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Prolonged limitation of tree growth due to warmer spring in semi-arid mountain forests of Tianshan, northwest China

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Abstract

Based on radial tree growth measurements in nine plots of area 625 m^2 (369 trees in total) and climate data, we explored the possibly changing effects of climate on regional tree growth in the temperate continental semi-arid mountain forests in the Tianshan Mountains in northwest China during 1933–2005. Tree growth in our study region is generally limited by the soil water content of pre- and early growing season (February–July). Remarkably, moving correlation functions identified a clear temporal change in the relationship between tree growth and mean April temperature. Tree growth showed a significant ($p < 0.05$) and negative relationship to mean April temperature since approximately the beginning of the 1970s, which indicated that the semi-arid mountain forests are suffering a prolonged growth limitation in recent years accompanying spring warming. This prolonged limitation of tree growth was attributed to the effects of soil water limitation in early spring (March–April) caused by the rapid spring warming. Warming-induced prolonged drought stress contributes, to a large part, to the marked reduction of regional basal area increment (BAI) in recent years and a much slower growth rate in young trees. Our results highlight that the increasing water limitation induced by spring warming on tree growth most likely aggravated the marked reduction in tree growth. This work provides a better understanding of the effects of spring warming on tree growth in temperate continental semi-arid forests.

1. Introduction

The growth dynamics of temperate continental semi-arid forests in the northern hemisphere in response to climate change have potentially great impact on vegetation changes, regional climate feedback and the carbon cycle (Van Mantgem *et al* 2009, Allen *et al* 2010, Williams *et al* 2010). At present, it is demonstrated that tree growth in temperate continental semi-arid forests is generally limited by soil water availability (Breshears and Barnes 1999, Wang *et al* 2005, Li *et al* 2006, Littell *et al* 2008, Shi *et al* 2008, Dulamsuren *et al* 2009), and shows a close negative relationship with temperature during
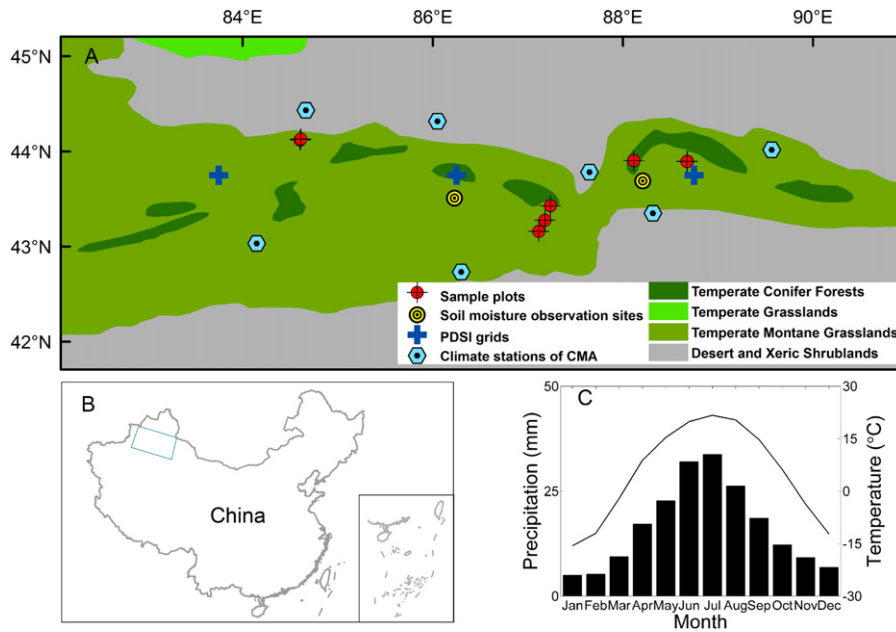
Figure 1. Geographic location of our study region in China ((A), (B)) and the climate features in our study region (C). Sample plots, meteorological stations of China Meteorological Administration, selected PDSI grids, soil moisture observation sites, and major biomes in our study region are shown in (A). Regional mean monthly temperature (curve) and total monthly precipitation (bars) based on available records (1951–2005) from the seven meteorological stations in our study region are shown in (C).

the early and middle growing season (e.g. May–August) (Li *et al* 2006, Littell *et al* 2008). Although great effort has been made, less is clear about the possibly changing response of tree growth to climate change in these temperate continental semi-arid forests (e.g. Zhang *et al* 2009), especially during spring.

The ongoing dramatic spring warming tends to advance the timing of spring for vegetation in temperate continental semi-arid regions (e.g. Piao *et al* 2006), which results in a longer growing season and probably leads to a prolonged drought stress (i.e. a much earlier drought stress) for tree growth. This prolonged drought stress could be linked to higher evaporative demands and/or changing dynamics of snow and seasonal frozen soil in a warming climate in such regions.

