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Moisture, Not Temperature, in the Pre-Monsoon Influences *Pinus wallichiana* Growth along the Altitudinal and Aspect Gradients in the Lower Himalayas of Central Nepal

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Abstract: Changing climate can strongly affect tree growth and forest productivity. The dendrochronological approach to assessing the impact of climate change on tree growth is possible through climate–growth correlation analysis. This study uses an individual tree-based approach to model *Pinus wallichiana* (*P. wallichiana*) radial growth response to climate across the physiographic gradients in the lower distributional range of Nepal. This study sampled six sites across the Makwanpur district of central Nepal that varied in elevation and aspect, obtaining 180 tree-ring series. Climate data series were obtained from Climate Research Unit (CRU 4.0). The pair correlation approach was used to assess *P. wallichiana* growth response to climate and site-level physiographic variables such as site-level environmental stress. The study also determined long-term growth trends across the elevation and aspect gradients. Trees at sites with higher elevation and northeast aspect (NEA) were more responsive to winter and spring precipitation, whereas trees with lower elevation and northwest aspect (NWA) were more responsive to winter and spring precipitation. Basal area increment (BAI) analysis showed the variation of growth at site-level environmental stress, suggesting that the sensitivity of forest ecosystems to changing climate will vary across the lower growth limit of *P. wallichiana* due to differences in local physiographic conditions.

Keywords: climate change; basal area increment; growth–climate response; radial growth; tree ring

1. Introduction

Climate change and land-use legacies may lead to changes in the stand structure, species composition, tree growth and forest productivity, and species range to a higher elevation [1–3]. A comprehensive understanding of tree growth response to climatic factors across the distribution range, especially at the lower or upper limit of distribution, is an essential ecological issue under global climate change. However, the extent to which populations of trees will follow climate shifts through migration is mainly unknown [4]. The Intergovernmental Panel on Climate Change (IPCC) [5] showed a higher rate of temperature increase in the Himalayan region. Therefore, species' growth response to changing climate is explored in more detail in the higher Himalayan range of Nepal using dendroclimatological approaches [6–10]. Tree rings are a critical source in analyzing variations in climatic factors and forest ecosystem dynamics [11].

Dendroclimatological studies in major forest ecosystems worldwide have shown heterogeneous results in growth and climatic factors. Tree growth and climate relationships are compounded by differences in tree compositions and site conditions [12–16] and differential impacts of environmental factors on tree growth along altitudinal and latitudinal gradients [17–19]. Tree growth conditions vary with elevation, as the climate–growth relationship may differ with altitude [20]. Fritts [11] argued that tree growth at lower elevations in semiarid ecosystems is shaped by the carryover effect of wintertime climate and controlled by precipitation. In contrast, the growing season's climate is mainly responsible for tree growth in high-elevation/-latitude areas. Despite the complex interaction between climate, ecology, and tree biology, dendroclimatological results are robust; however, studies have shown results challenging these general principles, as Fritts et al. [21] argued. For example, Liu et al. [22] observed significant similarity in climate–tree growth relationships of *Sabina przewalskii* at low and high elevation with a higher standard deviation and more significant correlations of low-elevation chronologies. At high elevation (>3500 masl), Liang et al. [23] reported uniform radial growth of *Abies georgei* across elevation, aspect, and tree age in response to common climatic signals. Moreover, *Abies spectabilis* trees from the higher Himalayan region (>3000 masl) were shown to have a positive association with summer temperature along the entire elevation gradient, while a stronger response with winter temperature was found at the uppermost forest boundary [10]. However, in dry sites, this species is showing a positive response with spring-season precipitation along the entire elevation distribution range. With most of the tree-ring studies being from the higher-altitudinal region of the Himalayas, more studies on the effects of altitude on climate–growth relationships should be undertaken in the lower Himalayas. *P. wallichiana* could be an ideal species to check the climatic response from the lower elevation range as it grows in a wide elevation range.

