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Forward modeling analysis of regional scale tree-ring patterns around the northeastern Tibetan Plateau, Northwest China

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Abstract

The process-based Vaganov–Shashkin (VS) model was used to simulate regional patterns of climate-tree growth relationships linking daily length, temperature and precipitation from meteorological data (AD 1957–2000) over the northeastern Tibetan Plateau (TP). The results exhibit that the leading principle component of the hypothetical growth curves is broadly consistent with that of the actual tree-ring chronologies, demonstrating the interpretability of the simulations as an accurate representation of the climatic controls on tree growth of Qilian Juniper. Output from this model both agrees well with the statistical relationships between tree-ring growth and climate factors as well as observational physiological behavior, i.e. precipitation in June acts as the most contributing role in annual ring formation of Qilian Juniper over the northeastern TP. The non-stationary and nonlinear response of tree growth to climate variability has important implications for calibration of tree-ring records for paleoclimate reconstructions and prediction for forest carbon sequestration.

1 Introduction

The Tibetan Plateau (TP) is widely regarded as an extremely important unit climatically and hydrologically, for it functions as a transitional region for the East Asian monsoon and Northern Hemisphere westerly winds (Morrill et al., 2003; Yang and Williams, 2003). Given its unique geographical and geological feature, scientists have paid considerable attention to climate variability over the TP spatially and temporally in the past decades (Barnett et al., 1988; Sirocko et al., 1993; Webster et al., 1998; Guo et al., 2002; Bansod et al., 2003; Kripalani et al., 2003; Zhang et al., 2003; Bräuning et al., 2004), which have greatly helped improve our knowledge of Asian monsoon dynamics and moisture variability in this region in the context of global warming. Amongst the variety of high-resolution proxy records for the TP, long time series of tree-ring growth are of particular value in that provide exactly dated, annually resolved information for

BGD
10, 9969–9988, 2013

reconstructing past records of precipitation, temperature, streamflow and drought during the late Holocene (Zhang et al., 2003; Shepppard et al., 2004; Shao et al., 2005; Gou et al., 2007; Li et al., 2008; Fang et al., 2010).

The conventional approach for dendroclimatic reconstructions assumes that a linear relationship exists between the tree-ring data and the single climate target (Fritts, 1976). Although in most cases these assumptions are shown to be broadly met, many studies have stressed that tree climate-growth response is a multivariate and nonlinear process (Evans et al., 2006; Vaganov et al., 2006; Fang et al., 2012). Therefore, the statistically approximated linear analysis may be unsuitable to present a physical or biological mechanism for variability in the climate-growth relationships and should be performed and interpreted with caution (Briffa et al., 1998; Wilson et al., 2007). Tree growth may not follow a linear association with climate variables, for example, when warming exceeds a certain threshold (D'Arrigo et al., 2004) or when the ability of tree rings to record extreme pluvial or dry conditions is limited (Fritts, 1976; Fang et al., 2012). To accommodate the possibility of nonstationarity and nonlinearity in tree-ring records, several palaeoclimatic studies have recently sought new methodologies, e.g. the Artificial Neural Network model (Zhang et al., 2000; Fang et al., 2012) and the VS-lite model (Tolwinski-Ward et al., 2010), to further explore the potential nonlinear associations between tree growth and climate as well as better understand the process of the formation of proxy records.

Amongst all kinds of models, the process-based Vaganov–Shashkin (VS) model is a tractable and efficient forward one that mainly focuses on the critical processes linking tree-ring formation and climate factors, i.e. daily precipitation, temperature and solar radiation. It has been successfully utilized to simulate and evaluate regional patterns of climate-growth relationships at both intra-annual and inter-annual scales under a variety of environmental conditions over different regions (Anchukaitis et al., 2006; Evans et al., 2006; George et al., 2008; Shi et al., 2008; Zhang et al., 2010; Touchan et al., 2012). The mechanistic model generally performs best in dry and cold regions, where variations in both temperature and rainfall influence tree growth dramatically.

