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Elevational Effects of Climate Warming on Tree Growth in a *Picea schrenkiana* Forest in the Eastern Tianshan Mountains

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Abstract: Considerable uncertainty exists regarding the overall effects of future climate change on forests in arid mountains, and the elevational range of drought-induced tree growth decline remains unclear. Tianshan is the largest mountain in arid regions globally. Here, we analyzed tree ring data of pure stands of Schrenk spruce (*Picea schrenkiana* Fisch. et Mey.) in the Jiangbulake region in the eastern Tianshan Mountains along an elevational gradient (1800–2600 m a.s.l.). The radial growth of *P. schrenkiana* trees declined in three of the nine sample strips (1800–2100 m a.s.l.) over the last two decades. *P. schrenkiana* growth response (measured by the tree ring width index, RWI) to temperature significantly changed at an elevational "inflection point" at 2100–2200 m. RWI was significantly negatively correlated with temperature at low elevations, whereas the opposite was observed at high elevations. Precipitation and minimum temperatures in winter and spring and mean temperatures in spring and summer were the main drivers of *P. schrenkiana* growth, with the effect of maximum temperatures on tree growth concentrated in the spring. In addition to climate warming in the study area since the 1970s, tree growth (as measured by the basal area increment, BAI) at elevations below 2200 m initially increased and then decreased. Tree growth at higher elevations continues to increase. Since 2000, the average RWI at high elevations exceeded that at low elevations. The average BAI values at high and low elevations have gradually approached each other in recent decades, although lower elevations exhibited higher values in the past.

Keywords: Tianshan mountain; *Picea schrenkiana*; climate change; elevation gradient; growth decline

Citation: He, J.; Shen, Z.; Ning, C.; Zhang, W.; Halik, Ü. Elevational Effects of Climate Warming on Tree Growth in a *Picea schrenkiana* Forest in the Eastern Tianshan Mountains. *Forests* **2024**, *15*, 2052. https://doi.org/10.3390/f15122052

Academic Editors: Francesca Giannetti, María Menéndez-Miguélez and Admir Avdagic

Received: 21 October 2024
Revised: 11 November 2024
Accepted: 19 November 2024
Published: 21 November 2024

1. Introduction

High mountains have a significant role in terrestrial forest ecosystems and are the primary distribution area for natural forests [1–3]. Aridity has worsened due to ongoing global warming, and this has resulted in slower tree growth and a reduction in the range of montane forests [4]. There is a great deal of stress on ecological processes such as carbon sequestration in montane forests [5–7]. The range of heights at which drought inhibits tree growth in mountains is also increasing, even when trees in mountains are shifting to higher elevations in response to warming [8]. Forecasts indicate that the average global forest area will decrease by approximately half [2]. Therefore, to address the challenges of global climate change, a precise estimate of the elevational range of the tree growth decline in forests is required.

Warming makes some regions wetter, whereas others become drier [9]. Climate change is also causing ecosystems to exhibit opposing ecological effects across elevational gradients. For example, many studies have confirmed that tree growth is positively correlated with temperature at high elevations, whereas it is negatively correlated with temperature at lower elevations [10,11]. Tree growth declined in two of five elevation sample strips in the Gongga Mountains of the eastern Tibetan Plateau [10]. In some regions, tree growth and temperature exhibit a positively correlated response pattern across all elevation sections [7,12]. Other local-scale factors can complicate the response; these include the faster growth of trees in areas of sparsely wooded treelines on Tianshan relative to areas of dense low- and high-elevation forests where trees have been distributed over the past few decades [13]. Other studies have reported that drought during the growing season is the main factor limiting radial growth in *P. schrenkiana* [3]. It has also been demonstrated that younger trees are more sensitive to climate response than older trees [14]. Collectively, these studies have enriched our understanding of the different responses of tree growth to climate change.

Tianshan is the largest mountain in arid regions of the world. Many studies have observed that the effects of climate warming and drought on ecosystems are reflected in various aspects, such as tree growth and biodiversity [3,15–17]. This has brought much attention to changes in the structure and extent of forest ecosystems in Tianshan under climate change scenarios, as well as their capacity and sustainability to provide ecosystem services [18]. However, as Tianshan extends for more than 1700 km from east to west, there is significant regional variability in temperature and precipitation. Related studies have primarily focused on the upper and lower treelines of tree distribution [19,20]. Currently, there is a lack of clarity regarding the elevational range of tree growth decline in *P. schrenkiana* in the Tianshan Mountains. To further our understanding of the adaptation mechanisms of forest tree growth to climate warming in arid zones, we collected tree core samples from all elevated sections of *P. schrenkiana* on the north slope of the Tianshan Mountains. We aimed to address three scientific questions. (1) Is there a decline in tree growth of *P. schrenkiana* in Tianshan, and what is the elevational range? (2) Are there positive or negative effects of temperature on *P. schrenkiana* tree growth? (3) What climatic factors drive the growth of *P. schrenkiana*?