The Himalayan region has a large area of natural *P. wallichiana* forest. In Nepal, *P. wallichiana* forest ranges from 1800–4100 masl. This species is often mixed with *P. roxburghii* in the southern aspect. *P. wallichiana* is a light demander, drought-tolerant, frost-hardy, and less fire-resistant than *P. roxburghii* [24]. This species has high dendrochronological potential due to its distinct annual rings and sensitivity to various climatic variables [25,26]. There were many studies on the upper limit of this species [8,25–27], but there is very limited research to date on the lower elevation range (e.g., Thapa and George [28]). The climate varies along with elevation and aspect; both elevation and aspect are the leading factors for the growth variability of the plants. Unfortunately, little is known about the tree-ring variability of *P. wallichiana* due to climatic variation along an elevation gradient in its lower altitudinal distribution. The knowledge of the effect of past climate change on tree growth in the region will help draft the policy and planning in the days to come for the forestry sector. Therefore, the objective of this study is: (a) to examine the relationship between tree-ring variability of *P. wallichiana* and climate along the elevation and aspect gradients in the lower Himalayas (lower limit of the *P. wallichiana* population) of central Nepal; (b) to compare the basal area increment difference patterns with respect to aspect and elevation gradients.

2. Materials and Methods

2.1. Study Area

The sampling sites are located along an elevation gradient of Makwanpur district (27.5546° N, 85.0233° E) lower-central Himalayas, Nepal (Figure 1). The elevation of sampled *P. wallichiana* forests ranges from 1800 to 2500 masl. Study sites mainly contain subtropical-to-temperate vegetation, including *P. wallichiana*, *P. roxburghii*, *Rhododendron arboreum*, and *Quercus* species. The community forestry initiation has significantly reduced the anthropogenic disturbances in the forests recently. The sampling sites lie in the NEA (northeast aspect) and NWA (northwest aspect) of a mountain slope. The sampling sites were situated in three elevation belts: 1800–1900 masl, 2100–2200 masl, and 2400–2500 masl of both aspects (Figure 1). The climate of the study site is influenced by Indian summer monsoon and westerly wind blowing from the Mediterranean Sea [29]. The summer is hot and winter is relatively cold and occasionally receives snowfall, usually in the upper elevation range.