Qilian Juniper (*Sabina przewalskii*), a dominant endemic tree species around the northeastern TP, is characterized by its longevity and aridity endurance. Though clustered width chronologies of Qilian Juniper have been used to reconstruct past climate over the region, reliable information on physiological process of this species response to climate variability is still scarce. In this paper, we aim at exploring the ability of the VS model to reproduce broad-scale patterns of growth variability of Qilian Juniper and investigating the biological mechanism of how this tree species respond to climatic variations, combined with physiological observations.

2 Materials and methods

The VS model permits us to investigate features of tree-ring width variations under specific environmental conditions linking daily temperature, soil water content and day length. This model is based on the hypothesis that external influences are directly related with tree growth through controls on the rates of cambial cellular processes. Simulations possess none of the biological trends associated with tree growth and simply preserve variations that are likely related to climatic fluctuations (Vaganov et al., 2006). The VS model calculates the growth rate (Gr) on a special day t as a product of the growth rate due to solar radiation (GrE) and the minimum of the growth rate due to either surface air temperature (GrT) or soil moisture (GrW):

$$\mathrm{Gr}(t) = \mathrm{GrE}(t) \times \min[\mathrm{GrT}(t), \mathrm{GrW}(t)].$$

The partial growth rate GrE(t) is defined by the harmonic function depending on latitude (Φ), declination angle (θ) and hour angles (h_s) (Gates, 1980) and can be described as:

$$\mathrm{GrE}(t) = \cos h_s \cdot \sin\Phi \cdot \sin\theta + \cos\Phi \cdot \cos\theta \cdot \sin h_s.$$

A water-balance equation is used to determine the dynamics of water content in soil (ΔW) from daily data of temperature and precipitation (Thornthwaite and Mather, 1955;

BGD
10, 9969–9988, 2013

Alisov, 1961):

$$\Delta W = f(P) - \mathrm{Ev} - Q,$$

where $f(P)$ is daily precipitation, Ev is daily water loss in soil by transpiration and Q is runoff. $f(P)$ is determined as:

$$f(P) = \min[k_1 \times P, P_{\max}],$$

where P represents the actual daily precipitation, k_1 denotes the part of precipitation falling into soil and $P_{\max}$ stands for maximum daily precipitation for saturated soil. The partial influence of temperature and soil moisture on tree-ring formation are both defined by piece-wise linear functions (Anchukaitis et al., 2006; Evans et al., 2006; Vaganov et al., 2006). The modeled tree growth rate throughout the growing season is largely determined by the primary limiting factor between temperature and soil moisture.

To exhibit the regional tree-growth response to climate variability robustly, we employed a multi-chronology modeling approach and principle components analysis (PCA) (Anchukaitis et al., 2006; George et al., 2008) to identify the dominant loadings of variability in the real and modeled tree-ring width network, respectively. Four simulated tree-ring width chronologies were created based on daily meteorological observations around the northeastern TP spanning from AD 1957 to 2000. Missing daily temperature data were linearly interpolated, while missing daily precipitation data were set to zero (Anchukaitis et al., 2006; Shi et al., 2008). In addition, five actual high-quality millennium-long tree-ring width chronologies from this region (Fig. 1), which have been developed and utilized for paleoclimatic reconstructions recently (Zhang et al., 2003, 2007, 2011; Shao et al., 2005; Gou et al., 2010) (Table 1), were used to evaluate the skillful performance of the VS model over the northeastern TP. As for the determination of reasonable biological parameters, we first followed the descriptions suggested by literature (Evans et al., 2010). Since physiological characteristics and water-use efficiency of conifer trees were different from one to another in dry environments (Oberhuber and Gruber et al., 2010; Gruber et al., 2010), we adjusted a few parameters to guarantee good agreement of hypothetical and observed tree-ring chronologies through repeated trial manually (Table 2). In this process, the climate variables during the period AD 1957–1978 is used to tune the parameters for model performance testing outside the period used to simulate the regional tree growth. In order to identify whether the relationship between tree growth and regional moisture availability exists over a large-scale domain, we also correlate the first PCs of the simulated and actual chronologies with regional gridded May–June precipitation data of CRU TS 3.0 (Mitchell and Jones, 2005) over the overlap period (AD 1957–2000).