Increasing evidence indicates that warmer and earlier springs lead to earlier snow melt and stronger evaporation in temperate continental semi-arid mountain forests in the northern hemisphere (Briffa *et al* 1998, Ye *et al* 1999, Barnett *et al* 2005, Xu *et al* 2008), where the water supply in the early growing season is dominated by the melting of winter snow (Barnett *et al* 2005, Adam *et al* 2009). Earlier snow melt leads to faster and earlier runoff in spring (Barnett *et al* 2005, Xu *et al* 2008) and a possible reduction of water storage available for active tree growth. These changes decrease the soil water content markedly during earlier springs.

Hence, it is reasonable to expect a net reduction in vegetation growth in such regions coupled with the dramatic spring warming, as has been shown in some previous studies (e.g. Dulamsuren *et al* 2011, Liu *et al* 2013). These studies give us some insight into the general limiting effects of spring warming on tree growth. However, the possibly temporally

changing relationships between tree growth and the spring warming are still unclear, which leads to difficulties in predicting the responses of temperate continental semi-arid forests to changing climate.

Here, we have hypothesized that tree growth in temperate continental semi-arid forests tends to suffer a prolonged growth limitation with continuous and strengthened spring warming. In this study, we used inventory tree growth data from temperate continental semi-arid mountain forests and corresponding climate data in northwest China, which has experienced one of the strongest spring warming on the Earth (Wang and Gong 2000, Yu *et al* 2003), to test our hypothesis and reveal the underlying processes.

2. Data and methods

2.1. Study area and sample collection

The study area was a transect of length about 800 km oriented approximately west–east and located in middle altitudes on the northern slope of the Tianshan Mountains in northwest China (figures 1(A) and (B)). As elevation increases from 1500 to 2400 m a.s.l., the dominant vegetation changes gradually from semi-arid steppe to forest. Steppe is mostly distributed on south-facing slopes, and forest on north-facing slopes. Forests are generally mono-dominated by Schrenk spruce (*Picea schrenkiana* Fisch. et Mey). Schrenk spruce distributed in middle altitudes of the Tianshan Mountains is generally drought stressed (e.g. Li *et al* 2006). The regional climate is continental with warm summers and cold winters. Climate records from seven meteorological stations of China Meteorological Administration (see figure 1(A)) show that

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Table 1. Site description and descriptive statistics for tree ring chronologies. (Note: chronology statistics include mean interseries correlation (r_{bt}), first-order serial autocorrelation (AC), mean sensitivity (MS), and available time span. A '\' indicates that there are no records.)

Site code	(A) Site description						(B) Descriptive statistics for chronologies			
	Longitude (°E)	Latitude (°N)	Altitude (m)	No. of trees	Quadratic mean diameter (cm)	Canopy cover (%)	r_{bt}	AC	MS	Chronology time span (years)
JM1	88.68	43.90	1886	64	16.67	55	0.828	−0.046	0.549	1856–2006
JM2	88.68	43.89	2005	20	28.66	\	0.822	−0.005	0.471	1906–2005
TC	88.12	43.90	1740	62	20.35	62	0.757	−0.053	0.352	1933–2005
WM1	87.12	43.16	2406	21	27.34	40	0.578	−0.04	0.218	1889–2005
WM2	87.19	43.28	2100	28	25.37	42	0.797	−0.013	0.362	1857–2005
WM3	87.24	43.43	1819	62	16.51	54	0.796	−0.016	0.568	1802–2005
WM4	87.18	43.28	1532	20	29.13	\	0.838	−0.034	0.487	1654–2006
WS1	84.60	44.12	2135	40	25.22	50	0.647	−0.018	0.377	1901–2006
WS2	84.61	44.13	1836	52	22.83	55	0.578	−0.026	0.482	1878–2006

July and January are the warmest and coldest months, respectively (figure 1(C)). The growing season for middle altitudinal forests in the Tianshan Mountains is generally from late April to late September/early October (Jiang *et al* 2011), during which about 67% of the mean annual precipitation is received (figure 1(C)).

Tree ring samples were collected from nine representative plots of 25 m × 25 m. Most of the plots were selected in relatively open and low to moderate density forest stands (table 1(A)), which were free from tree-to-tree competition and had minimal human disturbance (e.g. logging, livestock grazing, fire, etc). In each plot, all trees with dbh (diameter at breast height) larger than 10 cm were cored at a height of around 1.3 m using an increment borer. In general, two cores were taken from each tree and 20–60 trees were sampled in each plot. A total of 369 undamaged standing trees were sampled in these plots. The descriptive information of the sampling plots is shown in table 1(A).