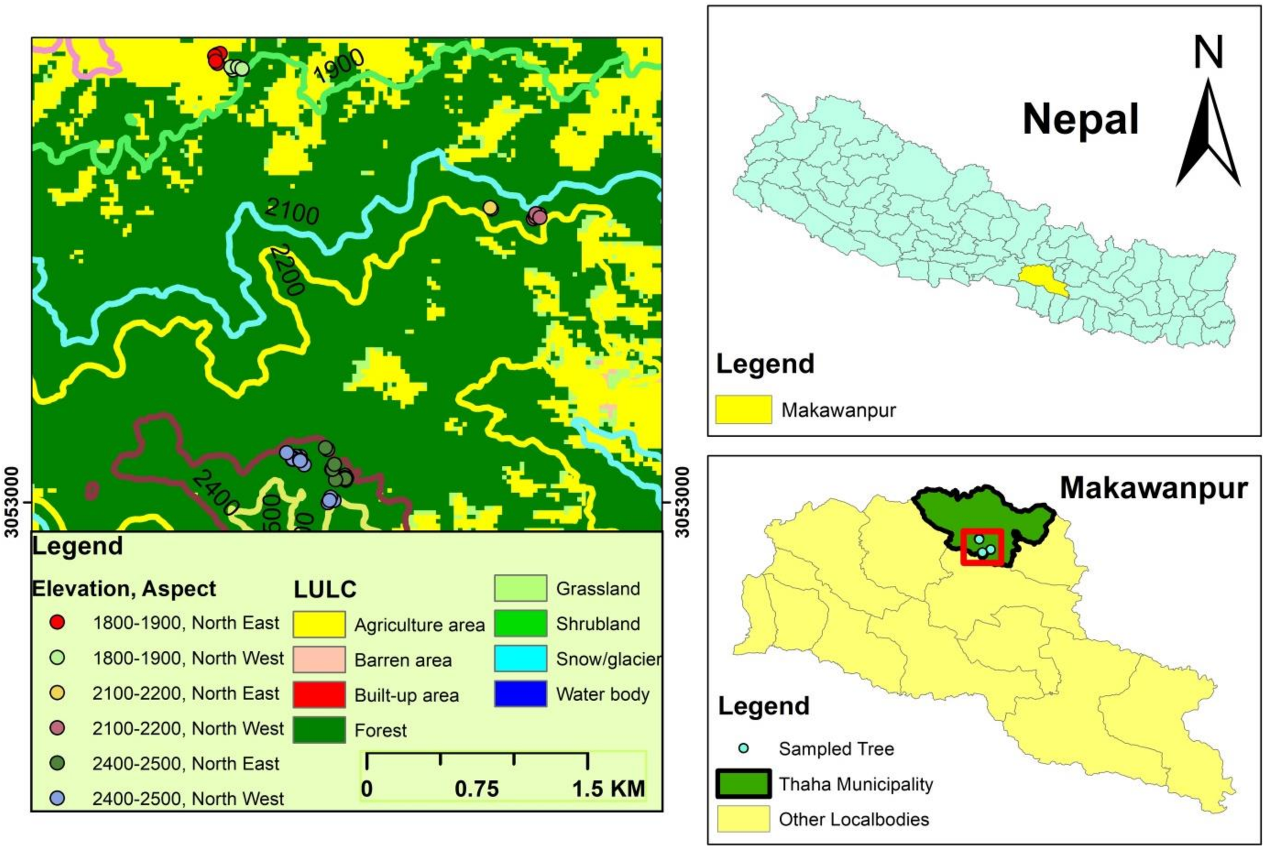


Figure 1. Map of the study area and sampling sites along the elevation and aspect gradients in the Makwanpur district in Nepal.

The CRU data of Daman show that the mean annual total precipitation and mean temperature was 1645 mm year^{-1} and 24.5 °C during the period of 1973 to 2018. During the same period, both maximum and minimum temperature were in an increasing trend at the rate of 0.016 °C and 0.02 °C per year, respectively. Precipitation showed a decreasing trend at the rate of 0.54 mm year^{-1} (Figure 2). About 80% of the total annual precipitation occurred during the monsoon season (June to September). November was the driest, whereas July was the wettest month. January was the coldest, whereas June was the hottest month (Figures 2 and 3).