3 Results and discussion

The leading principle component (PC) of the complete set of the five authentic tree-ring chronologies is significant and accounts for nearly 63 % of the total variance, indicating that the species strongly shares a common ring-width signal which reflects synchronized growth. Using the estimated optimal parameters, significant Pearson correlation ($r = 0.72$, $p < 0.01$, $n = 22$) between the leading PCs of the modeled and authentic chronologies are found in the calibration period AD 1957–1978, and broad agreement ($r = 0.63$, $p < 0.01$, $n = 22$) between two curves is also seen in the verification period AD 1979–2000 (Fig. 2). This finding highlights that the process-based VS model has excellent skill in simulating and interpreting tree-ring formation as well as reproducing large-scale patterns of tree-growth response to climate variability under extreme environmental conditions like the northeastern TP.

To our knowledge, many existing developed tree-ring chronologies of this species at other moisture-stressed sites have showed high correlations with May–June moisture availability over the northeastern TP (Zhang et al., 2003; Sheppard et al., 2004; Huang and Zhang, 2007; Li et al., 2008) and its vicinity (Fang et al., 2009). As shown in the correlation fields (Fig. 3), the leading PCs of the real and synthetic tree-ring width

BGD
10, 9969–9988, 2013

chronologies are both strongly and positively correlated with the May–June precipitation over the period AD 1957–2000, stressing that the May–June moisture availability probably makes a contributing effect on tree growth over the large areas of northeastern TP. On the other hand, the partial similarity of two correlation fields reflects that early summer moisture makes a rather critical effect in determination of variations in the annual ring-width from year to year in the hypothetical chronologies as well.

In order to better understand how climatic fluctuations influence ring width formation, we examine the difference in intra-annual tree growth between years when wide and narrow rings were formed (Fig. 4). Here, the wide (narrow) ring is defined as the mean ring width plus (minus) one standard deviation. According to this definition, narrow rings were developed in 1957, 1961, 1966, 1999, 1991 and 1995, while wide rings were shaped in 1958, 1985, 1987, 1989, 1993 and 1999 during the select period AD 1957–2000. As shown in Fig. 4a, no significant modeled difference in the average partial growth rate from temperature is observed in the simulations between wide ring years and narrow ring years, demonstrating that temperature in this region fails to be the determining factor to tree growth. This finding differs from some tree-ring studies based on statistical models over the northeastern TP, which frequently pointed out that temperature in the early growing season was significantly and negatively correlated with tree radial growth (Qin et al., 2003; Zhang et al., 2003; Sheppard et al., 2004; Shao et al., 2005; Gou et al., 2008). However, the finding here supports their conjecture that temperature might principally affect tree growth indirectly by warming-induced drought during the growing season in this region. Beside this, we also observe that tree growth at these sites is moisture-limited at the onset but temporarily temperature-limited at the end dates of the growing season, since the VS model integrates scaled point-wise minimum of two functions to determine the overall annual growth rates. However, the model-calculated mean relative growth rates due to soil moisture in narrow ring years are significantly lower than the ones of wide ring years through the growing season, especially in June (Fig. 4b). Therefore, we speculate that potential plant water stress reaches its peak in June, broadly influencing the year-to-year variability in radial

BGD
10, 9969–9988, 2013

growth over this study region. Since the modeled results agree well with the independent statistically-based conclusions earlier, it seems more reasonable that the arrival of early summer rainfall provides the main source of soil water for tree growth, which probably has strong impact on the enhancement of early wood formation that generally takes up a vast majority of total annual ring width of Qilian Juniper.

