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Moisture-Limited Tree Growth for a Subtropical Himalayan Conifer Forest in Western Nepal

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Abstract: Chir pine (*Pinus roxburghii* Sarg.) is a common tree species with ecological and economic importance across the subtropical forests of the central Himalayas. However, little is known about its growth response to the recent warming and drying trends observed in this region. Here, we developed a 268-year-long ring-width chronology (1743–2010) from western Nepal to investigate its growth response to climate. Based on nearby available meteorological records, growth was positively correlated with winter (November to February; $r = 0.39$, $p < 0.05$) as well as March to April ($r = 0.67$, $p < 0.001$) precipitation. Growth also showed a strong positive correlation with the sum of precipitation from November of the previous year to April of the current year ($r = 0.65$, $p < 0.001$). In contrast, a negative relationship with the mean temperature in March to April ($r = -0.48$, $p < 0.05$) suggests the influence of warming-induced evapotranspiration on tree growth. Spring droughts lasting 4–6 months constrain Chir pine growth. These results are supported by the synchronization between droughts and very narrow or locally missing rings. Warming and drying tendencies during winter and spring will reduce forest growth and resilience and make Chir pine forests more vulnerable and at higher risk of growth decline and dieback.

Keywords: dendrochronology; central Himalayas; western Nepal; *Pinus roxburghii*; climate change; subtropical forest; pre-monsoon season

1. Introduction

Global climate change is significantly affecting forest ecosystem functions and species distribution, thereby altering forest composition, increasing the risk of loss of some ecosystem services, and threatening human wellbeing [1]. With a warming rate that exceeds the global average and a drying trend in recent decades, the central Himalayas are one of the most vulnerable regions worldwide for climate-induced environmental disasters [2,3]. However, a paucity of long-term instrumental climatic records is a major challenge to understanding impacts of changing climate on Himalayan forest ecosystems [4]. To date, our understanding of responses of the forest ecosystem in this region to climatic change is still incomplete.

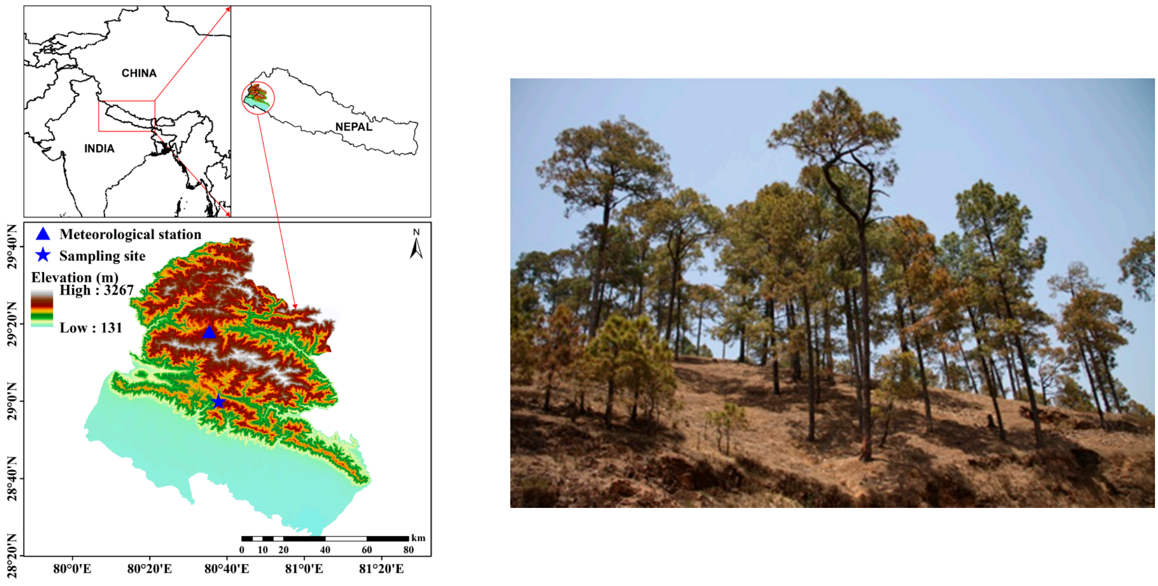
In recent decades, several studies have investigated forest radial-growth responses to changing climate in the central Himalayas and surrounding regions using tree-ring data [4–14]. However, most studies focused on subalpine forests, showing variable growth responses to climate across different species, sites, and topographical conditions. Some studies reported that tree growth near the alpine timberline is mainly controlled by pre-monsoon precipitation [5,6,9,10,12]. Meanwhile, other studies concluded that tree growth is mainly limited by cold pre-monsoon temperatures [7,15], cold conditions from February to June [4], and dry environments from July to September [16]. In comparison with subalpine forests, little is known about the growth response of subtropical and tropical forests to climate change in the central Himalayas. Several studies in the Himalayas revealed that subtropical and tropical tree species showed dendrochronological potentials [17–19] As a dominant tree (with total stem volume 11.62 m^3/ha and total biomass 9.9 t/ha) across the Himalayan subtropical zone [20], Chir pine (*Pinus roxburghii*) is a representative species for investigating impacts of climate change in recent decades on the subtropical forest ecosystem. However, its dendrochronological potential has not yet been fully explored [21,22].

The objective of this study was to investigate growth response to climate change of Chir pine from a subtropical region of western Nepal. We hypothesized that warming and drying climate trends would strongly limit radial growth of Chir pine, and if confirmed, this places subtropical Chir pine forests at risk of local dieback episodes in the event of a climate regime-shift.

2. Materials and Methods

2.1. Study Area

The study site was located in the mid-hills of far western Nepal, the junction of the western and the central Himalayas. It is located in the Kailali district (80°59′–80°62′ E and 28°96′–29°93′ N) in the Himalayan subtropical zone. The elevation of the sampled Chir pine (*Pinus roxburghii*) forest ranges from 1680 to 1710 m a.s.l. (Figure 1).



(**a**) (**b**)

Figure 1. Location map (**a**) of the tree-ring sampling site of Chir pine (⋆) and the Dadeldhura local meteorological station (▲), located in western Nepal, and (**b**) view of the sampled site.