2.2. Chronology construction and tree growth evaluation

All samples were processed using standard dendrochronological techniques (Fritts 1976, Holmes 1983). The residual ring width chronology for each plot was developed with the ARSTAN program using conservative detrending methods based primarily on the negative exponential function or linear regression with any slope (Cook 1985) (figure S1(A) available at stacks.iop.org/ERL/8/024016/mmedia). The criterion of the expressed population signal (EPS) with a threshold value of 0.85 was chosen to determine the most reliable time span of the chronologies (Wigley *et al* 1984, Cook and Kairiukstis 1990). Several descriptive statistics were used to compare chronologies (table 1(B)). Principal component analysis (PCA) based on the correlation matrix was performed for the nine residual chronologies during 1933–2005 to identify the regionally shared growth variability as indicated by the values of the first principal component (PC1) (Andreu *et al* 2007).

Given the bias in investigating tree growth trends on the basis of changing tree ring index (Phipps and Whiton 1988), basal area increment (BAI) series were calculated to evaluate the tree growth trend. BAI is much less dependent

on changes in tree age/size and is a good indicator of forest growth/productivity (Biondi 1999, Hogg *et al* 2005). A stem BAI series was constructed for each plot according to the method of Piovesan *et al* (2008). A regional mean BAI series (BAI$_{region}$, with an available time span of 1933–2005) was constructed by averaging the nine raw BAI series. We then compared the composited BAI$_{region}$ with the regional mean growing season normalized difference vegetation index (NDVI) series which were derived from the high quality GIMMS (Global Inventory Modeling and Mapping Studies) dataset (e.g. Paruelo *et al* 1997, Fang *et al* 2005) during 1982–2005. This comparison allowed us to assess whether the sample data obtained here were representative of larger scale tree growth patterns (Liang *et al* 2005), since NDVI has been demonstrated to be a high quality indicator of large-scale trends in vegetation activity. Piecewise linear regression with one breakpoint was performed to assess the possibly temporal changes in the BAI$_{region}$ (for more detail see Wang *et al* 2011).

We further compared the mean age-related growth curves (regional growth curve (RGC), Briffa *et al* 1992, Helama *et al* 2004) for the young (cambial age < 50 years), middle (cambial age between 50 and 90 years) and old (cambial age > 90 years) age classes (similarly to Dulamsuren *et al* 2010). This comparison can be used to evaluate the differences in mean ring width increments for different age classes at given cambial ages (Dulamsuren *et al* 2010). The slopes of linear regression were calculated and compared for the raw ring width increments of trees belonging to different age classes during the first 40 years. Ages referred in this study are cambial ages at sampling height (around 1.3 m). We did not consider the age loss from ground level to sampling height since we sampled all trees at a consistent height (e.g. Sankey *et al* 2006).

2.3. Climatic data

The monthly temperature and precipitation dataset, CRU TS 3.1 (1901–2009), used in this study was obtained from the Climatic Research Unit at the University of East Anglia (Mitchell and Jones 2005). This gridded dataset, with a spatial resolution of 0.5° × 0.5°, was based on climate observations from more than 4000 meteorological stations (Wang *et al*

2011). It is widely used in northwest China to assess long-term growth/climate relationships (e.g. Zhang *et al* 2009). The gridded monthly temperature and precipitation data derived from the CRU TS 3.1 dataset showed high similarity to the climate records from seven meteorological stations of China Meteorological Administration (see figure 1(A)) in our study region during 1951–2005, with Pearson correlation coefficients for monthly temperature ranging from 0.66 ($p <$ 0.0001) in November to 0.97 ($p <$ 0.0001) in February, and for monthly precipitation ranging from 0.65 ($p <$ 0.0001) in October to 0.89 ($p <$ 0.0001) in May. Based on careful comparison, we selected the CRU grid points that were closest to sample stands to calculate regional climate trends (figure 1(A)). We used the observed soil water content (1981–1999) at Turpan and Shihezi (Li *et al* 2005) and a monthly Palmer drought severity index (PDSI) dataset (1870–2005) (Dai *et al* 2004) to analyze the changes of soil water content in this region and their links to early spring warming. Several studies have shown that the PDSI can well depict the large-scale interannual variations in soil water content in northwest China and central Asia (Dai *et al* 2004, Li *et al* 2006). Each year, the early spring (March–April) soil water limitation (SWL_{ESP}) during the period 1951–2005 was estimated based on a simple water balance model using the equation

$$SWL_{ESP} = PRE_{PGS} - PET_{ESP} \qquad (1)$$

where PRE_{PGS} is the total precipitation during the pre-growing season (October of the previous year to April of the current year); PET_{ESP} is the potential evapotranspiration during early spring, calculated by summing up the monthly PET values of March and April using the Thornthwaite formulation (Thornthwaite 1948).