The large disparity of the model output between years with wide and narrow rings inspires us to investigate seasonal dynamics of cambial activity of Qilian Juniper over the northeastern TP to test the performance of the simulator meticulously. Through repeated micro-sampling of the developing tree-rings of mature trees, we are allowed to observe the onset and end of wood formation, temporal dynamics of cell divisions along radical cell files and cell enlargement in details (Deslauriers et al., 2003; Rossi et al., 2006; Gruber et al., 2009). As presented in Fig. 5, the new xylem length formed in June 2011 accounted for approximately 56 % of total annual ring width of Qilian Juniper during the whole growing season. Hence, we propose that the radial increment of Qilian Juniper in June is the main contributor for the width of an annual ring over this region. Suitable external conditions in May and June probably boost the photosynthesis rate of this species substantially and thus can offer sufficient energy or organics for maintaining the high level of cell division and enhancement in June (Su et al., 2011). Since the temperature remains relatively stable during this phase, the arrival of abundant rainfall in June may correspond with wide ring formation of Qilian Juniper over the northeastern TP. On the contrary, the failure of early summer precipitation is expected to give rise to the development of narrow rings.

Taken all together, the process-based VS model reveals its suitability for analyzing non-linear climate influence, evaluating physiological dynamics of tree-ring formation during the vegetation period and assessing of potential impacts of climate fluctuations on regional forest growth in this extremely arid environment. For instance, diverging growth trends have been documented in nearby regions, such as several Qilian Juniper sites in the Qilian Mountains where the correlations between tree growth and climate change are instable at different periods of the instrumental record (Zhang et al., 2009).

BGD
10, 9969–9988, 2013

Our current model findings have uncovered that drought-stress still appears to be the contributing climate limitation for Qilian Juniper ring formation in recent decades over this region, while the warming temperature may only affect tree growth through a modification of evapotranspiration. In addition, a few studies have claimed that precipitation in the northeastern TP has been experiencing an ongoing wetting tendency in the past decades, especially in summer (Shi et al., 2007; Li et al., 2008). If such moisture pattern transformation is a long-term behavior, we expect that there will be a gradual climb in the Qilian Juniper tree growth and accordingly its capacity of carbon sequestration over this region in the future.

4 Conclusions

Based on climate variables alone, the process-based VS model herein is used to reproduce large-scale patterns of Qilian Juniper tree growth over the northeastern TP for the period AD 1957–2000. Broad agreement is observed between the leading PCs of the simulated chronologies and the original ones, suggesting that daily precipitation, temperature and daylength alone are sufficient under this model framework to exhibit ring-width variations of this species. Meanwhile, the VS model yields important diagnostic information about the difference in intra-annual radial growth between years when wide and narrow rings were formed. In accordance with statistical analysis between tree-ring width and climate factors, output from the VS model reveals that precipitation in June largely determines the radial growth. Finally, through microscopically observing seasonal dynamics of cambial activity of Qilian Juniper in detail, the strength of the VS model is tested once again for its ability to simulate a nonlinear tree-growth to climate change.

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BGD

10, 9969–9988, 2013

Table 1. Characteristics of the five tree-ring chronologies recovered from the northeastern TP. See Fig. 1 for locations.

Site Code	Sample Area	Latitude (E)	Longitude (N)	Elevation (m)	Time Span (AD)	Number (cores/tree)	Literature
DLH1	Delingha	37.47°	97.24°	3770	982–2001	25/41	Shao et al. (2005)
DLHA	Delingha	37.45°	97.93°	3500–3900	980–2001	42/62	Zhang et al. (2007)
WL	Wulan	36.68°	98.42°	3700	977–2001	25/42	Shao et al. (2005)
DL	Dulan	36.16°	98.00°	3100–3700	BC 326–2000	44/88	Zhang et al. (2003)
MQB	Anemaqin	34.79°	99.79°	3550–3650	771–2004	82/111	Gou et al. (2010)

Table 2. Model parameters estimated calibration of the VS model over the period AD 1957–1978. Description of these parameters is according to Evans et al. (2006).