Chir pine is widely distributed across the Himalayas (from Afghanistan to Bhutan) and can grow up to 30–40 m in height. It grows at elevations from 800 to 2100 m a.s.l. across the subtropical

Himalayas and their foothills, commonly on sunny and well-drained slopes with sandy and acidic soils [23]. It is commonly associated with *Shorea robusta* Gaertner f., *Terminalia alata* Heyne ex Roth., *Terminalia bellirica* (Gaertn.) Roxb., *Syzygium cumini* (L.) Skeels, and *Toona ciliata* M. Roem. at lower elevations, and with *Juglans regia* L., *Schima wallichii* (DC.) Korth., *Quercus* and *Rhododendron* species at its upper elevation distribution. Harvested timber is locally used for construction and furniture, and resin is tapped from the trunks of living trees. Resin tapping is one of the most important income sources for the local communities.

The central Himalayas are strongly influenced by the South Indian monsoon during summer and by the westerly jet stream during winter [3]. The study region receives less monsoon precipitation than eastern Nepal. As the climate is influenced by two different weather systems, a high inter-annual variability in climate is common across the central Himalayas [24]. Monthly mean maximum and minimum temperature recorded at the Dadeldhura climate station (29°18′ N, 80°35′ E, 1848 m a.s.l., located ca. 30 km from the tree-ring sampling site) were 15.5 °C and 4.1 °C in winter and 26.0 °C and 17.2 °C in summer, respectively (Figure 2). Annual precipitation is ca. 1300 mm (1972–2016) and ca. 70% of total annual precipitation occurs during the monsoon season (June to September). This region is characterized by four distinct seasons: spring (March to May), summer (June to August), autumn (September to November), and winter (December to February). The growing season starts at ca. mid-April and ends in late September. In recent decades, winter and pre-monsoon temperatures have been significantly increasing ($p < 0.05$) and precipitation shows a decreasing trend (not significant) (Figure 3).

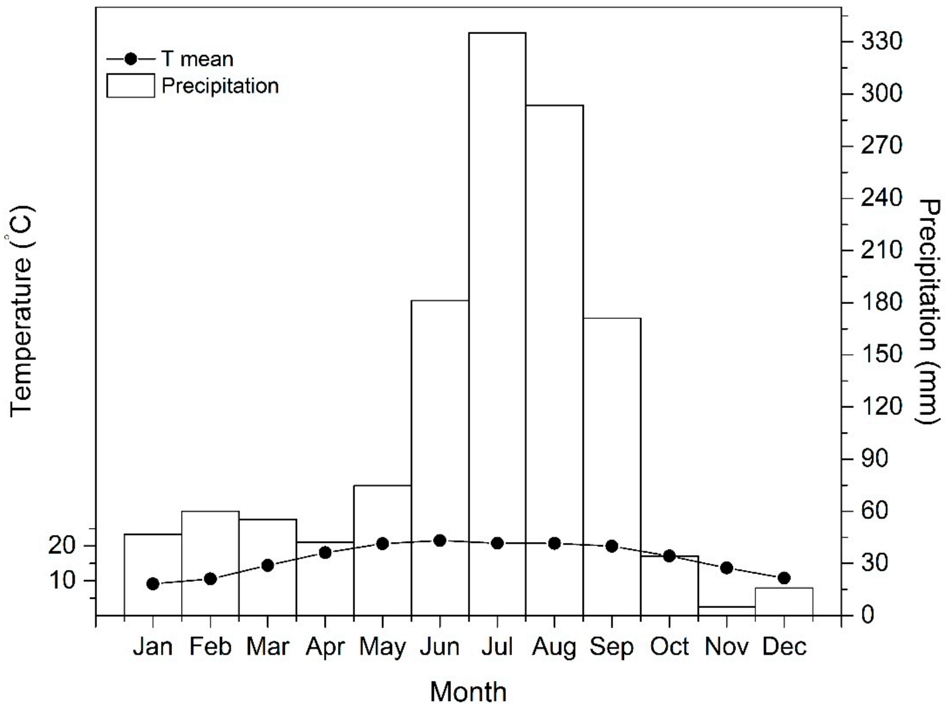


Figure 2. Climate diagram showing monthly mean temperature (1978–2016) and precipitation (1972–2016) records in Dadeldhura, western Nepal.

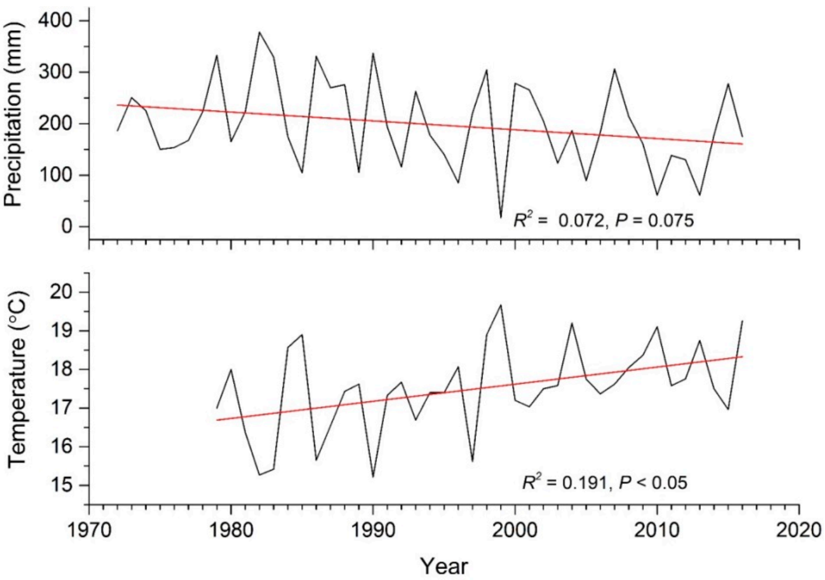


Figure 3. Time series of spring (March to May) precipitation (1972–2016) and temperature (1978–2016) from the Dadeldhura meteorological station. Spring temperature showed a significantly increasing trend, and spring precipitation showed a decreasing trend, but not significant.

2.2. Sample Collection and Dendrochronological Analyses

To highlight influence of climatic change on forest growth, we selected a natural forest site without resin tapping and logging. The sampling site is located on a gentle slope (5–8°). Sampling was carried out with an increment borer by extracting cores at 1.3 m (breast height) from mature trees. A total of 49 increment cores from 39 healthy living trees were included to assess climate–growth relationships of Chir pine.