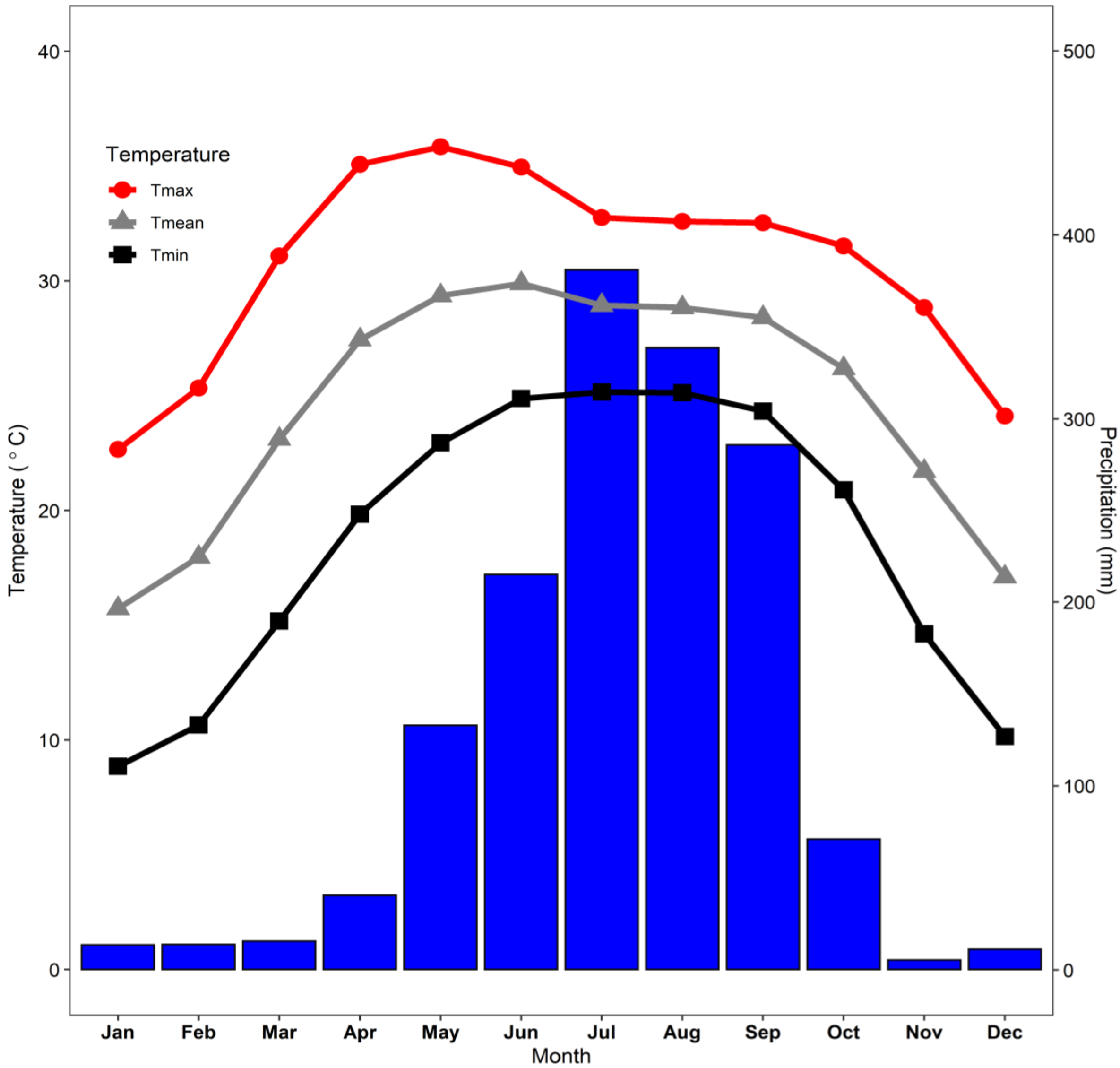


Figure 2. Average monthly temperature and precipitation in the study area based on temporal data (1973–2018). Tmax (redline) indicates average maximum temperature, Tmean (grey line) denotes average monthly temperature, and black line indicates the minimum monthly temperature (Tmin). The bar height shows the average monthly mean precipitation (secondary *Y*-axis label).