2. Materials and Methods

2.1. Study Area

The study area is located on the eastern section of Tianshan mountain in Xinjiang, China, and belongs to the Jiangbulake Scenic Area in Qitai County (Figure 1), which covers an area of approximately 4800 ha (43°25′06″–43°39′42″ N, 89°25′15″–90°16′49″ E). According to the data from the meteorological station in Qitai County (approximately 800 m a.s.l. and approximately 50 km from Jiangbulake), the mean annual temperature from 1952 to 2021 was approximately 0–3 °C, and the annual precipitation was approximately 250–500 mm. *P. schrenkiana* is primarily distributed on the northern slope of the Tianshan Mountains and less so on the southern slope, and it is primarily present at elevations ranging from 1800 $\pm$ 50 m to 2600 $\pm$ 50 m. *Populus davidiana* grows at lower elevations, while higher-elevation sections grow coniferous species.

2.2. Field Sampling and Climate Data

During July–August 2022, we sampled tree cores at 100 m intervals from the lower treeline to the upper treeline of the forest belt (1800 $\pm$ 50 m–2600 $\pm$ 50 m) at a total elevation of 800 m in the Jiangbulake area in eastern Tianshan, and we chose a total of three 30 m $\times$ 30 m sample plots at a horizontal interval of approximately 50 m for each elevation section to represent this elevation condition. We investigated the DBH (diameter at breast height) and density of the trees. Approximately ten healthy trees of different ages were selected from each sample site, and one core was drilled from each tree in both the E- and S-directions using an increment borer (CO700, Haglof, Torsång, Sweden, entrance). Healthy and intact cores were fixed in wooden troughs to air-dry. Then, using a sanding machine, the cores were sanded with 200-, 600-, and 1200-grit sandpaper until the tree rings were clearly visible. Tree ring width was measured using a Lintab 5 analyzer (accuracy 0.001 mm) and cross-dated with the COFECHA program. Finally, standardized chronology of trees at different elevations was made (Figure 2).

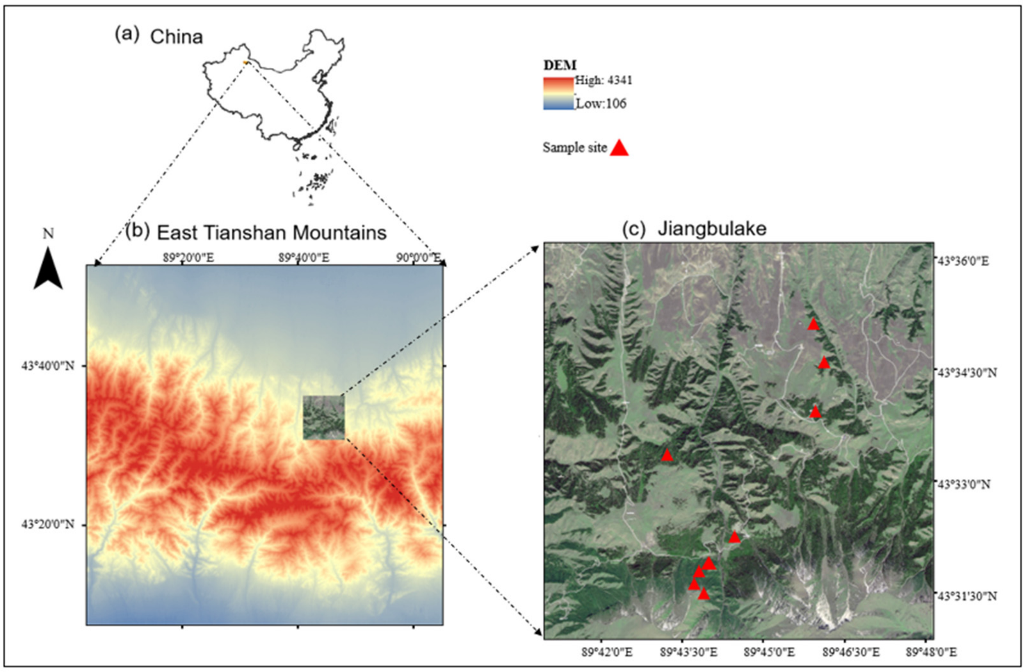

Figure 1. Geographic location map of the study area and sampling sites. (**a**) is China, (**b**) is the eastern section of the Tianshan, and (**c**) is Jiangbulake, which is also the sampling area of this study.