Collected cores were kept in paper straws in the field and processed according to standard dendrochronological techniques [25]. Firstly, dried wood samples were fixed in the slots of wooden core mounts, then sanded and polished with gradually finer grades of sand paper until ring borders were clearly visible under a stereoscope microscope. Ring width was measured with the LINTAB measuring system at 0.01 mm accuracy (Rinntech, Heidelberg, Germany). The measurement and quality of cross-dating were checked using the computer program COFECHA (http://www.ltrr.arizona.edu/software.html) [26]. Due to the lack of reliable synchronization of a few ring-width series, those samples that did not cross-date well were excluded from the site chronology. The standard ring-width chronology was developed with ARSTAN software (http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software) [27] and detrended with the linear or negative exponential functions based on graphical check of the growth trend of raw ring-width measurements. Then, the detrended individual ring-width series were averaged using a biweight robust mean. Such detrending and standardization processes remove the age-dependent trends from the raw chronology and maximize the climatic signal of the resulting chronology or mean series of ring-width indices [25]. In order to retain more low-frequency variations, the standard chronology was used for further analysis.

The mean sensitivity (MS, relative variation in width between consecutive rings), the first-order autocorrelation (AC1), the mean series inter-correlation (RBAR), and the Expressed Population Signal (EPS) of the chronology were calculated for the common interval (1900–2010). The portion of the chronology with expressed population signal (EPS) values exceeding 0.85 [28] and including more than 10 samples was used for further analysis. A 50-year moving window with a 25-year overlap was used to compute running RBAR and EPS, which revealed the variation in tree growth over the common period.

2.3. Climate-Growth Relationships

To investigate the climate-growth response of Chir pine, we used monthly climatic data (mean temperatures and total precipitation) from the Dadeldhura meteorological station, where instrumental precipitation and temperature records were available since 1972 and 1978, respectively. We also used Climate Research Unit (CRU) data from the nearest 0.5° grid (29–29.5° N, 80.5–81° E) to further test climate-growth responses. CRU climate data were downloaded using the Climate Explorer webpage (https://climexp.knmi.nl/). Pearson correlations were calculated between the chronology and local climate records from previous July to current September including different seasons to identify dominant climatic factors limiting radial growth. Partial correlation was also used to measure the linear relationship between two variables, such as tree-ring chronology and pre-monsoon precipitation, after having excluded the effect of a third variable, such as pre-monsoon temperature. Due to short climate data, we did not assess the temporal stability of the climate-growth correlations. We used this approach due to its simpler interpretation as compared with response functions based on the reduction of climate data variability using principal components analysis.

To estimate drought severity we used the Standardized Precipitation Evapotranspiration Index (SPEI), a widely used drought index that assesses the cumulative climatic water balance (difference between precipitation and potential evapotranspiration) at multiple time scales [29]. It can show a lagged influence on growth. The SPEI data were calculated for the 1978–2010 period using local climate data. Pearson correlations were then calculated between ring-width indices and SPEI values from 1- to 20-month-long periods obtained with January to December data to assess the sensitivity of Chir pine growth to different drought time scales. For example, correlation of 5-month-long May SPEI to growth means that reduced growth would correspond to cumulative drought lasting from January to May.

3. Results

3.1. Statistics of Chir Pine Site Chronology

Narrow rings (at least 2 standard deviations below the average) were observed in 1915, 1937, 1938, 1969, 1970, 1971, and 2007. The most frequent locally missing rings dated at 1970 (20.5%, N = 39), followed by 1938 (12.8% N = 36) and 1969 (8.3% N = 39) (Figure 4a). More than 35% of locally missing rings occurred from 1969 to 1975.

A 268-year tree-ring width chronology (time span 1743–2010) of Chir pine was developed from the subtropical belt of Kailali, western Nepal (Figure 4b). A total of 4757 rings were measured with an average (±SD) annual ring width of 0.97 ± 0.29 mm (Table 1). Among them, only 34 rings were locally missing. The high value of mean sensitivity (0.36) indicates a remarkable inter-annual variation likely driving by climate. RBAR and EPS statistics show that the chronology is reliable for the period 1875–2010 (Figure 4c). However, RBAR peaked in the 1900s and then showed a declining trend thereafter, indicating maximum growth coherence in the early 20th century.

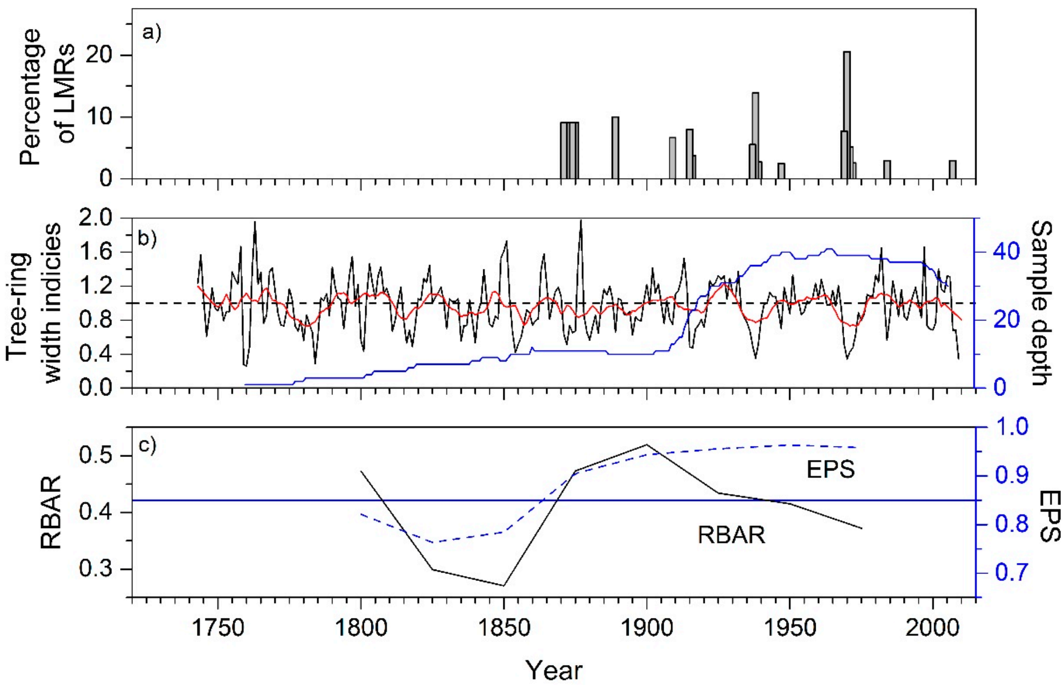


Figure 4. (**a**) Percentage of locally missing rings (LMRs) over the well-replicated period (1875–2010); (**b**) Tree-ring width chronology of Chir pine from Kailali, western Nepal Himalayas, with the 10-year moving average curve (solid red line), sample depth (the blue line shows the number of sampled trees or sample depth); (**c**) variation of mean series inter-correlation (RBAR) and Expressed Population Signal (EPS, dashed blue line) over time (the horizontal blue line represents the EPS threshold (i.e., 0.85) often used to demonstrate well-replicated chronologies). RBAR and EPS were calculated using 50-year moving windows with a 25-year overlap.