2.4. Regional tree growth–climate relationships

Simple correlation functions (CF_S) were performed to quantify the general relationships between regional tree growth (PC1) and climate data during 1933–2005. Moving correlation functions (MCF_S) were further analyzed using DENDROCLIM2002 to investigate the possibly changing relationships between regional tree growth and the climate data during 1933–2005 by adopting a sliding window of 25 years (i.e. first calculation 1933–1957, second calculation 1934–1958, etc) (Biondi and Waikul 2004, Carrer and Urbinati 2006, Zhang *et al* 2009). The selection of this window length is a compromise between having a large enough sample size in each sliding window (i.e. 25 years) for correlation and obtaining enough sliding windows for evaluation of changing growth/climate relationships. The statistical significance and stability of CF_S and MCF_S were tested with a bootstrap procedure with 1000 replications. All significance levels were according to $p < 0.05$. In this study, we also evaluated the possible effects of stochastic processes on the variations of MCF_S by performing the test suggested by Gershunov *et al* (2001).
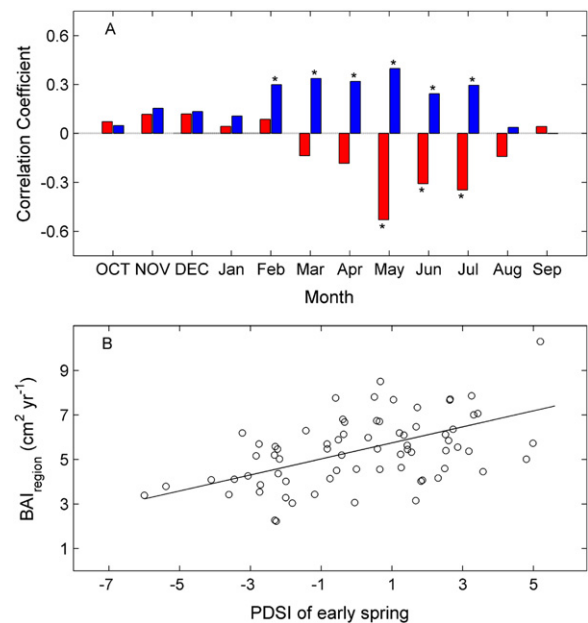

Figure 2. Relationships between regional tree growth and climate. Simple correlations between regional growth pattern (PC1) and monthly temperature (red bars) and precipitation (blue bars) from October of previous year to September of current year during 1933–2005 are shown in (A). Values that are statistically significant are marked by asterisks. Capitals in (A) indicate prior year months; lower case letters indicate current year months. The relationship of regional basal area increment (BAI_{region}) and PDSI of early spring during 1933–2005 with a linear fit is shown in (B) (linear fit, $y = 0.36x + 5.39$, $r^2 = 0.29$, $p < 0.001$).

3. Results

3.1. Regionally shared growth variability and climate relationships

The PC1 is significant, representing 70.3% of the total variance (figure S1 available at stacks.iop.org/ERL/8/024016/mmedia). Although the nine residual chronologies show different loadings with the PC1, all of them have positive correlations with it (figure S1(B) available at stacks.iop.org/ERL/8/024016/mmedia), showing that the nine sampled forests share common growth variability.

Tree growth in this region shows significant ($p < 0.05$) negative correlation with the mean monthly temperature of May, June and July (figure 2(A)). In contrast, tree growth shows significant positive correlation with the total monthly precipitation of February–July (figure 2(A)). There is a close relationship between the BAI_{region} and the PDSI of early spring during 1933–2005 (figure 2(B), $y = 0.36x + 5.39$, $r^2 = 0.29$, $p < 0.001$).