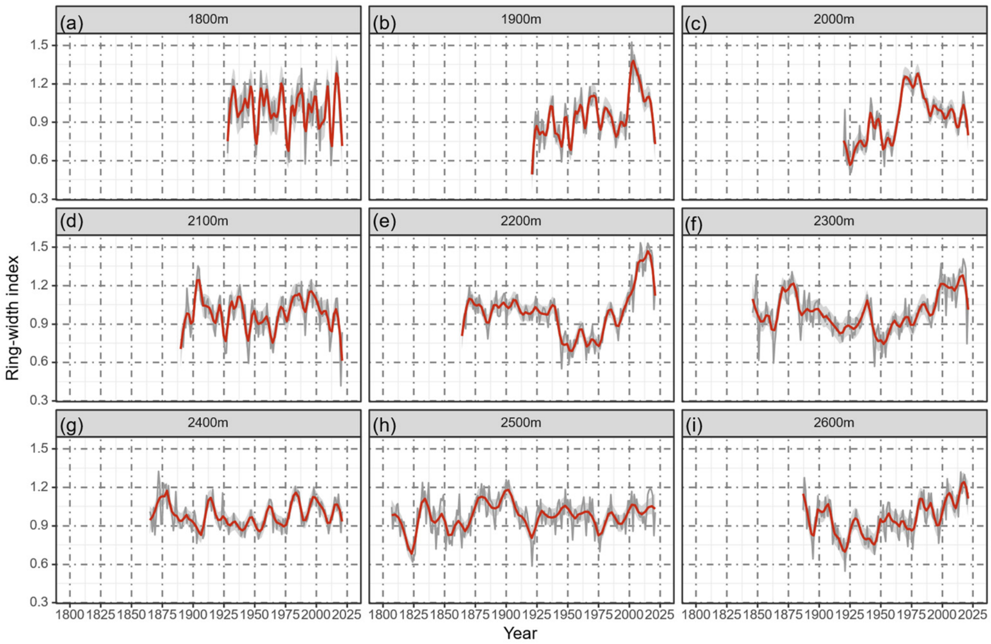

Figure 2. Tree ring width index of *P. schrenkiana* along the elevation of 1800 m to 2600 m.

A comparison of recent weather station data with gridded point data from the CRU (Climatic Research Unit gridded Time Series) climate dataset "https://climexp.knmi.nl/start.cgi (accessed on 14 August 2024)" reveals that the station data are more suitable for data analysis than the CRU gridded point data (Figure S1). Accordingly, this study focuses on utilizing climate data obtained from meteorological stations. Monthly climate data were obtained from the National Center for Environmental Information (NCEI) "https://www.ncei.noaa.gov/ (accessed on 23 November 2023)". A segmented linear regression was performed on the annual mean temperature at the site. It was determined that there has been a continuous increase in temperature in the study area since 1969 (Figure 3).

Thus, all data analyses were selected after this date. The standardized precipitation evapotranspiration index (SPEI) was employed to characterize the drought conditions in the study area. SPEI is a time-accumulated index. For example, SPEI 03 represents the overall dryness or wetness in January, February, and March. The SPEI data used in this study were sourced from the Xinjiang SPEI dataset [20,21].

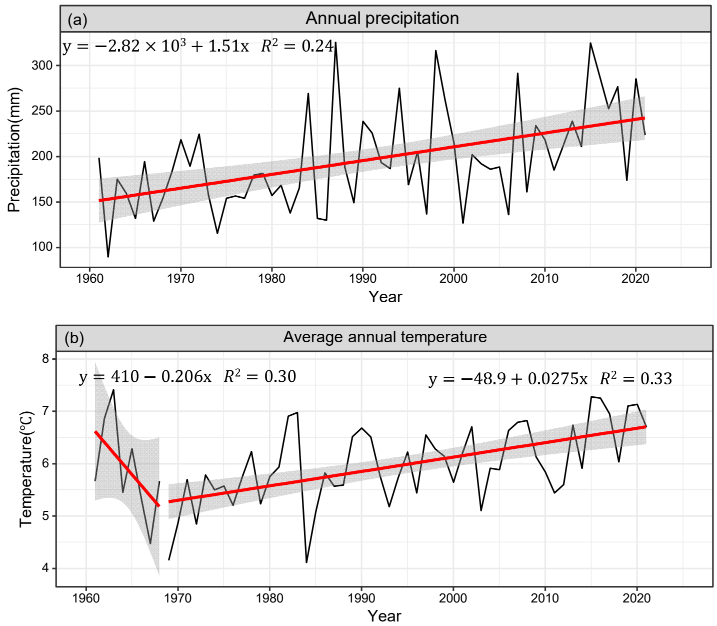

Figure 3. Trends in average annual temperature and precipitation at meteorological stations in the vicinity of the study area since 1960 yr. (**a**) is the change and trend in precipitation dynamics over the years in the study area, and (**b**) is the change and trend in temperature dynamics over the years.