Table 1. Characteristics of the *Pinus roxburghii* ring-width chronology for a common interval, i.e., the best-replicated period (1900–2010).

Variable (Units)	Values
No. trees/No. cores	39/49
Mean tree-ring width (mm)	0.97
AC1, first-order autocorrelation	0.59
Locally missing rings (%)	0.71
MS, mean sensitivity	0.36
RBAR, mean series inter-correlation	0.45

3.2. Climate- and Drought-Growth Relationships

There is a significant ($p < 0.05$) warming trend in spring since the 1970s in association with a non-significant drying tendency in the study area (Figure 3). As shown by the correlation analyses, the radial growth of Chir pine is likely limited by winter and pre-monsoon precipitation (Figures 5 and 6). Tree growth is positively correlated with March ($r = 0.42$, $p < 0.05$) and April precipitation ($r = 0.46$, $p < 0.05$) (Figure 6a). On the other hand, its growth is negatively correlated with March ($r = -0.45$, $p < 0.05$) and April ($r = -0.38$, $p < 0.05$) temperatures (Figure 5). Overall, growth was significantly associated with March-April (MA) precipitation ($r = 0.67$, $p < 0.001$) and temperature ($r = -0.48$, $p < 0.05$) (Figure 5). Similarly, the sum of precipitation in November of the previous year up to April of current year (pN-A) showed a positive correlation with growth ($r = 0.65$, $p < 0.001$). In addition, the sum of precipitation in winter and November-December prior to the growing season was also significantly correlated with tree growth ($p < 0.05$). Likewise, we found similar but weaker climatic signals using CRU gridded climate data. The radial growth of Chir pine was positively correlated with pre-monsoon precipitation ($r = 0.26$, $p < 0.01$) and MA precipitation ($r = 0.23$, $p < 0.05$), while it was negatively correlated with pre-monsoon temperature ($r = -0.26$, $p < 0.01$) and May temperature ($r = -0.29$, $p < 0.01$). In addition, it showed significant and negative correlations with precipitation in June ($r = 0.25$, $p < 0.05$) (Figure 6b).

The partial correlation analyses further supported the likely domination of radial growth of Chir pine by winter and pre-monsoon precipitation. The correlation between mean temperature and sum of precipitation in MA is $r = -0.69$ ($p < 0.001$), and $r = -0.58$ ($p < 0.001$) for pN-A. As shown by the partial correlation analyses, the correlations between tree growth and precipitation in MA and pN-A are still significant ($r = 0.57$ and 0.58, $p < 0.001$) when controlling for the influence of temperature in corresponding seasons. In contrast, the correlations with temperature in both seasons are not significant ($r = -0.12$ and 0.18, $p > 0.05$) when controlling for the influence of precipitation.

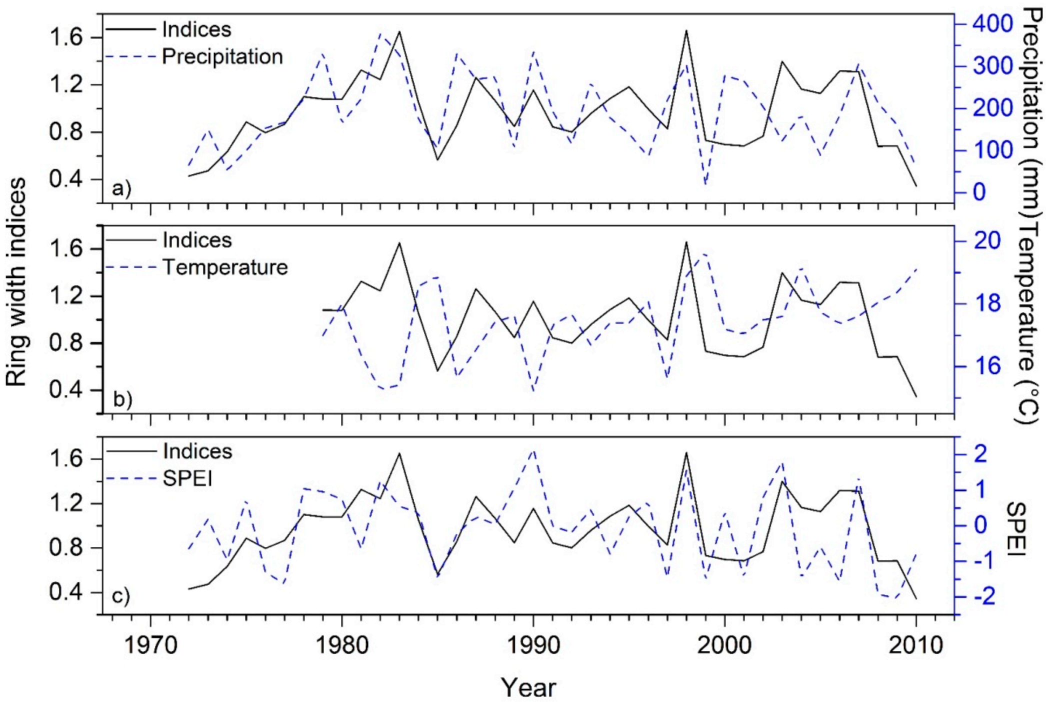


Figure 5. Comparison between ring-width indices of Chir pine and March-April precipitation (1972–2010) (**a**), temperature (1978–2010) (**b**) from meteorological records at Dadeldhura, and March Standardized Precipitation Evapotranspiration Index (SPEI) calculated at 5-month-long intervals (1972–2010) (**c**).

The correlations with the SPEI drought index confirmed what was observed with climate data, namely that Chir pine radial growth is mainly constrained by dry March-April conditions (Figures 5c and 7). This species is particularly sensitive to winter/spring drought for a 4–6 month window.