Model parameter	Description	Value
T_{min}	Minimum temperature for tree growth (°C)	4.0
T_{opt1}	Lower optimal temperatures (°C)	14.6
T_{opt2}	Upper optimal temperatures (°C)	22.0
T_{max}	Maximum temperature for tree growth (°C)	31.0
W_{min}	Minimum soil moisture for tree growth (v/v)	0.04
W_{opt1}	Lower end of range of optimal soil moisture (v/v)	0.18
W_{opt2}	Upper end of range of optimal soil moisture (v/v)	0.8
W_{max}	Maximum soil moisture for tree growth (v/v)	0.9
T_{beg}	Temperature sum for initiation of growth (°C)	60
P_{max}	Maximum daily precipitation for saturated soil (mm)	20
k_1	Fraction of precipitation penetrating soil (dimensionless)	0.86
k_2	First coefficient for calculation of transpiration (mm/day)	0.12
k_3	Second coefficient for calculation of transpiration (1/degree)	0.176
Λ	Coefficient for water infiltration from soil (dimensionless)	0.002

BGD
10, 9969–9988, 2013

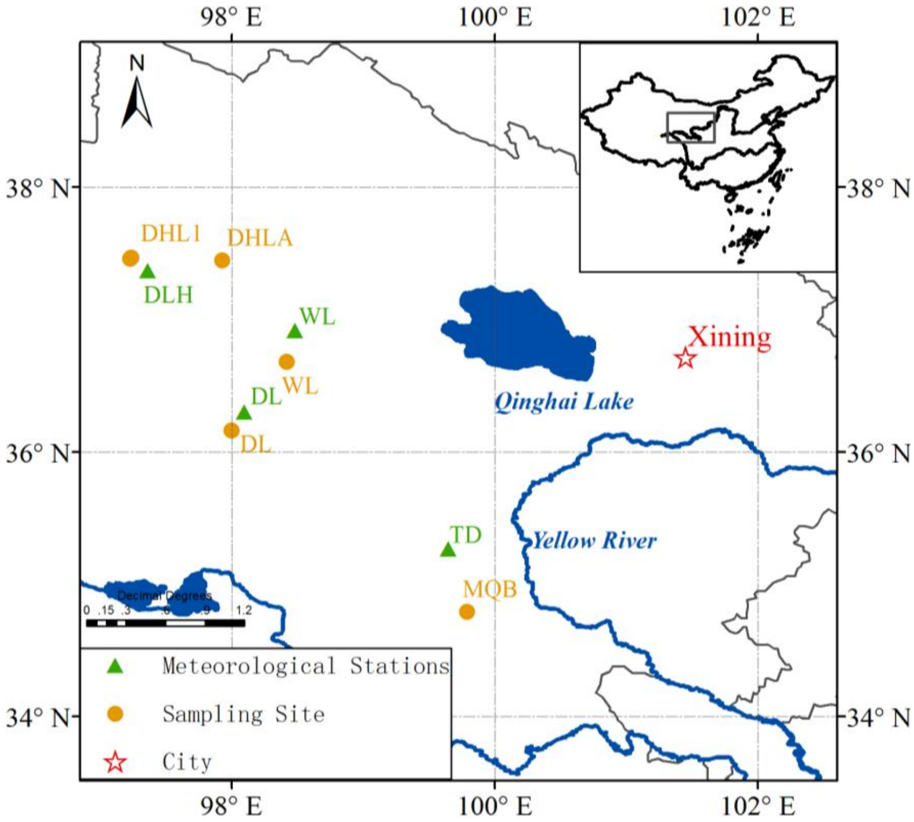

Fig. 1. Locations of sampling sites and meteorological stations in the northeastern TP. Circular identifiers denote the five tree-ring width chronology sites (for details see Table 1). Triangular identifiers mark the four meteorological stations: DLH (Delingha), DL (Dulan), WL (Wulan) and TD (Tongde).