2.3. Data Analysis

In accordance with the findings of preceding research, the negative exponential method was employed to eliminate the growth trend from the tree ring width and to establish a chronology, and this was implemented in the "dplR" package in R4.3.2 "https://www.r-project.org/, (accessed on 18 November 2024)" [22]. Seasonal classification was based on the following periods: winter (December of the previous year to February); spring (March to May); summer (June to August); autumn (September to November). Correlation analysis (Pearson, London, UK) of the tree ring width index and climate was conducted using the R4.3.2 software. Basal area increment (BAI) is a useful metric for characterizing the growth trend of a tree (Equation (1)), where R represents the average tree ring width and t denotes the year in which the tree rings were formed. The BAI was calculated using R4.3.2. The "segment" package of R4.3.2 was employed for the implementation of segmented linear fitting, and the "segment" package can identify the time nodes where the tree growth changes significantly. The time point at which significant changes in tree growth occurred in all elevation transects was approximately 2000 yr; therefore, we fitted the BAI segments using 2000 yr as the time point.

$$\mathrm{BAI_t} = \pi\left(\mathrm{R_t^2} - \mathrm{R_{t-1}^2}\right) \tag{1}$$

3. Results

3.1. Characteristics of Standardized Chronology

The trees were younger at lower elevations and older at higher elevations (Table 1). The AC1 values of the sample trees were lowest at 2400 m above sea level, indicating a significant variation in growth among the trees at this elevation. The expression of all samples exceeded the confidence threshold value (0.85), with the exception of the 2400-meter elevation, indicating that the climate signals present in the samples were representative of the overall characteristics. According to the tree ring width index, tree growth at elevations of 1900 m, 2000 m, and 2100 m has decreased significantly in recent years (Figure 2).

Table 1. Information of sampled trees at various elevations. MS, mean sensitivity; AC1, autocorrelation of level 1; Rbar, mean inter-series correlation; EPS, expressed population signal.

Elevation (m)	Trees	Cores	MS	Rbar	Start Year	End Year	EPS	Average Age	Average DBH (cm)	Density (Number/ha)	AC1
1800	25	39	0.28	0.26	1928	2021	0.93	71	19.9	881	0.57
1900	21	31	0.18	0.36	1921	2021	0.95	71	20.2	725	0.51
2000	20	28	0.16	0.60	1920	2021	0.93	64	15.3	1481	0.33
2100	32	52	0.21	0.46	1890	2021	0.98	62	23.2	851	0.55
2200	20	26	0.17	0.59	1864	2021	0.97	127	30.5	492	0.46
2300	20	32	0.18	0.32	1846	2021	0.91	129	24.7	774	0.46
2400	18	21	0.19	0.07	1865	2021	0.55	114	16.1	1103	0.24
2500	22	31	0.19	0.23	1807	2021	0.90	137	18.4	811	0.44
2600	22	30	0.18	0.194	1887	2021	0.865	66	22.0	129	0.522

3.2. Response of Growth to Climate

The total annual precipitation in the vicinity of the study area has increased since 1960 (Figure 3). The effect of precipitation on tree growth was primarily concentrated between 2000 and 2300 m above sea level, and the correlation between tree growth and precipitation was weaker at higher and lower elevations. Precipitation exerted both positive and negative effects on tree growth. Elevations of 2000 m and 2100 m experienced negative effects, whereas other elevations experienced positive effects (Figure 4). Winter and spring precipitation exerted the most significant effects on *P. schrenkiana* tree growth.

