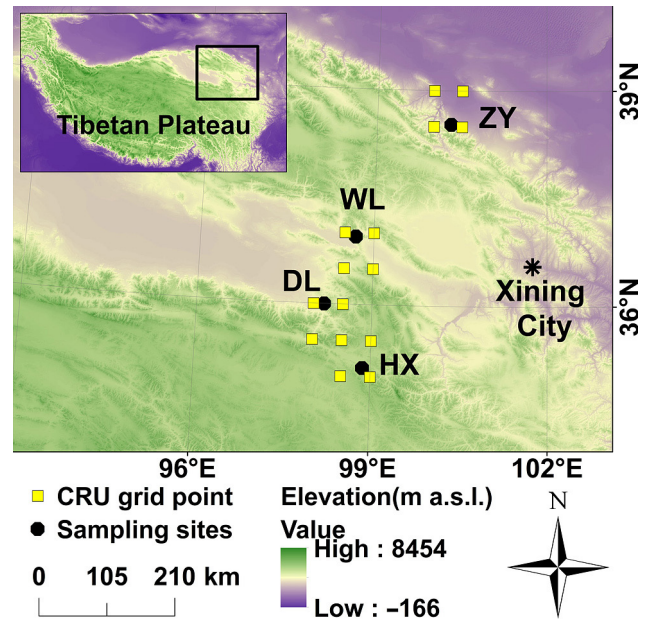


Fig. 1. The study area and four sampling sites (black dots) on the northeastern Tibetan Plateau. The yellow boxes are the climate research unit (CRU) grid points. Abbreviations: ZY, Zhangye; WL, Wulan; DL, Dulan; HX, Huashixia.

grows in an erect form, commonly ranging from 0.6–1.2 m in height. However, we observed that many individuals can reach a height of 1.6 m. It also occupies a wide elevational range (3200–4600 m a.s.l.) and individuals are distinguishable from one another.

The study was conducted along a latitudinal transect extending from the Qilian Mountains to the Anyemaqen Mountains (35–39° N, 97–100° E) on the northeastern Tibetan Plateau (Fig. 1). Four *S. oritrepha* sites were selected (from north to south): Zhangye (ZY), Wulan (WL), Dulan (DL) and Huashixia (HX) (see details in Table 1). In the study area, forests are dominated by coniferous tree species of *Picea crassifolia* from 2300 to 3877 m a.s.l. and *Juniperus przewalskii* from 2100 to 4200 m a.s.l.

Table 1. The locations, features and statistics of *S. oritrepha* site chronologies

Variables	Site (code)			
	Zhangye (ZY)	Wulan (WL)	Dulan (DL)	Huashixia (HX)
Latitude N (°)	38.53	36.94	36.00	35.12
Longitude E (°)	100.3	98.69	98.18	98.87
Elevation (m a.s.l.)	3400	3828	4270	4257
Aspect (°)	19	24	44	52
Dominant tree vegetation	Spruce treeline	Spruce treeline	Juniper treeline	Juniper treeline
No. individuals	27	28	35	27
No. radii	67	76	105	74
Time span	1963–2015	1953–2015	1969–2014	1988–2015
Mean ring width \pm SD (mm)	0.36 \pm 0.14	0.27 \pm 0.12	0.25 \pm 0.13	0.34 \pm 0.14
MS	0.21	0.17	0.29	0.15
R_{bar}	0.26	0.3	0.32	0.34
EPS > 0.85 since	1970	1975	1980	1990

Abbreviations: SD, standard deviation; MS, mean sensitivity; R_{bar} , mean series inter-correlation; EPS, expressed population signal.