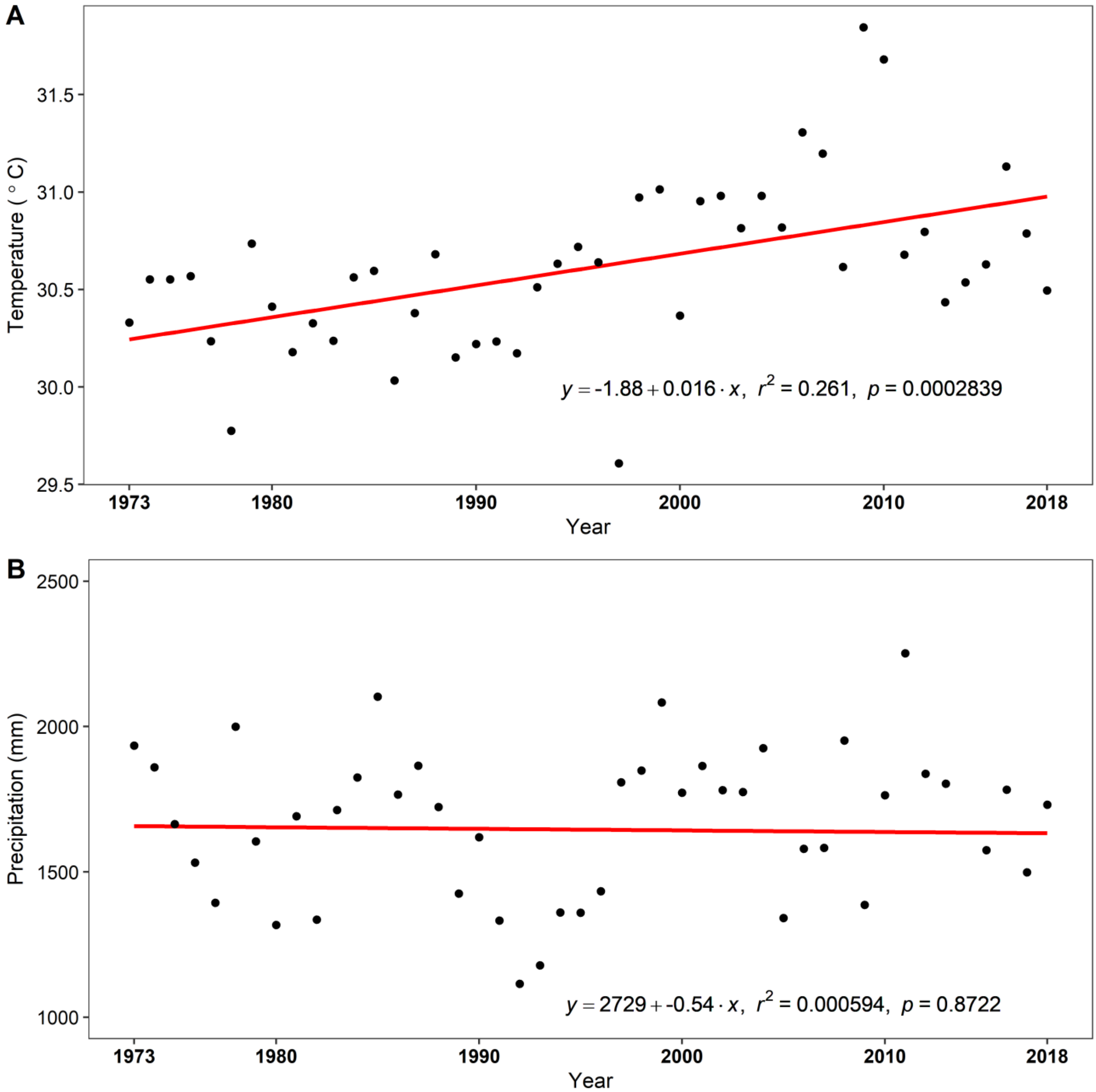


Figure 3. The trend of annual mean temperature (**A**) and precipitation (**B**) in the study area (CRU data).

2.2. Sample Collection and Chronology Development

Dominant and codominant trees in each sampling belt were selected purposively along the contour line. Trees selected within the range of 100 m elevation were considered as one sampling site or one elevation belt (Figure 1). A total of 30 trees were selected from each sampling site and one core per tree was extracted from diameter at breast height (1.3 m) using an increment borer. Each extracted core was labeled and inserted in a plastic straw and assembled in the Dendro lab of Nepal Academy of Science and Technology for further analysis.

In the laboratory, cores were air-dried and mounted in the wooden frame. Air-dried, mounted cores were sanded and polished using successively fine-grit sandpaper ranging from 120, 200, 320, 400, and 800 grit. The ring widths of sanded and polished cores were measured by LINTAB measuring system at 0.01 mm precision using TSAP-WIN software [30]. Ring widths from each core were cross-dated using alignment technique and looking at the math graph [31], and quality of cross-dating was further checked using quality control program called COFECHA [32–34]. Total of 48 cores that were twisted, partially broken and very young (<40 years) were discarded for further analysis. Detrending of each sample was made using ARSTAN and dp1R [35]. Forty-five-year cubic smoothing spline was used to standardize and remove age-related growth trends and standard chronology (SC) was developed. SC was selected for further analysis since it has higher-expressed population signals (EPS) and Rbar (mean correlation between individual tree-ring series) [36,37].

2.3. Growth–Climate Relationship

To assess the influence of annual climate variability on *P. wallichiana* growth, the relationship between the standard chronologies and mean monthly climatic data (temperature, precipitation, drought indices) was calculated using the Pearson correlation analysis on a monthly and seasonal basis. We used CRU 4.0 (Climate Research Unit) climatic data to calculate the tree growth–climate relationship [38]. We used self–calibrating Palmer Drought Severity Index (scPDSI) to calculate the drought severity in the study area and its influence on the pine tree growth. The scPDSI is based on a supply and demand model of soil moisture and is an effective indicator of long-term droughts of several months to years [25,39].

2.4. Basal Area Increment (BAI) Analysis

We computed the basal area increment (BAI) chronology of pine to understand the long-term growth along elevation using dplR package in R [35]. We estimated the BAI from the ring widths of *P. wallichiana* to measure the radial growth trend. BAI was widely used to quantify the radial growth trend of the tree. BAI estimates natural growth patterns and helps to generate a ring width index (RWI) chronology [40]. The BAI chronology was produced using the bai.out function in the dplR package [35]. The formula used to estimate BAI is given in Equation (1).