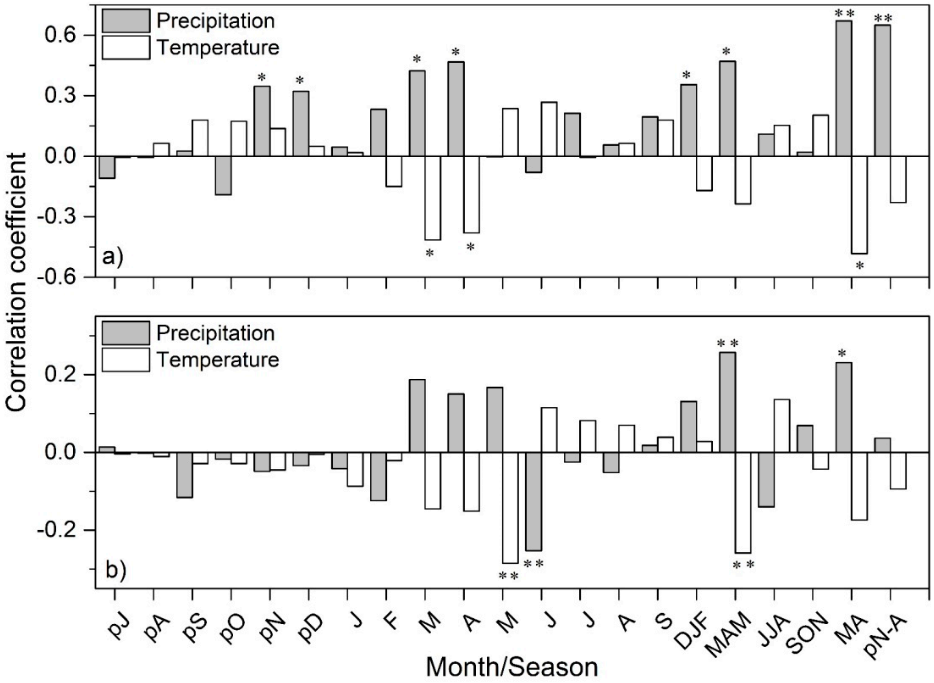


Figure 6. Pearson correlation coefficients calculated between ring-width indices and the mean of monthly, seasonal temperatures, and sum of monthly and seasonal precipitation from previous-year July (pJ) to current-year September (S), previous-year November to current year April (pN-A) based on climatic data from the meteorological records at Dadeldhura (**a**), Climate Research Unit (CRU) grid (29–29.5° N, 80.5–81° E) (**b**), and the Chir pine ring-width chronology from western Nepal. Significance levels: * $p < 0.05$ and ** $p < 0.001$. DJF: December to February; MAM: March to May; JJA: June to August; SON: September to November; MA: March to April.

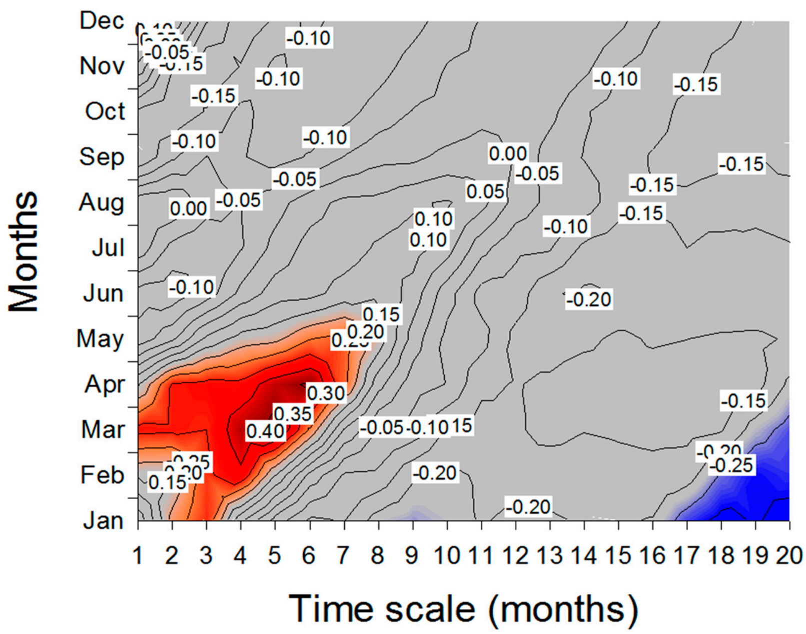


Figure 7. Fields of highest Pearson correlation coefficients calculated between monthly values of the Standardized Precipitation Evapotranspiration Index (SPEI) (1972–2010) and the Chir pine ring-width chronology. Correlations above 0.25 and below −0.25 (shown as color-filled contours) are significant at the 0.05 level. SPEI values were calculated for 1- to 20-month-long intervals (X axis).

4. Discussion

4.1. Chir Pine Tree-Ring Chronology: Locally Missing Rings and Drought

This study developed a tree-ring width chronology of Chir pine for a subtropical forest in western Nepal. The high MS suggests that Chir pine in the subtropical forest is suitable for dendroclimatic studies. A high frequency of locally missing rings implies that the growth of Chir pine is likely limited by moisture, as is also seen in Himalayan birch in the central Himalayas [5,6]. In spite of a comparable frequency of locally missing rings (0.74%), their occurrence is not synchronized with Himalayan birch at alpine timberlines in the central Himalayas [5,6]. Given similar climatic responses of Chir pine and Himalayan birch, such a discrepancy might be due to different microclimatic conditions and tree species. Even though we cannot compare the frequency of locally missing rings or narrow rings with local climate over an extended time period due to a lack of long-term instrumental records, some of the narrow tree rings from this study were synchronized with drought events across Asian monsoon-influenced areas [9]. The growth of *Picea smithiana* in the western Himalayas is also significantly correlated with pre-monsoon precipitation [11]. Both Chir pine and *Picea smithiana* had locally missing rings in 1970 and 1937, suggesting that moisture deficiency limits tree growth and even causes the formation of locally missing rings. Similarly, most of the locally missing rings were observed during dry or low soil-moisture episodes (e.g., 1859–1876, 1933–1957, 1964–1973) in the western Himalayas [30]. Therefore, the frequency of locally missing rings in Chir pine represents a promising proxy of extreme climatic conditions for subtropical forests growing in western Nepal.