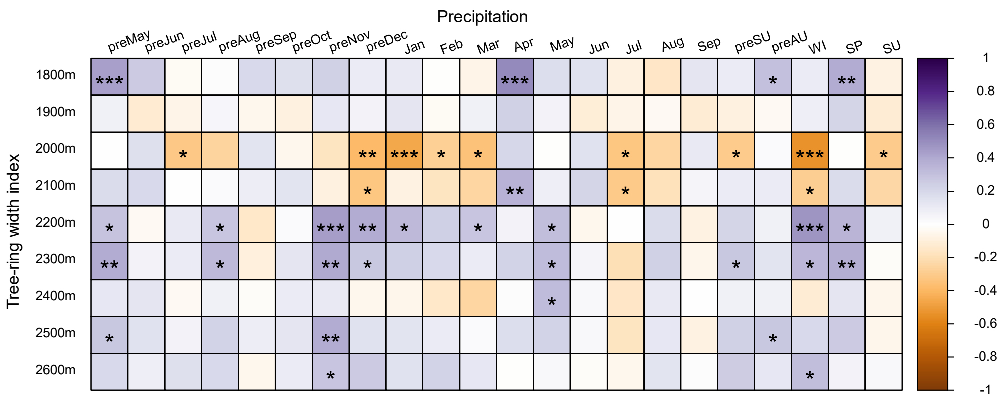

Figure 4. Correlation analysis between tree ring width index at different elevations and precipitation in different seasons and months (* is $0.01 \leq p \leq 0.05$; ** is $0.001 \leq p \leq 0.01$; *** is $p \leq 0.001$).

Tree growth at lower elevations exerted roughly negative effects on the mean, maximum, and minimum monthly temperatures, and the opposite was observed for trees at higher elevations (Figure 5). The mean temperatures in spring and summer, maximum temperatures in spring, and minimum temperatures in winter and spring exerted the most significant effects on *P. schrenkiana* tree growth at all elevations. Notably, minimum temperatures in winter inhibited high-elevation tree growth, whereas minimum temperatures in spring promoted tree growth (Figure 5c).

The standardized precipitation evapotranspiration index (SPEI) was significantly and positively correlated with tree growth at lower elevations (Figure 6). When comparing SPEI03 and SPEI06, longer cumulative drought affected tree growth over a wider range of elevations (Figure 6). Tree growth at an elevation of 1800 m was more sensitive to SPEI response.

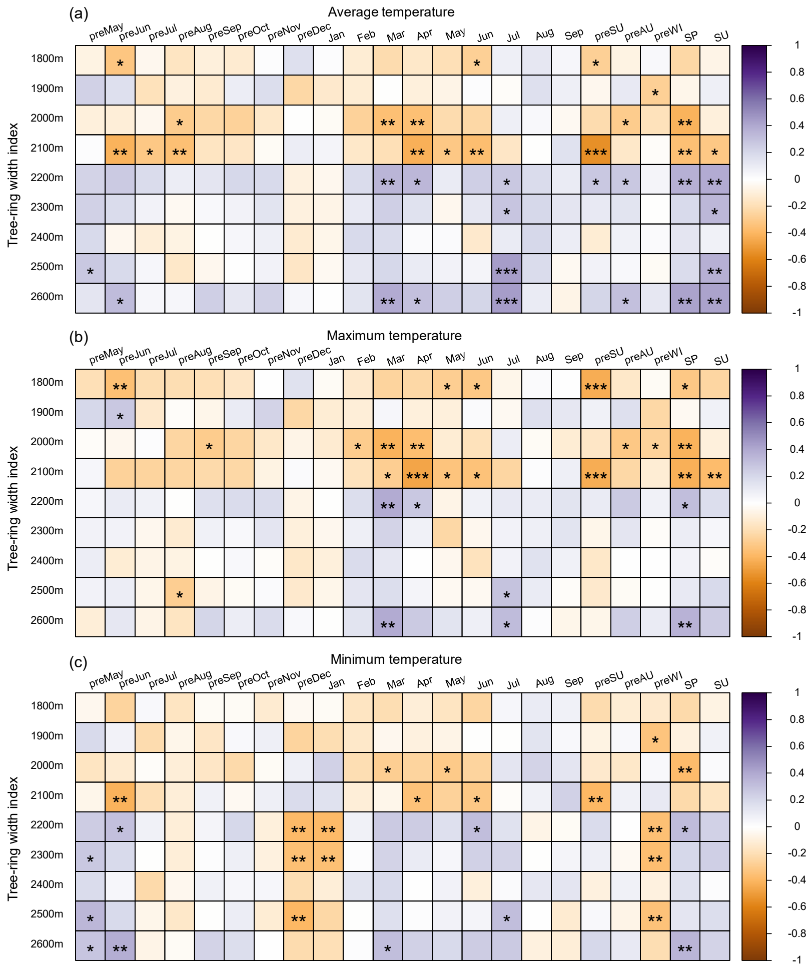

Figure 5. Correlation analysis of tree ring width index at different elevations with temperature in different seasons and months. (**a**–**c**) are the correlation analyses of tree ring width index and average, maximum, and minimum temperature, respectively. The number of * represents the significance level of the correlation (* is $0.01 \leq p \leq 0.05$; ** is $0.001 \leq p \leq 0.01$; *** is $p \leq 0.001$).