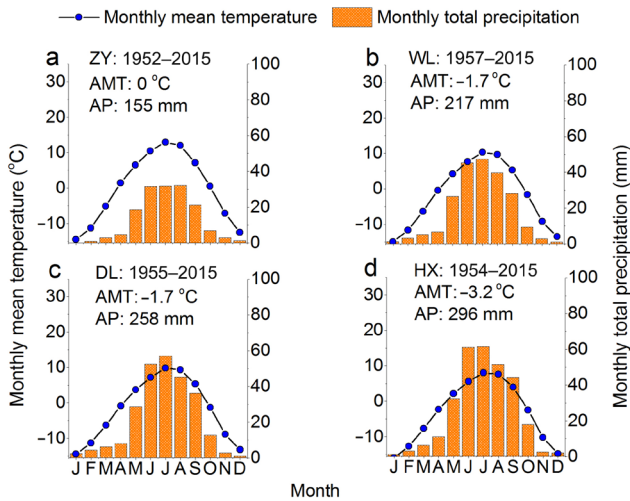


Fig. 2. The monthly climate data (mean temperature and total precipitation) for the grid points of the CRU dataset corresponding to the four study sites (sites' codes are as in Fig. 1). The period with available climate data is shown for each site

Abbreviations: AMT, annual mean temperature; AP, annual total precipitation.

P. crassifolia and *J. przewalskii* form natural treelines from 3385 to 3877 m a.s.l. and from 3558 to 4250 m a.s.l., respectively (Zhu et al., 2008; Gou et al., 2012; Liang et al., 2016). *P. crassifolia* treeline shifted upward 13 to 80 m during the past 100 years in our study area (Liang et al., 2016).

S. oritrepha shrubs were selected from the near-treeline alpine sites (Table 1). ZY (3400 m a.s.l., northeast-facing slope) is situated above the *P. crassifolia* treeline in the central Qilian Mountains. WL (3828 m a.s.l., northeast-facing slope) and DL (4270 m a.s.l., northeast-facing slope) sites are above the *P. crassifolia* treeline and the *J. przewalskii* treeline, respectively. Both of them are located at the eastern margin of the Qaidam Basin. HX (4257 m a.s.l., northeast-facing slope) lies in the alpine steppe on the northwestern Anyemaqen Mountains, where *J. przewalskii* treeline reaches up to 4200 m a.s.l. (Zhang et al., 2015).

Due to the influence of the Asian monsoon and the Westerly, the study area is characterized by a continental arid climate, with mild summer but dry and cold winter. The gridded dataset of climate research unit (CRU TS4.0, 0.5° resolution) in study area was used for analyses (Harris et al., 2014; data retrieved from climate explorer webpage, <http://climexp.knmi.nl/>). The halfway grid points method was used to keep grid point data nearest to the study sites. Annual total precipitation (AP) decreases northward from 296 mm (HX) to 155 mm (ZY) (Fig. 2). Annual mean temperature (AMT) increases from -3.2 °C (HX) in the south to 0 °C (ZY) in the north of the study area. Variations in the annual mean temperature from four study sites are highly correlated from

1957 to 2015 ($r > 0.72$, $P < 0.001$). Correlations of annual total precipitation between four sites are also significant ($r > 0.51$, $P < 0.001$).

Dendrochronological methods

In April and October 2015, we collected 27 to 35 discs of *S. oritrepha* close to the soil level at ZY, WL, DL and HX (Table 1). We cut these discs from the largest stem of each individual. The discs were air dried, sanded and visually cross dated under stereomicroscope (Stokes & Smiley, 1996). Ring widths were then measured along two to three radii in Lintab 6 system (Rinntech, Heidelberg, Germany) with a resolution of 0.01 mm. We used COFECHA program to verify the quality of visual cross-dating and measurement (Holmes, 1983).

The ring-width series were detrended using ARSTAN program (Cook & Krusic, 2008). We first fitted these raw ring-width series by a negative exponential curve, linear regression of any slope or a smoothing spline with 50 % frequency response cutoff width equal to 67 % of the series length. We then obtained standard chronology of each site by averaging (biweight robust means) the detrended ring-width indices. We calculated the mean sensitivity (MS), the mean series inter-correlation (R_{bar}) as well as the expressed population signal (EPS). The MS is a measurement of relative difference between adjacent rings and the R_{bar} is the mean correlation between all ring-width series (Fritts, 1976; Briffa & Jones, 1990). The EPS is usually used as an indicator of the reliability of site chronology with a threshold of 0.85 (Wigley et al., 1984).