4.2. Climate- and Drought-Growth Associations: The Pivotal Role of Winter to Spring Conditions

The radial growth of Chir pine is significantly correlated with precipitation in winter and pre-monsoon season prior to tree growth based on both local meteorological records and CRU gridded data. However, it is difficult to understand the significant and negative correlation between growth and June precipitation derived from CRU gridded data, which can be related to the coarse spatial scale of these climate data. Previous studies in the central Himalayas have shown that pre-monsoon precipitation is the major growth-limiting factor for Himalayan birch (*Betula utilis*) [5,6], Himalayan fir (*Abies spectabilis*) [8], alpine dwarf shrubs (*Cassiope fastigiata*) [31], Himalayan spruce (*Picea smithiana*), Himalayan blue pine (*Pinus wallichiana*) [9,10], and Chir pine (*Pinus roxburghii*) [22]. Similar growth responses in different conifer trees species were also reported from surrounding areas such as in the western Himalayas [11,12,32,33], subtropical broadleaf tree Toon (*Toona ciliata*) in the eastern Himalayas [17], and in the southeastern Tibetan Plateau [34,35]. However, our study shows that precipitation from November of the previous year to April of the growth year limits the radial growth of Chir pine, suggesting a stronger drought stress for tree growth in the subtropical forest belt in the central Himalayas. The warming trend in spring will enhance moisture stress for the early growing season and ultimately limit tree growth [36]. Winter precipitation is also important to balance soil moisture during the early growing season and ultimately affects tree physiology during the early growing season and drives the onset of radial growth [37]. Moreover, thin or sandy soil layers and hilly slopes cannot hold enough water to counteract winter and spring drought stress to maintain tree growth and survival [38]. Thus, dry winters with warm air masses from the continental interior could retard tree growth reactivation in spring and reduce growth rates [39]. Similarly, winter drought further amplifies drought stress during the onset of radial growth and causes forest dieback, especially in low elevations and in drought-prone areas [40]. Given that a large proportion of total annual growth (earlywood formation) occurs in the early growing season [41,42], moisture availability during the early growing season is a primary control on tree growth [21,32].

Our sampling site is located in a warm subtropical region with mild conditions. The negative relationship between tree growth and pre-monsoon temperature indicates that tree growth can be further reduced by ongoing climate warming. The rising temperature could further amplify drought stress by increasing evapotranspiration rates or by raising vapor pressure deficit [24]. This is supported by previous studies from the Himalayas and surrounding areas [5,6,9,10,15,34,43]. In contrast, a significant positive correlation between tree growth and temperature was observed in the central Himalayas [4,7,13]. Such different climate responses might be due to different tree species across different macro- and micro-climates [44,45].

The Chir pine forest may be highly vulnerable to warming-induced drought stress under ongoing climatic changes due to a high loss of moisture by evapotranspiration, which would not be replenished unless pre-monsoon precipitation can make up the difference. Decreasing trends in winter and pre-monsoon precipitation were observed, with increasing drought and rising temperatures in recent decades across western and northwestern Nepal [24,46]. Under severe drought conditions, high competition for moisture between neighboring trees will further exacerbate drought stress for tree growth [47–50]. As shown in a recent study, low winter and spring precipitation can cause a delay of the initiation of xylogenesis and contribute to the occurrence of the locally missing rings in years with extremely dry springs [51]. Ongoing warming temperatures could not only cause soil moisture deficiency but also amplify temperature-induced drought stress, thereby limiting tree growth and posing a risk of die-off under a warming climate [52–56].

5. Conclusions

Chir pine from the subtropical belt of the western Nepal Himalayas is sensitive to moisture availability during winter and spring. Since the 1970s, the central Himalayas have been experiencing a warming and drying tendency, and thus Chir pine forests may become more vulnerable to warming-induced drought stress. To further improve our understanding of the growth response of trees in the subtropical Himalayan forest, additional research is needed on other tree species and localities in the region. This will help to more completely evaluate the potential impacts of global warming on subtropical forests and related local livelihoods in the central Himalayas.

Author Contributions: E.L. and B.D. performed field sampling and tree-ring measurements; S.R.S. and J.J.C. performed most statistical analyses; S.R.S., B.D., J.J.C., E.L. and S.W.L. led the writing of the paper and contributed to data interpretation and analyses.

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References

1. IPCC. *Climate Change 2014—Impacts, Adaptation and Vulnerability: Regional Aspects*; Cambridge University Press: Cambridge, UK, 2014.
2. Shrestha, A.B.; Bajracharya, S.R.; Sharma, A.R.; Duo, C.; Kulkarni, A. Observed trends and changes in daily temperature and precipitation extremes over the Koshi river basin 1975–2010. *Int. J. Clim.* **2017**, *37*, 1066–1083. [CrossRef]
3. Yao, T.; Thompson, L.; Yang, W.; Yu, W.; Gao, Y.; Guo, X.; Yang, X.; Duan, K.; Zhao, H.; Xu, B.; et al. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nat. Clim. Chang.* **2012**, *2*, 663–667. [CrossRef]
4. Cook, E.R.; Krusic, P.J.; Jones, P.D. Dendroclimatic signals in long tree-ring chronologies from the Himalayas of Nepal. *Int. J. Clim.* **2003**, *23*, 707–732. [CrossRef]
5. Dawadi, B.; Liang, E.; Tian, L.; Devkota, L.P.; Yao, T. Pre-monsoon precipitation signal in tree rings of timberline *Betula utilis* in the central Himalayas. *Quat. Int.* **2013**, *283*, 72–77. [CrossRef]