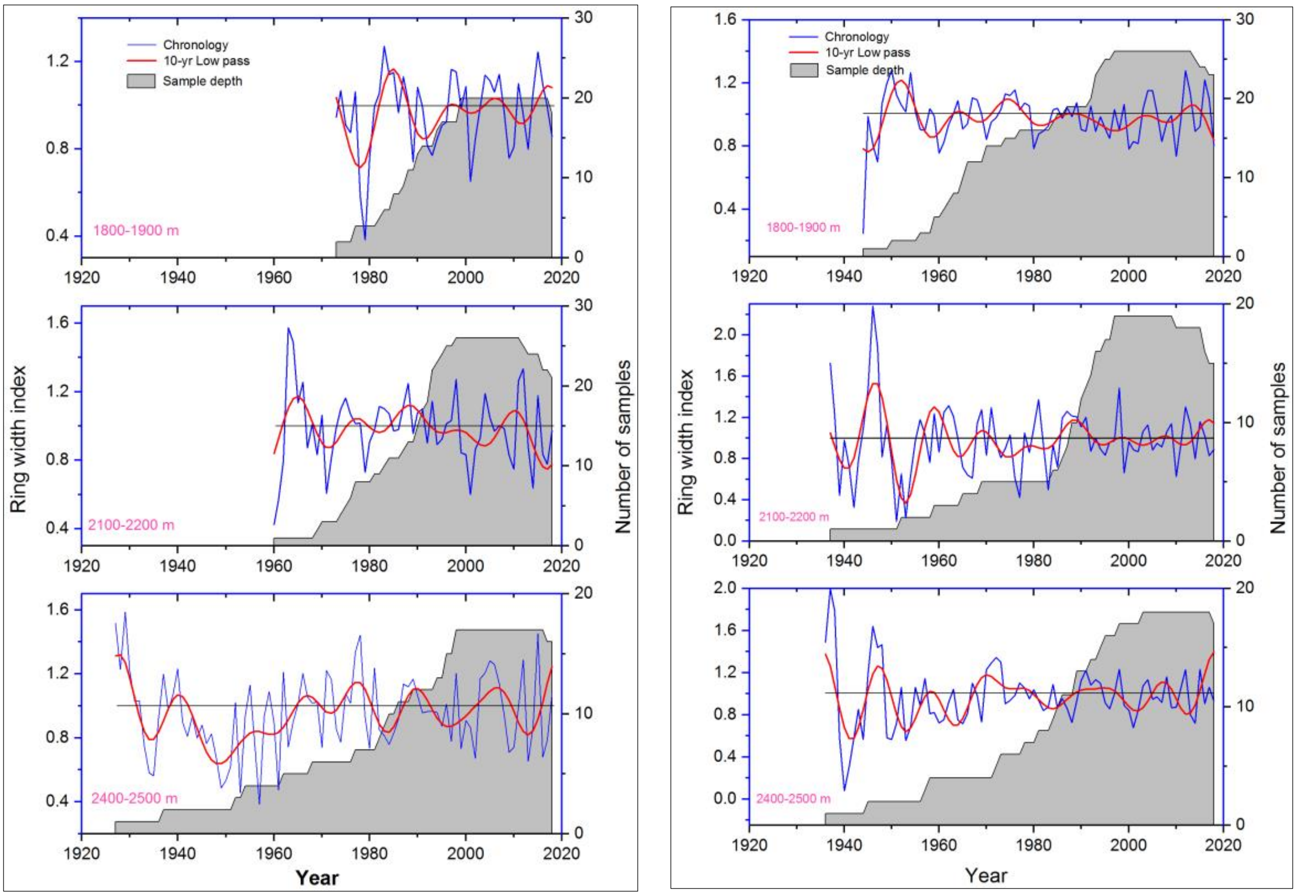
$$BAI = \pi \left(R_n{}^2 - R_{n-1}{}^2\right) \quad (1)$$

where R_n and R_{n-1} are radii at year n and $n - 1$, respectively. The mean BAI values were calculated by averaging all BAI series.

3. Results

3.1. Tree-Ring Width Chronologies of P. wallichiana along the Elevation and Aspect Gradients

We developed six site chronologies of *P. wallichiana* with three replications for northeast (NEA) and northwest (NWA) aspects in the lower Himalayas of Nepal (Figure 4). Three chronologies were further divided into three elevation belts (Table 1). In spite of the relatively young forest, we were able to develop the longest chronology of 92 years from the upper, 59 years from the middle, and 46 years from the lower elevation belts in the NEA. Similarly, we developed 83-year, 82-year, and 75-year-long chronologies from the upper, middle, and lower elevation belts. Less than one percent of total rings were missing (Table 1).



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

Figure 4. Tree-ring width chronologies of *P. wallichiana* along the elevation belts in the Makwanpur district: lower (1800–1900 masl), middle (2100–2200 masl), and upper (2400–2500 masl) elevation belts: (**a**) northeast aspect; (**b**) northwest aspect.