Data analysis

We calculated Pearson correlation coefficients for the four standard chronologies. The period with $\text{EPS} \geq 0.85$ was selected for the analysis at each site. Pearson correlation analysis was also used to investigate the climate-growth relationships. We quantified the climate sensitivity of *S. oritrepha* growth as the signal strength of main climate variable. Climate factors include monthly mean temperature and monthly total precipitation for a 15-month period from July of the previous year to September of the current year. Partial correlation analysis was also used to avoid the inter-correlation between climate variables. It measures the linear relationship between two variables after excluding the effect of the third variable.

Results

Along the latitudinal transect, we developed four standard ring-width chronologies with the longest

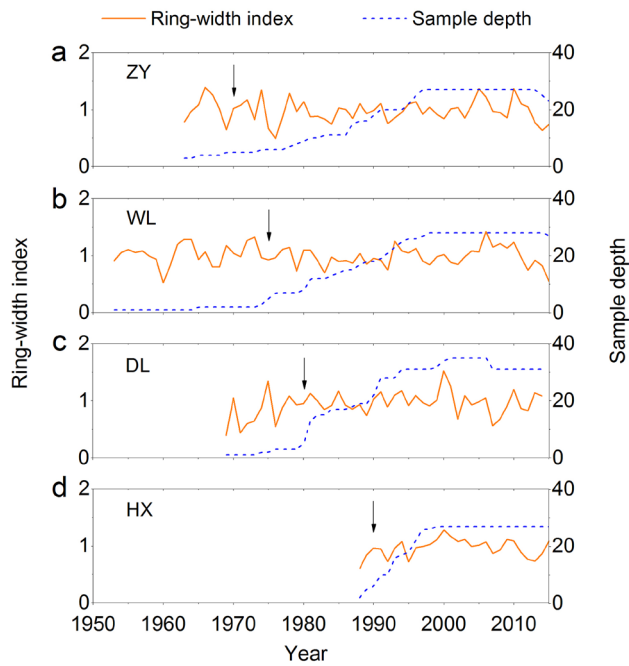


Fig. 3. Standard ring-width chronologies of *S. oritrepha* shrub in ZY (a), WL (b) and HX (d) sites. The orange lines are ring-width indices (left x axes) and the dashed blue lines are sample depth (right y axes), respectively. The vertical arrows indicate the years when expression population signal (EPS) value was higher than usually accepted threshold of 0.85. DL (c) chronology is also shown (Lu et al., 2016)

one (WL) spanning 63 years (Fig. 3; Table 1). Mean ring-width ranged from 0.25 mm (DL) to 0.36 mm (ZY). The highest MS was observed at DL (0.29), followed by ZY, WL and HX (Table 1). R_{bar} varied from 0.26 (ZY) to 0.34 (HX). All of the *S. oritrepha* chronologies showed an EPS value higher than 0.85 when the sample depth reached 5 (including 10–15 ring-width series). Chronologies from ZY and WL were highly correlated ($r = 0.400, P < 0.05$) (Table 2). In addition, significant positive correlation was also found between the DL and HX chronologies ($r = 0.465, P < 0.05$). However, positive correlations were weak between the chronologies from northern sites (ZY and WL) and southern sites (DL and HX). Negative correlation was also observed between ZY and DL sites ($r = -0.059, P = 0.778$).

As shown by both Pearson and partial correlation analyses, the radial growth of *S. oritrepha* is

Table 2. Pearson correlations between the four standard chronologies during their common period of 1990–2014. The values above and below the diagonal are significant levels and Pearson correlation coefficients, respectively