The MCF_S reveals consistently significant and negative correlation of the regional tree growth with mean May, June and July temperature during all sliding windows (figure 3). Although the regional tree growth does not correlate to mean February and March temperature significantly during any of the sliding windows, there seem to be strong temporally negative trends in their correlation (figure 3). For example, the correlations between tree growth and mean February
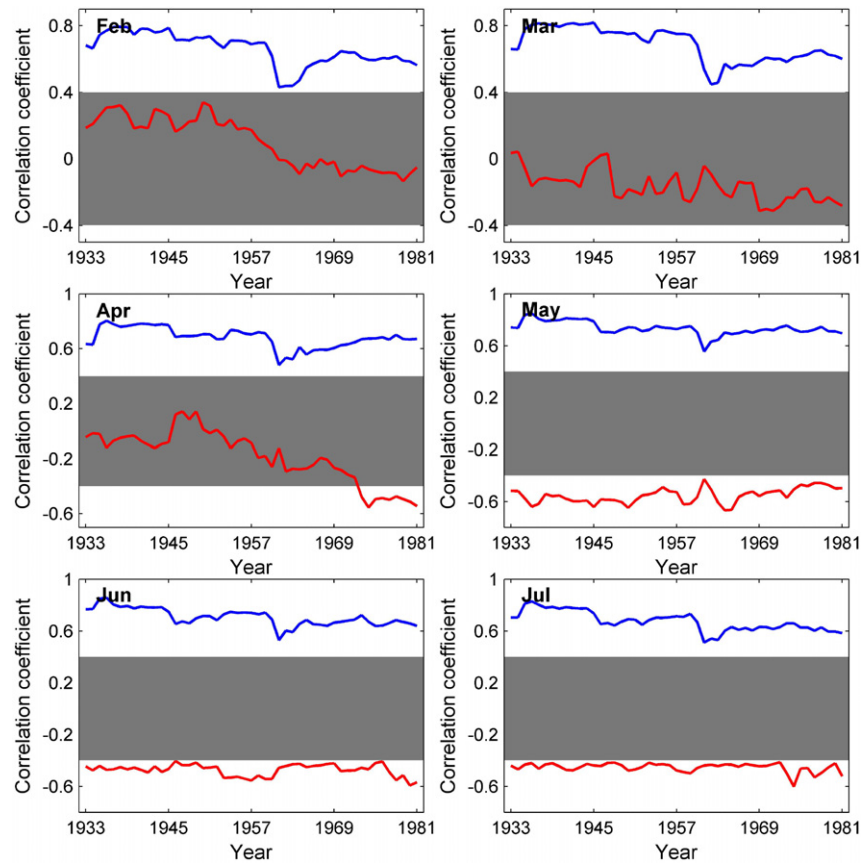
Figure 3. Temporal changes of growth–climate relationships as shown by moving correlations between PC1 and monthly temperature (red lines) and monthly PDSI (blue lines) from February to July using a sliding window of 25 years. The shaded areas are the 95% confidence limits.

temperature move from positive values towards negative values since approximately the time interval of 1961–1985. Notably, the relationship between tree growth and mean April temperature shows a clear temporal change. Tree growth in this region has been significantly negatively correlated to mean April temperature since approximately the beginning of the 1970s (figure 3). This marked temporal change in MCF_S between the regional tree growth and mean April temperature since the early 1970s cannot be explained by an effect of stochastic processes, as revealed by the Gershunov test (Gershunov *et al* 2001). Differently from the changing growth–temperature relationships, all monthly PDSI values correlate to tree growth in this region significantly and positively during all sliding periods (figure 3).

3.2. Tree growth trends

BAI_{region} provides a good representation of tree growth patterns at larger scales due to the close relationship ($r^2 = 0.46, p < 0.001$) between BAI_{region} and regional growing season NDVI during 1982–2005 (figure 4(A), figure S4 available at stacks.iop.org/ERL/8/024016/mmedia). Tree growth in this region shows large interannual and decadal variations (figure 4(B)). In spite of the large variations, tree growth in this region seems to be suffering a marked decline since approximately 1959, as identified by a piecewise linear

regression. The mean rate of regional growth decline is about 0.6 cm^2/10 years during 1959–2005 ($p < 0.05$). The results of BAI_{region} anomalies show that negative anomalies of tree growth are dominant in recent decades (i.e. 1970s–2000s) when compared to the early period (i.e. 1930s–1960s), when positive anomalies of tree growth are prevalent (figure 4(C)). The perplexing peak in BAI_{region} around 1959 (figures 4(B) and (C), figure S5 available at stacks.iop.org/ERL/8/024016/mmedia) is most likely triggered by a wet pulse occurring concurrently during that period with a much higher mean growing season PDSI value (figure S5). Overall, tree growth in our study region has recently suffered a marked decline.