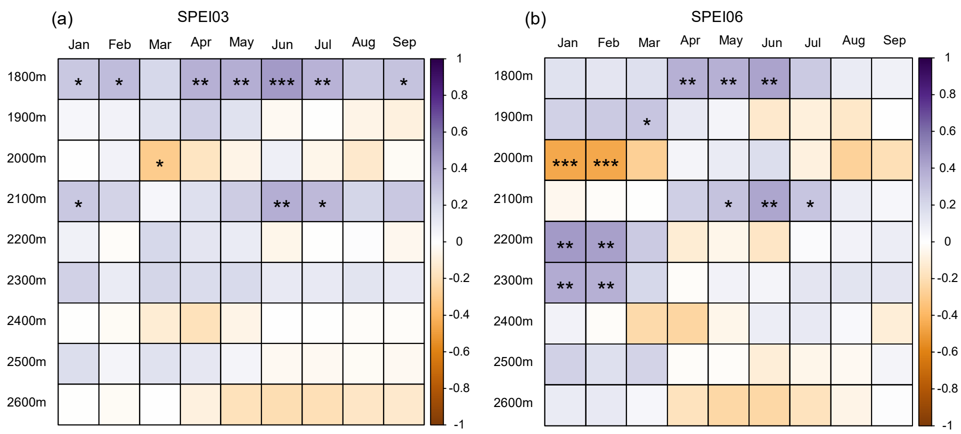

Figure 6. Correlation analysis between tree ring width index and standardized precipitation evapotranspiration index at different elevations (* is $0.01 \leq p \leq 0.05$; ** is $0.001 \leq p \leq 0.01$; *** is $p \leq 0.001$).

3.3. Long-Term Growth Trend

Since 1969, tree growth at lower elevations has increased and then decreased, whereas tree growth at higher elevations has continued to increase (Figure 7). Between 1969 and 2000, tree growth at elevations of 1800, 1900, 2000, 2100, 2200, 2400, and 2600 m exhibited an increasing trend (slope > 0), whereas tree growth at other elevations exhibited a decreasing trend (slope < 0). Between 2000 and 2021, tree growth decreased significantly at 1800 m, 1900 m, and 2100 m (slope < 0) and increased significantly at other elevations. It is worth noting that tree growth at high elevations was very low at first and then significantly increased.

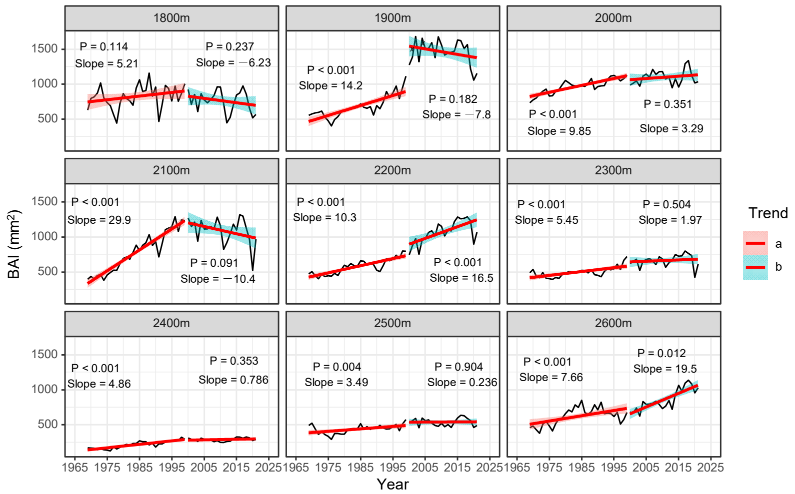

Figure 7. Segmentation and linear fitting of BAI at different elevations from 1969 to 2021. a and b represent the growth trend of trees at different times.

Between 1969 and 1985, the average RWI at low elevations was higher, whereas between 1985 and 2003, it was approximately the same. Between 2003 and 2021, the average RWI at high elevations was greater than that at low elevations (Figure 8a). The RWI of trees at high and low elevations exhibited a consistent decreasing trend (Figure 8c). From 1969 to the present, the average BAI at low elevations was still higher than that at high elevations (Figure 8b), but the narrowing trend from 2008 onwards was very clear (Figure 8d).