	ZY	WL	DL	HX
ZY		0.047	0.778	0.450
WL	0.400		0.843	0.158
DL	-0.059	0.042		0.019
HX	0.158	0.291	0.465	

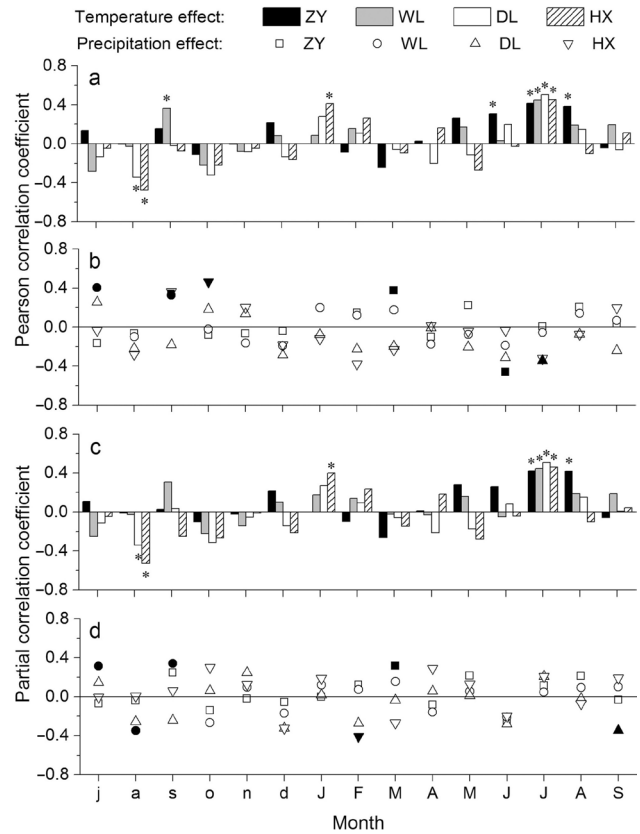


Fig. 4. Pearson (a, b) and partial (c, d) correlation coefficients calculated between four site chronologies (analysis period: 1970–2015 for ZY, 1975–2015 for WL, 1980–2014 for DL and 1990–2015 for HX) and monthly mean temperature and monthly total precipitation records. Monthly climate variables of previous (abbreviated in lowercase) and current year (abbreviated in capital letters) are used for analysis. For the temperature effect, the significant correlation coefficients ($P < 0.05$) are indicated by an asterisk symbol above or below the column bar. For the precipitation effect, the significant correlation coefficients ($P < 0.05$) are indicated by the solid black symbols.

significantly and positively correlated with the July mean temperature across the four sampling sites (Fig. 4a, c). The highest correlation occurs at DL. In addition, the mean temperature in August of the previous year shows significant and negative correlation with the DL and HX chronologies. The ZY chronology has significant and positive correlation with the August mean temperature of the current year. The radial growth of *S. oritrepha* at HX is significantly and positively correlated with the January mean temperature.

The relationships between the four standard chronologies and monthly total precipitation are not uniform (Fig. 4b, d). March precipitation has a significant and positive effect on the growth of *S. oritrepha* at ZY. The WL chronology is significantly and positively correlated with precipitation in July and September of the previous year.

Discussion

The Tibetan Plateau is characterized by a large-area of alpine ecosystem and relatively little is known about the influence of climate change on this biome (Shen et al., 2015; Lu et al., 2019). Taller shrubs are considered to be more sensitive to climate change than low statured shrub species (Myers-Smith et al., 2015). As a dominant tall shrub species across the alpine biome on the northeastern Tibetan Plateau, *S. oritrepha* may serve as an indicator species to show influence of climate change on alpine ecosystem by annual ring records.

In spite of a short age span, *S. oritrepha* can be used to establish robust ring-width chronology characterized by common signal. During the cross-dating analysis, we found very few wedging and missing rings. The mean ring-widths at DL and WL were similar to those measured in nearby treeline juniper trees (Liang et al., 2006; Zheng et al., 2008). Compared to other arctic willow shrubs, the mean ring-width is wider than prostrate species of *S. polaris* (0.08 mm, Svalbard) (Buchwal et al., 2013), *S. arctica* (0.12 mm, NE Greenland) (Schmidt et al., 2010) and erect species of *S. pulchra* (0.21 mm, NE Siberia; 0.19 mm, Alaska) (Blok et al., 2011; Ackerman et al., 2017), but much narrower than erect *S. alaxensis* shrubs (1.0 mm, Victoria Island) (Zalatan & Gajewski, 2006). The MS is lower than many arctic willow shrubs (Schmidt et al., 2010; Blok et al., 2011). The R_{bar} and EPS values confirm that the four standard chronologies are applicable for dendroecological analysis.