RGC analyses show that young trees grew generally more slowly than middle- and old-aged trees during the first decades of their lifespan (figure 5). Comparisons of the slopes of linear regression between young (-0.041 ± 0.022 mm yr^{-1}), middle-aged (-0.023 ± 0.021 mm yr^{-1}) and old-aged trees (-0.01 ± 0.03 mm yr^{-1}) show that the relationship between annual increment and tree age during the first 40 cambial years is much more ($p < 0.05$) negative in young than in middle- and old-aged trees. These results imply that the annual increment in tree growth has declined increasingly more rapidly during the last four decades (1970s–2000s) (figure 5).
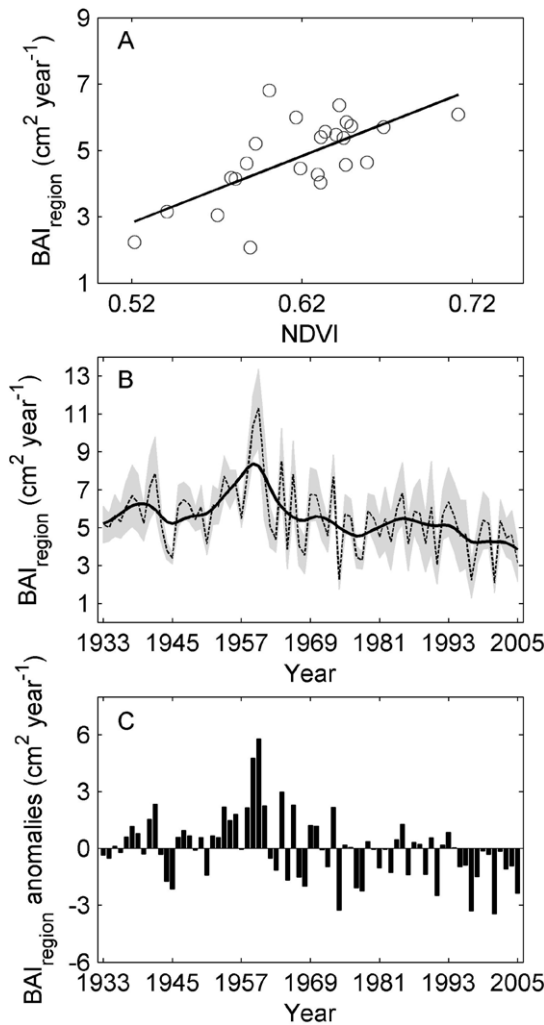
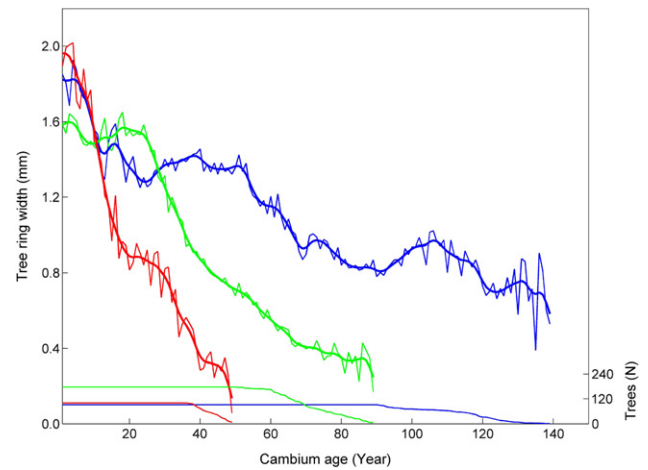**Figure 5.** Regional growth curves (RGCs) for young (<50 years, red lines), middle-aged (50–90 years, green lines) and old-aged (>90 years, blue lines) trees in this region. The bold lines are the fitted cubic smoothing splines for the RGCs. The sample depths for the RGCs of the young (red line), middle-aged (green line) and old-aged (blue line) trees are also shown.

Figure 4. (A) Comparison of regional basal area increments (BAI$_{region}$) and growing season normalized difference vegetation index (NDVI) during 1982–2005 with a linear fit (solid line, $y = 20.11x - 7.64$, $r^2 = 0.46$, $p < 0.001$). (B) Regional BAI series during 1933–2005 with uncertainties (shaded areas). The bold line in (B) is the cubic smoothing spline of regional BAI. (C) The anomalies of BAI$_{region}$ relative to the mean of BAI$_{region}$ during 1933–2005.

3.3. Spring warming and soil water content

The temperature shows a dramatic increase in the winter and spring months during 1951–2005 (figure 6(A), figure S2 available at stacks.iop.org/ERL/8/024016/mmedia), with warming rates ranging from 0.26 to 0.84 °C/10 years (figure 6(A)). Comparatively, the summer temperature does not show a marked increase (figure 6(A), figure S2). Precipitation in this region shows large interannual variations but does not change markedly except for an increasing trend in December and July (figure 6(A), figure S3 available at stacks.iop.org/ERL/8/024016/mmedia). Taking the winter and early spring together, precipitation in this region appears to somewhat increase, although the increase is not significant in most cases (figure 6(A), figure S3).