Table 1. Overall statistics of tree-ring width data of *P. wallichiana*.

Northeast Aspect (NEA)			
Statistics	**Upper**	**Middle**	**Lower**
Elevation (masl)	2400–2500	2100–2200	1800–1900
Slope (°)	≤40	≤40	≤40
Chronology span	1927–2018 (92)	1960–2018 (59)	1973–2018 (46)
Number of cores	17	26	20
Missing rings (%)	0.013	0.010	0
First order autocorrelation (AC1)	0.125	0.210	0.199
Standard deviation (SD)	0.414	0.345	0.323
Mean sensitivity (MS)	0.435	0.305	0.323
Mean series intercorrelation (Rbar)	0.376	0.466	0.404
Expressed population signal (EPS)	0.855	0.881	0.852
Northwest Aspect (NWA)			
Statistics	**Upper**	**Middle**	**Lower**
Elevation (masl)	2400–2500	2100–2200	1800–1900
Slope (°)	≤40	≤40	≤40
Chronology span	1936–2018 (83)	1937–2018 (82)	1944–2018 (75)
Number of cores	18	19	26
Missing rings (%)	0.012	0.021	0.005
First order autocorrelation (AC1)	0.219	0.137	0.229
Standard deviation (SD)	0.381	0.382	0.294
Mean sensitivity (MS)	0.389	0.428	0.270
Mean series intercorrelation (Rbar)	0.223	0.324	0.356
Expressed population signal (EPS)	0.852	0.852	0.848

In NEA, the average radial growth is higher in the lower elevation belt (EB). The AC1 is higher in the middle EB. The SD and MS are higher in the upper EB. The value of Rbar is higher in the middle EB. The EPS value of all the elevation belts has more than the threshold limit of 0.850 (Table 1). In NWA, the average radial growth is higher in the middle EB. The AC1 is higher in the lower EB. Both SD and MS are higher in the middle EBs. The value of Rbar was recorded highest in the lower (0.356) EB. The EPS value of both the upper and middle elevation belts has more than the commonly used threshold limit of 0.850, while at the lower elevation belt, it is just at the boundary (Table 1).

3.2. Climate–Growth Response

The growth–climatic response of *P. wallichiana* varied along the elevational and aspect gradients. In NEA, the growth of *P. wallichiana* has a less strong relationship with climate at the lower EB (Figure 5). In the middle EB, tree growth showed a positive correlation with the precipitation of April (r = 0.387, $p < 0.05$) and the winter season (r = 0.301, $p < 0.05$), and a negative correlation with the temperature of the months of December (r = 0.370, $p < 0.05$), April (r = 0.346, $p < 0.05$), and August (r = 0.305, $p < 0.05$) and the winter season (r = 0.281, $p < 0.05$). At the same middle EB, tree growth showed a positive significant correlation with the scPDSI of April (r = 0.516, $p < 0.05$) and during monsoon season (r = 0.327, $p < 0.05$). In the upper EB, tree growth was negatively correlated with the temperature of October (r = 0.295, $p < 0.05$) only. On the other hand, tree growth was positively correlated with the precipitation of April (r = 0.400, $p < 0.05$) and the winter season (r = 0.371, $p < 0.05$). Similarly, tree growth showed a positive significant correlation with the scPDSI of April (r = 0.502, $p < 0.05$ (Figure 5).

In NWA, the climate–growth response of *P. wallichiana* also varied along the elevational and aspect gradients. In the lower EB, tree growth showed a positive correlation with the precipitation of July (r = 0.291, $p < 0.05$) and a negative correlation with the temperature of January (r = 0.252, $p < 0.05$) and July (r = 0.344, $p < 0.05$), while showing a significant positive correlation with the scPDSI of November (r = 0.361, $p < 0.05$), December (r = 0.295, $p < 0.05$), January (r = 0.389, $p < 0.05$), and February (r = 0.385, $p < 0.05$) and the winter (r = 0.324, $p < 0.05$) and pre-monsoon (r = 0.268, $p < 0.05$) seasons. In the middle EB, tree growth showed a positive correlation with the precipitation of December (r = 0.492, $p < 0.05$), March (r = 0.402, $p < 0.05$), and the winter season (r = 0.481, $p < 0.05$). On the other hand, tree growth was negatively correlated with the temperature of October (r = 0.388, $p < 0.05$) and March (r = -0.303, $p < 0.05$). There was a significant positive correlation between the growth and scPDSI in March (r = 0.292, $p < 0.05$), April (r = 0.434, $p < 0.05$), and the pre-monsoon (r = 0.278, $p < 0.05$) season. In the upper EB, tree growth showed a significant positive correlation only with scPDSI in April (r = 0.278, $p < 0.05$) (Figure 5).