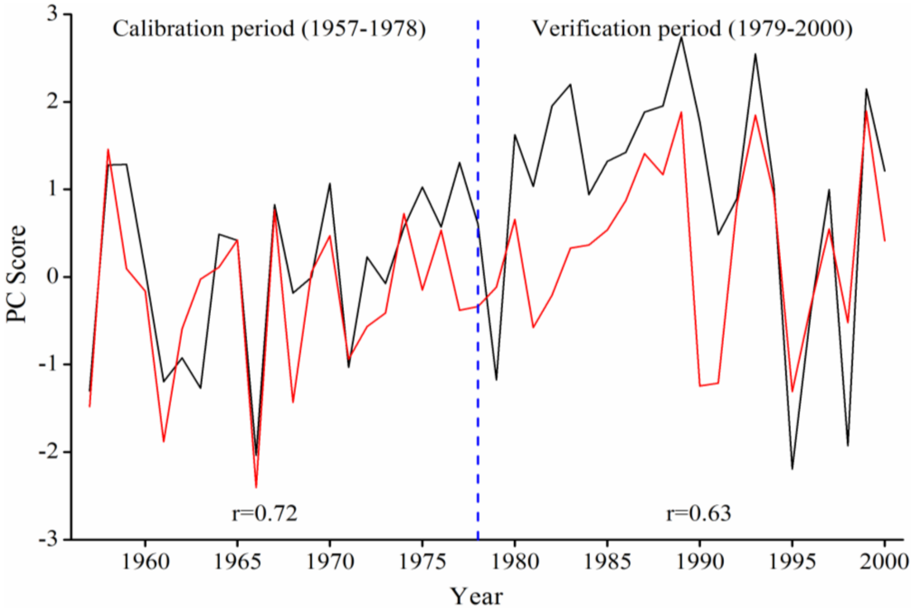

Fig. 2. Comparison between the first principle components of actual (dark) and synthetic (red) tree-ring width chronologies for calibration period (1957–1978) and verification period (1979–2000).

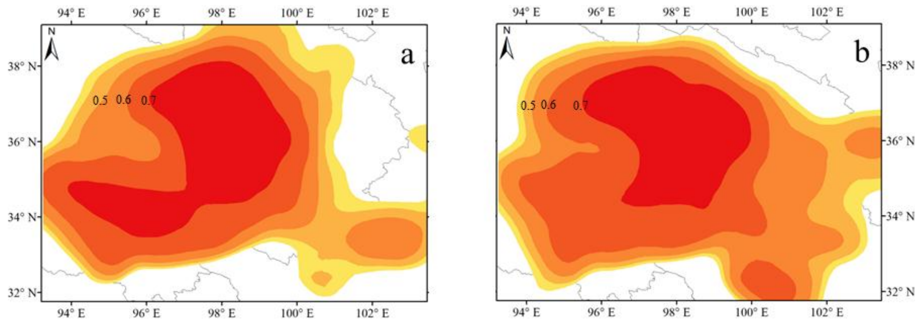

Fig. 3. Correlation fields between the gridded May to June precipitation data of CRU TS 3.0 (Mitchell and Jones, 2005) and the first principle component of the **(a)** actual and **(b)** simulated tree-ring with chronologies for the full overlapping period (AD 1957–2000).