A close and negative relationship between early spring temperature and observed soil water content shows that the early spring warming is prone to reducing the soil water content in this region (figure 6(B)). Linear regression shows that the soil water content decreases by 0.57 cm on average accompanied by one degree of warming ($y = -0.57x + 12.78$, $r^2 = 0.25$, $p < 0.05$). In spite of the strong interannual variability, water limitation in early spring shows a clear increase with time during 1951–2005 (figure 6(C), $y = -0.36x + 678.67$, $p < 0.05$). The regional mean early spring PDSI series also shows a decreasing trend ($y = -0.013x + 24.64$, $p = 0.25$) during 1933–2005 although the linear trend is not significant (figure S5 available at stacks.iop.org/ERL/8/024016/mmedia).

4. Discussion and conclusions

The results presented above confirmed our hypothesis that the temperate continental semi-arid forests on the Tianshan Mountains in northwestern China are suffering from prolonged growth limitation in recent years accompanying spring warming. It is illustrated that high temperature during the early growing season (e.g. May–July) generally tends to limit tree growth in this region (e.g. Li *et al* 2006). It is of particular interest that we identify a clear temporal change in the relationship between tree growth and mean April temperature. Tree growth shows significantly negative correlation to April temperature since approximately the beginning of the 1970s (figure 3), indicating that tree growth in these semi-arid forests is suffering from prolonged limitation in recent years.

The strong spring warming in recent decades in the semi-arid forests of northwestern China has led to an earlier spring and longer growing season (Piao *et al* 2006, Zhou *et al* 2001). Warmer and earlier spring without concurrent significant increase in precipitation (figure 6(A), figures S2
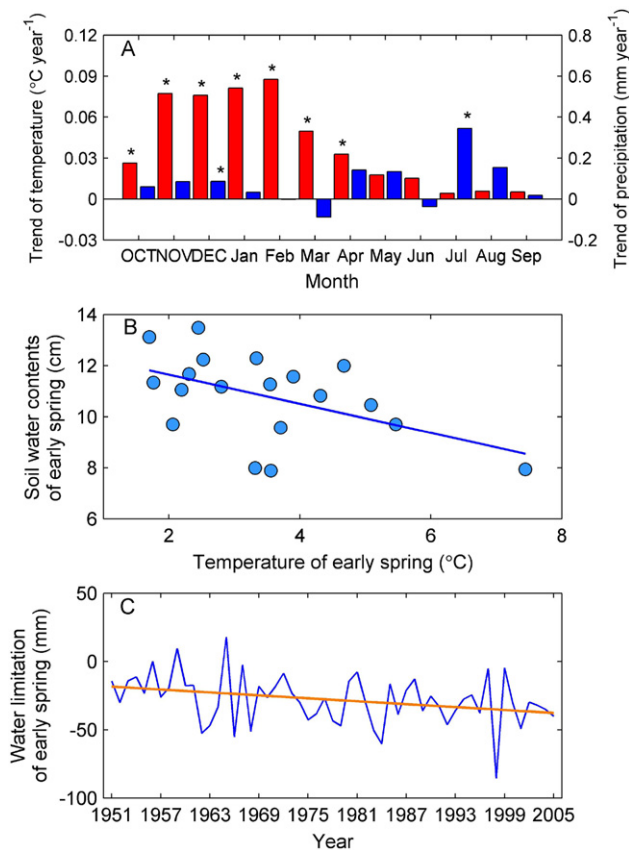
Figure 6. (A) Linear trend of monthly temperature (red bars) and monthly precipitation (blue bars) from October of previous year to September of current year during 1951–2005. Values that are statistically significant in (A) are marked by asterisks. Capitals in (A) indicate prior year months; lower case letters indicate current year months. (B) Relationship between early spring (March–April) temperature and the observed soil water content (blue points) during 1981–1999. The solid line in (B) denotes the linear regression ($y = -0.57x + 12.78$, $r^2 = 0.25$, $p < 0.05$). (C) Estimated water limitation in early spring during 1951–2005 (blue line). The marked increase (note the sign of the values) of water limitation in this region is revealed by a linear fit (solid orange line, $y = -0.36x + 678.67$, $p < 0.05$).

and S3) could have a large effect on water balance in semi-arid regions, possibly due to higher evaporative demands and/or the degradation of snow and seasonal frozen soil.

Water supply during the early growing season in this region is currently dominated by spring snow melt (Li 1999, Barnett *et al* 2005, Adam *et al* 2009), which generally starts in the middle of March and ends in the middle of April in middle altitudinal forest belt (Wang *et al* 2009, Ye *et al* 1999). Although some evidence shows that there is a subtle increase in maximum snow depth in spring in this region (Li 2001), earlier snowmelt and increased evaporation coupled with warmer and earlier spring have markedly reduced the soil water content in this region (Mao *et al* 2007, figure 6(B)).