6. Liang, E.; Dawadi, B.; Pederson, N.; Eckstein, D. Is the growth of birch at the upper timberline in the Himalayas limited by moisture or by temperature? *Ecology* **2014**, *95*, 2453–2465. [CrossRef]
7. Thapa, U.K.; Shah, S.K.; Gaire, N.P.; Bhuju, D.R. Spring temperatures in the far-western Nepal Himalaya since AD 1640 reconstructed from *Picea smithiana* tree-ring widths. *Clim. Dyn.* **2015**, *45*, 2069–2081. [CrossRef]
8. Tiwari, A.; Fan, Z.X.; Jump, A.S.; Li, S.F.; Zhou, Z.K. Gradual expansion of moisture sensitive *Abies spectabilis* forest in the Trans-Himalayan zone of central Nepal associated with climate change. *Dendrochronologia* **2017**, *41*, 34–43. [CrossRef]
9. Gaire, N.P.; Bhuju, D.R.; Koirala, M.; Shah, S.K.; Carrer, M.; Timilsena, R. Tree-ring based spring precipitation reconstruction in western Nepal Himalaya since AD 1840. *Dendrochronologia* **2017**, *42*, 21–30. [CrossRef]
10. Panthi, S.; Bräuning, A.; Zhou, Z.K.; Fan, Z.X. Tree rings reveal recent intensified spring drought in the central Himalaya, Nepal. *Glob. Planet. Chang.* **2017**, *157*, 26–34. [CrossRef]
11. Sohar, K.; Altman, J.; Lehečková, E.; Doležal, J. Growth-climate relationships of Himalayan conifers along elevational and latitudinal gradients. *Int. J. Clim.* **2017**, *37*, 2593–2605. [CrossRef]
12. Yadav, R.R.; Misra, K.G.; Kotlia, B.S.; Upreti, N. Premonsoon precipitation variability in Kumaon Himalaya, India over a perspective of ~300 years. *Quat. Int.* **2014**, *325*, 213–219. [CrossRef]
13. Bräuning, A. Tree-ring studies in the Dolpo-Himalaya (western Nepal). *Tree Rings Archaeol. Climatol. Ecol.* **2004**, *2*, 8–12.
14. Bhattacharyya, A.; Chaudhary, V. Late-summer temperature reconstruction of the eastern Himalayan region based on tree-ring data of *Abies densa*. *Arct. Antarct. Alp. Res.* **2003**, *35*, 196–202. [CrossRef]
15. Yadav, R.R.; Singh, J. Tree-ring analysis of *Taxus baccata* from the western Himalaya, India, and its dendroclimatic potential. *Tree-Ring Res.* **2002**, *58*, 23–29.
16. Sano, M.; Ramesh, R.; Sheshshayee, M.; Sukumar, R. Increasing aridity over the past 223 years in the Nepal Himalaya inferred from a tree-ring $\delta^{18}O$ chronology. *Holocene* **2012**, *22*, 809–817. [CrossRef]
17. Shah, S.K.; Mehrotra, N. Tree-ring studies of *Toona ciliata* from subtropical wet hill forests of Kalimpong, eastern Himalaya. *Dendrochronologia* **2017**, *46*, 46–55. [CrossRef]
18. Singh, N.D.; Venugopal, N. Cambial activity and annual rhythm of xylem production of *Pinus kesiya* royle ex. Gordon (pinaceae) in relation to phenology and climatic factors growing in sub-tropical wet forest of north east India. *Flora* **2011**, *206*, 198–204. [CrossRef]
19. Bhattacharyya, A.; Shah, S.K. Tree-ring studies in India past appraisal, present status and future prospects. *IAWA* **2009**, *30*, 361–370. [CrossRef]
20. DFRS. *State of Nepal's Forests*; Ministry of Forests and Soil Conservation, Department of Forest Research and Survey: Kathmandu, Nepal, 2015.
21. Bhattacharyya, A.; LaMarche, V.C., Jr.; Hughes, M.K. Tree-ring chronologies from Nepal. *Tree Ring Bull.* **1992**, *52*, 59–66.
22. Aryal, S.; Bhuju, D.R.; Kharal, D.K.; Gaire, N.P.; Dyola, N. Climatic upshot using growth pattern of *Pinus roxburghii* from western Nepal. *Pak. J. Bot.* **2018**, *50*, 579–588.
23. Malla, S.B.; Rajbhandari, S.; Shrestha, T.; Adhikari, P.; Adhikari, S.; Shakya, P. *Flora of Kathmandu Valley*; Ministry of Forests and Soil Conservation-Department of Medicinal Plants: Kathmandu, Nepal, 1986; 963p. Available online: http://lib.icimod.org/record/2906 (accessed on 8 May 2018).
24. Wang, S.Y.; Yoon, J.H.; Gillies, R.R.; Cho, C. What caused the winter drought in western Nepal during recent years? *J. Clim.* **2013**, *26*, 8241–8256. [CrossRef]
25. Cook, E.R.; Kairiukstis, L.A. *Methods of Dendrochronology: Applications in the Environmental Sciences*; Kluwer: Dordrecht, The Netherlands, 1990.
26. Holmes, R.L. Computer-assisted quality control in tree-ring dating and measurement. *Tree Ring Bull.* **1983**, *43*, 69–78.
27. Cook, E.R. A Time Series Analysis Approach to Tree Ring Standardization. Ph.D. Thesis, University of Arizona, Arizona, AZ, USA, 1985.
28. Wigley, T.M.; Briffa, K.R.; Jones, P.D. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *J. Clim. Appl. Meteorol.* **1984**, *23*, 201–213. [CrossRef]
29. Vicente-Serrano, S.M.; Beguería, S.; López-Moreno, J.I. A multi-scalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index-SPEI. *J. Clim.* **2010**, *23*, 1696–1718. [CrossRef]