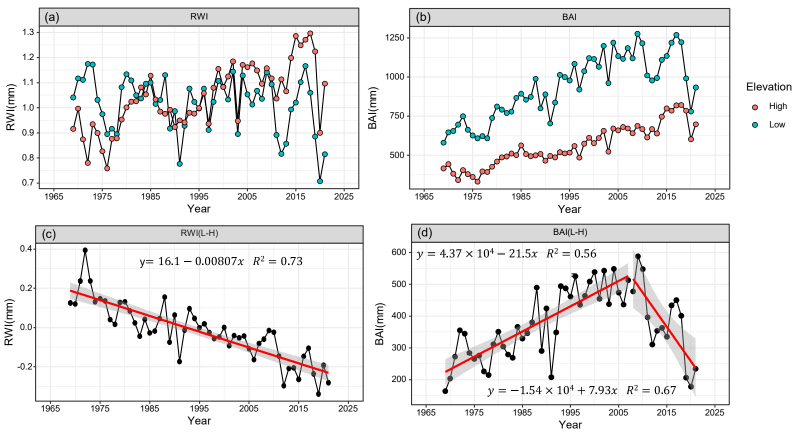

Figure 8. Average RWI and BAI changes in high- and low-elevation trees. (**a**) Average RWI; (**b**) average BAI; (**c**) low-elevation RWI minus high-elevation RWI; (**d**) low-elevation BAI minus high-elevation BAI.

4. Discussion

4.1. Elevational Effects of Temperature on Tree Growth

Numerous studies have been conducted investigating the responses of tree growth and climate in montane forests [5,23–27]. These studies focused on the growth of trees above and below the treeline of forest distribution and at middle elevations [13,18,28]. However, the magnitude of warming is not consistent between low and high elevations [29–31]. It is critical to determine the elevational range at which tree growth declines. Traditional sampling methods do not provide a good understanding of the effects of climatic elevation on tree growth. Several studies have demonstrated that there is a temperature threshold "inflection point" for tree growth across an elevational gradient and that tree growth is positively correlated with temperature in habitats at elevations where the average temperature is below 12–13 °C [32,33]. In the present study, we observed that the inflection point of *P. schrenkiana* in the eastern Tianshan Mountains was between 2100 and 2200 m above sea level. Both positive and negative correlations between tree growth and temperature exist in some regions, whereas others are largely positive [7,10,12,34]. Compared to studies in other mountain ranges, the decline in tree growth in eastern Tianshan was more extensive over a wider range of elevations. It is possible that tree growth was inhibited in more elevated sections due to the more arid eastern Tianshan region. *P. schrenkiana* tree growth was significantly negatively correlated with temperature at low elevations but not at high elevations, and this is more in line with the results of studies in the Gunga Mountains than those in the Himalayas [7,10]. This suggests that this growth pattern is no exception in global montane forests. However, the patterns of tree growth with elevation in response to temperature in different mountainous regions of the world remain to be elucidated. Additionally, it remains unknown whether there is a specific temperature threshold. More observations are required to answer these questions.

4.2. Growth Response Pattern to Climate

P. schrenkiana tree growth was significantly correlated with precipitation during winter and spring. Snow accumulation in the early part of the growing season plays a key role in the growth of trees in arid mountainous regions [35–37]. Tree growth was significantly correlated with precipitation in May of the previous year, indicating that precipitation exerted a lagging effect on tree growth. Some studies have reported that precipitation is significantly associated with tree growth only at low elevations [38,39]. The effect of precipitation on tree growth in *P. schrenkiana* in our study covered all elevation transects, indicating that in dryland montane forests, even high-elevation tree growth is dependent on precipitation [25,40]. In general, precipitation promoted tree growth. However, tree growth at 2000 and 2100 m was significantly negatively correlated with winter snowfall. This is possible in temperate forests where excessive winter snowfall can break branches and cause frostbite [41,42].

A clear pattern of variation was observed in the response of *P. schrenkiana* tree growth to temperature on the eastern Tianshan Mountains. Temperature promotes tree growth at high elevations and suppresses tree growth at low elevations. This is consistent with the characteristics of tree growth response to climate in many arid mountainous regions [41,43–45]. Although precipitation has been increasing in the study area in recent years, water evaporation has also increased. Therefore, tree growth at lower elevations is also affected by drought, whereas trees at higher elevations are less susceptible to drought [46,47]. In recent years, certain studies have suggested a warming and humidification trend in the arid and semi-arid regions of Northwest China over the past decades [48,49]. However, evidence of tree decline on the north-eastern slopes of the Tianshan Mountains suggests that warming and humidification do not promote tree growth at lower elevations and that although precipitation has increased in the mountains, higher temperatures at lower elevations have led to more intense evaporation that has weakened or even suppressed the positive effects of increased precipitation.