The growth variation of *S. oritrepha* was not consistent across the four study sites (Table 2). *S. oritrepha* growth at the northern sites (ZY and WL) is different from the southern sites (DL and HX). Such result suggested that the growth of *S. oritrepha* was also influence by microsite conditions. This may potentially due to their elevational differences which may lead to differentiation in phenology and growth (Vitasse et al., 2009). Another explanation is that *S. oritrepha* growth is influenced by variation in precipitation. The annual total precipitation gradually decreases northward from HX to ZY (Fig. 2) which could lead to different soil moisture at the site level. Study in the alpine treeline sites in Yukon also showed that willow shrub growth variation is influenced by the soil moisture content in early growth season (Dearborn & Danby, 2018).

July temperature is a common climate factor driving the growth of *S. oritrepha* across the latitudinal gradient on the northeastern Tibetan Plateau. It is assumed that low temperature drives the onset of the alpine shrub growth (Li et al., 2016). Furthermore, warm summer temperature could benefit new wood tissue formation and more than half of the ring-width is completed in July (Li et al., 2016). In a

recent synthesis, summer temperature was found to be the dominant climate variable controlling shrub growth across different taxa and locations in the tundra biome (Myers-Smith et al., 2015). On the southeastern Tibetan Plateau, summer temperature is also a primary limiting factor for the radial growth of alpine rhododendron shrubs (Liang & Eckstein, 2009; Li et al., 2013; Lu et al., 2015).

Given that our study sites are located at the transition zone between erect trees forming the treeline and *S. oritrepha* shrub, climate-growth relationships between *S. oritrepha* and treeline *P. crassifolia* and *J. przewalskii* trees could be compared. As shown by dendrochronology studies at *P. crassifolia* and *J. przewalskii* treelines on the northeastern Tibetan Plateau, the growth of both tree species is also strongly driven by the growth season temperatures (Liu et al., 2005; Liang et al., 2006; Zheng et al., 2008; Zhu et al., 2008; Fang et al., 2009; Liu et al., 2016). Similar growth responses of shrubs and trees to climate have also been reported on the southeastern Tibetan Plateau (Liang & Eckstein, 2009; Li et al., 2013), Alps (Francon et al., 2017) and Scandes (Bär et al., 2007). In addition, shrub growth shows similar climate signal across gender and species in the northeastern Greenland (Schmidt et al., 2010), Siberian (Blok et al., 2011) and Central Anatolia (Kahveci et al., 2018). However, dwarf shrubs and trees can also respond differently to the climate factors at latitudinal or altitudinal treeline in Mediterranean, Polar and central Alps (Gazol & Camarero, 2012; Pellizzari et al., 2017). Shrubs are lower stature life forms than trees. Thus, shrub growth is less coupled to air temperatures than nearby trees. Similar growth responses to climate for shrub and coexisting tree indicate suitable hydrothermal conditions for both of them. In our case, *S. oritrepha* shrub and coexisting trees may respond differently to the same climate factor following the rapid climate warming in the future.

The radial growth of *S. oritrepha* did not show common signal of precipitation between four sites. At ZY and WL, annual precipitation is lower than that at DL and HX (Fig. 2). As a result, the growth of *S. oritrepha* at ZY and WL is likely affected by drought stress. It was supported that precipitation prior to the growing season benefited *S. oritrepha* growth at ZY and WL. The northeastern Tibetan Plateau has experienced climate warming and moistening process in the past three decades (Yang et al., 2014). Based on our results, future climate could enhance the growth of *S. oritrepha* in our study area.

In summary, *S. oritrepha* growth is primarily limited by July temperature along the latitudinal gradient on the northeastern Tibetan Plateau, and shows a common climate signal as nearby alpine treeline trees. In our study area, *P. crassifolia* treeline has shifted upward significantly in response to climate warming

over the past century (Liang et al., 2016). This has already changed the species interactions. We could infer that increased tree cover may limit the growth of *S. oritrepha* shrub and reduce its above-ground productivity in the treeline ecotone. Such a knowledge gap needs to be tested. Future study should assess impacts of climate change and species interaction on *S. oritrepha* population dynamics on the northeastern Tibetan Plateau.

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