30. Ram, S. Tree growth-climate relationships of conifer trees and reconstruction of summer season palmer drought severity index (PDSI) at Pahalgam in Srinagar, India. *Quat. Int.* **2012**, *254*, 152–158. [CrossRef]
31. Liang, E.; Liu, W.; Ren, P.; Dawadi, B.; Eckstein, D. The alpine dwarf shrub *Cassiope fastigiata* in the Himalayas: Does it reflect site-specific climatic signals in its annual growth rings? *Trees* **2015**, *29*, 79–86. [CrossRef]
32. Shah, S.K.; Shekhar, M.; Bhattacharyya, A. Anomalous distribution of *Cedrus deodara* and *Pinus roxburghii* in Parbati valley, Kullu, western Himalaya: An assessment in dendroecological perspective. *Quat. Int.* **2014**, *325*, 205–212. [CrossRef]
33. Ram, S. Tree ring width variations over western Himalaya in India and its linkage with heat and aridity indices. *Nat. Hazards* **2018**, *92*, 635–645. [CrossRef]
34. Li, J.; Shi, J.; Zhang, D.D.; Yang, B.; Fang, K.; Yue, P.H. Moisture increase in response to high-altitude warming evidenced by tree-rings on the southeastern Tibetan Plateau. *Clim. Dyn.* **2017**, *48*, 649–660. [CrossRef]
35. Liang, E.; Lu, X.; Ren, P.; Li, X.; Zhu, L.; Eckstein, D. Annual increments of juniper dwarf shrubs above the tree line on the central Tibetan Plateau: A useful climatic proxy. *Ann. Bot.* **2012**, *109*, 721–728. [CrossRef] [PubMed]
36. Fu, Y.H.; Piao, S.; Zhao, H.; Jeong, S.J.; Wang, X.; Vitasse, Y.; Ciais, P.; Janssens, I.A. Unexpected role of winter precipitation in determining heat requirement for spring vegetation green-up at northern middle and high latitudes. *Glob. Chang. Biol.* **2014**, *20*, 3743–3755. [CrossRef] [PubMed]
37. Cleaveland, M.K.; Stahle, D.W.; Therrell, M.D.; Villanueva-Diaz, J.; Burns, B.T. Tree-ring reconstructed winter precipitation and tropical teleconnections in Durango, Mexico. *Clim. Chang.* **2003**, *59*, 369–388. [CrossRef]
38. Sarris, D.; Christodoulakis, D.; Koerner, C. Recent decline in precipitation and tree growth in the eastern Mediterranean. *Glob. Chang. Biol.* **2007**, *13*, 1187–1200. [CrossRef]
39. Bräuning, A. Tree-ring evidence of 'Little Ice Age' glacier advances in southern Tibet. *Holocene* **2006**, *16*, 369–380. [CrossRef]
40. Voltas, J.; Camarero, J.J.; Carulla, D.; Aguilera, M.; Ortiz, A.; Ferrio, J.P. A retrospective, dual-isotope approach reveals individual predispositions to winter-drought induced tree dieback in the southernmost distribution limit of Scots Pine. *Plant Cell Environ.* **2013**, *36*, 1435–1448. [CrossRef] [PubMed]
41. Savva, Y.; Oleksyn, J.; Reich, P.B.; Tjoelker, M.G.; Vaganov, E.A.; Modrzynski, J. Interannual growth response of Norway spruce to climate along an altitudinal gradient in the Tatra Mountains, Poland. *Trees* **2006**, *20*, 735–746. [CrossRef]
42. Deslauriers, A.; Rossi, S.; Anfodillo, T.; Saracino, A. Cambial phenology, wood formation and temperature thresholds in two contrasting years at high altitude in southern Italy. *Tree Physiol.* **2008**, *28*, 863–871. [CrossRef] [PubMed]
43. Yadav, R.R.; Park, W.K.; Singh, J.; Dubey, B. Do the western Himalayas defy global warming? *Geophys. Res. Lett.* **2004**, *31*, L17201. [CrossRef]
44. Kobe, R.K.; Coates, K.D. Models of sapling mortality as a function of growth to characterize interspecific variation in shade tolerance of eight tree species of northwestern British Columbia. *Can. J. For. Res.* **1997**, *27*, 227–236. [CrossRef]
45. Rollinson, C.R.; Kaye, M.W.; Canham, C.D. Interspecific variation in growth responses to climate and competition of five eastern tree species. *Ecology* **2016**, *97*, 1003–1011. [CrossRef] [PubMed]
46. Sigdel, M.; Ikeda, M. Spatial and temporal analysis of drought in Nepal using standardized precipitation index and its relationship with climate indices. *J. Hydrol. Meteorol.* **2010**, *7*, 59–74. [CrossRef]
47. Gleason, K.E.; Bradford, J.B.; Bottero, A.; D'Amato, A.W.; Fraver, S.; Palik, B.J.; Battaglia, M.A.; Iverson, L.; Kenefic, L.; Kern, C.C. Competition amplifies drought stress in forests across broad climatic and compositional gradients. *Ecosphere* **2017**, *8*, e01849. [CrossRef]
48. Martin-Benito, D.; Kint, V.; del Río, M.; Muys, B.; Cañellas, I. Growth responses of west-mediterranean pinus nigra to climate change are modulated by competition and productivity: Past trends and future perspectives. *For. Ecol. Manag.* **2011**, *262*, 1030–1040. [CrossRef]
49. Linares, J.-C.; Delgado-Huertas, A.; Camarero, J.J.; Merino, J.; Carreira, J.A. Competition and drought limit the response of water-use efficiency to rising atmospheric carbon dioxide in the Mediterranean fir *Abies pinsapo*. *Oecologia* **2009**, *161*, 611–624. [CrossRef] [PubMed]
50. Liang, E.; Leuschner, C.; Dulamsuren, C.; Wagner, B.; Hauck, M. Global warming-related tree growth decline and mortality on the north-eastern Tibetan plateau. *Clim. Chang.* **2016**, *134*, 163–176. [CrossRef]

51. Ren, P.; Rossi, S.; Camarero, J.J.; Ellison, A.M.; Liang, E.; Peñuelas, J. Critical temperature and precipitation thresholds for the onset of xylogenesis of *Juniperus przewalskii* in a semi-arid area of the north-eastern Tibetan Plateau. *Ann. Bot.* **2018**, *121*, 617–624. [CrossRef] [PubMed]
52. Allen, C.D.; Macalady, A.K.; Chenchouni, H.; Bachelet, D.; McDowell, N.; Vennetier, M.; Kitzberger, T.; Rigling, A.; Breshears, D.D.; Hogg, E.H.; et al. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For. Ecol. Manag.* **2010**, *259*, 660–684. [CrossRef]
53. Zhang, Q.B.; Evans, M.N.; Lyu, L. Moisture dipole over the Tibetan Plateau during the past five and a half centuries. *Nat. Commun.* **2015**, *6*, 8062. [CrossRef] [PubMed]
54. Bayramzadeh, V.; Zhu, H.; Lu, X.; Attarod, P.; Zhang, H.; Li, X.; Asad, F.; Liang, E. Temperature variability in northern Iran during the past 700 years. *Sci. Bull.* **2018**, *63*, 462–464. [CrossRef]
55. Camarero, J.J.; Gazol, A.; Galván, J.D.; Sangüesa-Barreda, G.; Gutiérrez, E. Disparate effects of global-change drivers on mountain conifer forests: Warming-induced growth enhancement in young trees vs. CO_2 fertilization in old trees from wet sites. *Glob. Chang. Biol.* **2015**, *21*, 738–749. [CrossRef] [PubMed]
56. Liu, B.; Liang, E.; Liu, K.; Camarero, J.J. Species- and elevation-dependent growth responses to climate warming of mountain forests in the Qinling Mountains, central China. *Forests* **2018**, *9*, 248. [CrossRef]