4.3. Growth Trends and Decline

Basal area increment (BAI) is an important indicator of radial tree growth, reflecting changes in tree growth rate and forest ecosystem carbon stocks [50–52]. We observed that since 1969, tree growth of *P. schrenkiana* in the Tianshan Mountains first increased and then decreased at lower elevations, whereas radial growth at higher elevations almost always continued to increase. This suggests that the effect of climate change on tree growth is not linear [53]. This may be because photosynthesis in trees at lower elevations may be promoting tree growth, when temperatures are not as high and do not inhibit tree growth. However, as the climate warms, increased evaporation at lower elevations exacerbates the arid conditions and limits tree growth [25,40,54]. In contrast, trees at higher altitudes, originally limited by low temperatures, grow faster because climate warming has freed them from the negative effects of low temperatures on growth [55]. In the context of climate warming, trees at higher elevations in arid zones can benefit from long-term increases in temperature. In contrast, tree growth at lower elevations benefited only during the first period of warming. Therefore, it is necessary to distinguish between the different periods to study the response mechanisms of tree growth to climate in subsequent studies.

Studies have reported that a significant change in tree growth occurred in 1980 [7]. However, the time points of significant changes in the growth *trend of P. schrenkiana* at different elevations in eastern Tianshan were not consistent, and this is possible due to the observation that the ecosystems of arid mountainous regions are more fragile and that the growth of trees at different elevations is susceptible to interference by local factors. Based on our previous sample plot surveys, we observed that the growth rate of trees at an elevation of 2400 m was much lower than that at other elevations, and there was high variability in tree growth. This could be caused by excessive tree diameter at breast height (DBH) and density [56]. Compared to the past higher mean RWI at low elevations, the mean RWI at high elevations is higher than that at low elevations from 1995 to the present. This may have been due to the positive and negative effects of temperature at both low and high elevations. The mean BAI was higher at low elevations than it was at high elevations, but the gap in BAI scores between high and low elevations exhibited a clear narrowing trend. It is foreseeable that under future climate scenarios that will continue to warm, the BAI of trees at high elevations is likely to exceed that at low elevations.

5. Conclusions

Our study demonstrated that the radial growth of the pure forest of *P. schrenkiana* in the Tianshan Mountains declined over nearly half of the elevational range and that there were two distinctly different growth–temperature patterns of *P. schrenkiana* across the elevational gradient that occurred at low elevations (1800–2100 m) and at high elevations (2200–2600 m). The tree ring width index was significantly negatively correlated with temperature at low elevations and was positively correlated at high elevations, with the elevation inflection point leading to positive and negative effects at 2100–2200 m. The tree ring width index (RWI) was significantly negatively correlated with temperature at low elevations, whereas the opposite was observed at high elevations. Precipitation and minimum temperatures in winter and spring and mean temperatures in spring and summer were the main drivers of tree growth in *P. schrenkiana*, with the effect of maximum temperatures on tree growth concentrated in the spring. Due to climate warming, tree growth at low elevations increased and then decreased, whereas tree growth at high elevations continued to increase. Future growth of *P. schrenkiana* is likely greater at higher elevations than it is at lower elevations. Therefore, the negative effects of drought on tree growth cannot be disregarded. The conservation and management of mountain forests in arid zones requires urgent attention, particularly at low elevations, and measures should be taken to address the challenges posed by the decline in growth.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/f15122052/s1, Figure S1: Comparison of the results of the correlation analysis between the climatic data and the tree ring width index.

Author Contributions: Methodology, J.H. and Z.S.; Software, J.H.; Validation, Z.S.; Formal analysis, J.H.; Investigation, J.H., C.N., W.Z. and Z.S.; Resources, Z.S.; Data curation, J.H., C.N. and W.Z.; Writing—original draft, J.H. and Ü.H.; Writing—review and editing, J.H., Ü.H. and Z.S.; Supervision, Ü.H.; Project administration, Z.S. and Ü.H.; Funding acquisition, Z.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (2022YFF0801804) and the National Natural Science Foundation of China (41790425).

Data Availability Statement: The data presented in this study are available upon reasonable request from the authors.

Acknowledgments: Thanks to the management staff of Jiangbulake Scenic Spot for their full support in data collection. We also thank Lin Zhang for his help in measuring tree ring width.

Conflicts of Interest: The authors declare no conflicts of interest.

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