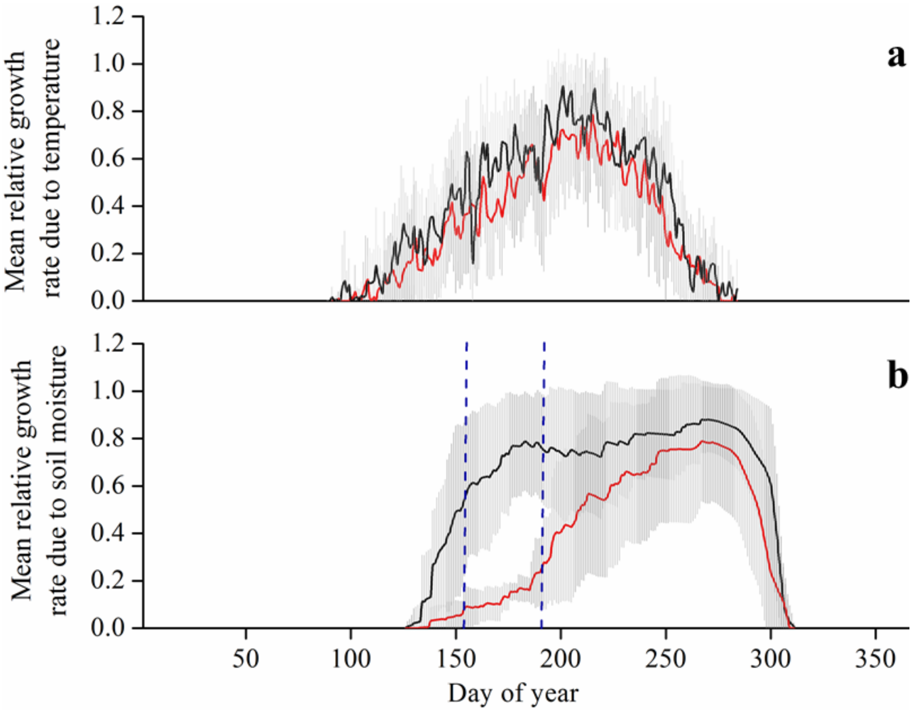

Fig. 4. Modeled average growth rate due to **(a)** temperature and **(b)** soil moisture for region-wide simulations for wide (black) and narrow (red) rings. Shared regions in the top figure are the mean ± one standard deviation, demonstrating that the growth rates due to temperature and soil moisture are indistinguishable between years with wide and narrow rings except the part shown by dashed box.

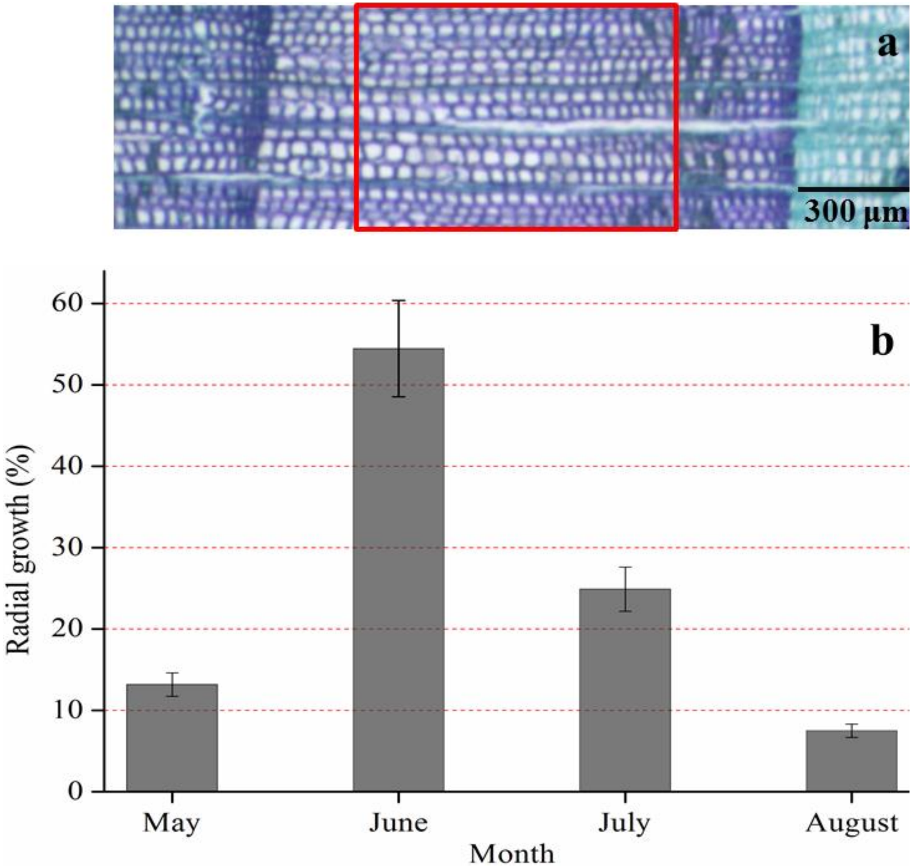

Fig. 5. (a) Transverse section of Qilian Juniper on the northeastern TP; Boxed part representing the new formed xylem in June 2011; **(b)** average monthly dynamics of radial increment during the whole growing season in 2011. Bars symbolizing mean ± one standard deviation.

BGD
10, 9969–9988, 2013