Changes in the sporadic seasonal frozen soil in our study region could also modify the soil moisture conditions. The seasonal frozen soil can provide a direct source of water for vegetation growth in water-limited regions or under drought stress (Sugimoto *et al* 2002). Tree growth in this

region could benefit from the seasonal frozen soil, especially during the early growing season when summer rainfall is not available. Observations showed that the ground temperature in this region has suffered a rapid increase (ranging from 0.3 °C to 0.6 °C) during the last 30 years, and the average active-layer thickness has increased by 23% in comparison to the early 1970s (Marchenko *et al* 2007, Zhao *et al* 2010). The organic layer depth in this region is shallow (0–5 cm), which renders seasonal frozen soil melting easy and vulnerable to spring warming (Anisimov and Reneva 2006). The coarse soil texture in our study region has low water holding capacity for the melt water from frozen soil and may additionally intensify the drought conditions on tree growth. Hence, the degradation of seasonal frozen soil caused by rapid spring warming (Zhao *et al* 2004, Marchenko *et al* 2007) will further exacerbate the soil moisture conditions in this region.

The results of the water balance model used in our study confirmed that the spring warming in recent decades has already led to a more severe soil water limitation during early spring in this region where precipitation amounts are small (figure S3, available at stacks.iop.org/ERL/8/024016/mmedia, figure 6(C), Hu and Willson 2000). The degradation of soil moisture conditions during the early growing season arising from spring warming is considered here as being the main cause of a marked decline in tree growth in this region (figures 2(B), 3, 4(B) and 5), because soil moisture in the early growing season is proven to be crucial for tree growth in such water-limited regions (figure 2, Li *et al* 2006). This is why tree growth in this region is suffering from prolonged limitation and young trees have grown much more slowly than middle- and old-aged trees during the first decades of their lifespan (figures 3 and 5). However, our conclusions cannot be simply extended to other semi-arid forests, such as the semi-arid forests in the Mediterranean region where the climate regime is quite different from the one in our study region. Several studies have shown that tree growth in the Mediterranean region is mainly dominated by water supply during the current summer and the winter of the previous year (Andreu *et al* 2007, Sarris *et al* 2007), and there tends to be a stronger negative relationship between tree growth and late summer/autumn temperatures in the year before growth in recent decades (Andreu *et al* 2007).

Our findings suggest that spring warming is becoming the limiting factor for tree growth in temperate continental semi-arid mountainous forests in northwestern China. It is of particular interest that the warming-induced tree growth decline is likely prevalent in not only mid-latitudinal water-limited regions but also some boreal forests in high latitudes (e.g. Barber *et al* 2000, Driscoll *et al* 2005, Littell *et al* 2008, Allen *et al* 2010, Williams *et al* 2010). These results suggest that at least some of the world's forested ecosystems are already becoming increasingly vulnerable to future warming and drought (Allen *et al* 2010). Specifically, dramatic spring warming could, though poorly understood, threaten forests in regions where the water supply during the early growing season relies mainly on snow and frozen soil melting. However, we are not clear about the possible 'homeostatic-like' plasticity of peak activity for tree growth

in our study region accompanying the spring warming (Rotenberg and Yakir 2010). Previous studies have shown that this homeostatic-like ecosystem-scale behavior is different between different ecoregions (e.g. Rotenberg and Yakir 2010, Camarero *et al* 2010). Our results have highlighted the long-term impact of spring warming on tree growth. In particular, warmer springs and more prolonged and intense heat waves are expected in the future, based on a large number of model simulations of the human-induced increase in greenhouse gases (IPCC 2007). In a warmer climate, the effects of spring warming will cause tight but currently poorly constrained limitations on tree growth and will in turn intensify the pervasive and chronic forest dieback in semi-arid regions (see Allen *et al* 2010). Our results therefore allow a better understanding of the links between tree growth and climate warming, to aid in modeling and predicting the potentially extensive climate-driven forest dieback (see Allen *et al* 2010, McDowell 2011).

In summary, our results have revealed a prolonged limitation of tree growth due to spring warming-induced water limitation in the semi-arid mountain forests of northwestern China. This has important implications for forest management in temperate continental semi-arid regions and in regions liable to become increasingly prone to drought stress, as springs become warmer and extreme drought events become more frequent over the coming decades (IPCC 2007, Meehl and Tebaldi 2004). Nevertheless, further research is still urgently required to investigate the extent of the observed reduction in tree growth over larger areas and to provide a comprehensive understanding of the causes.

Acknowledgments

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