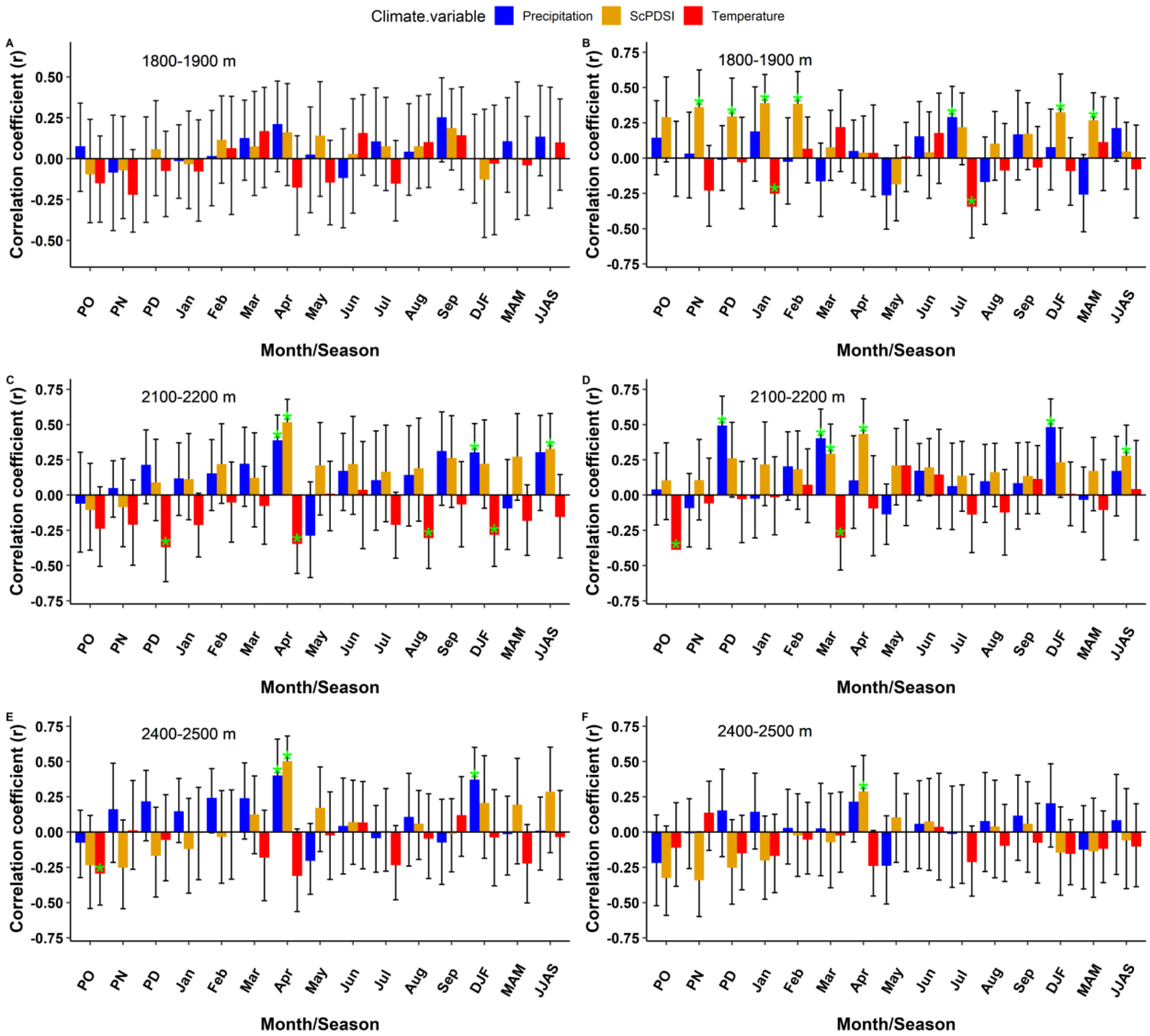
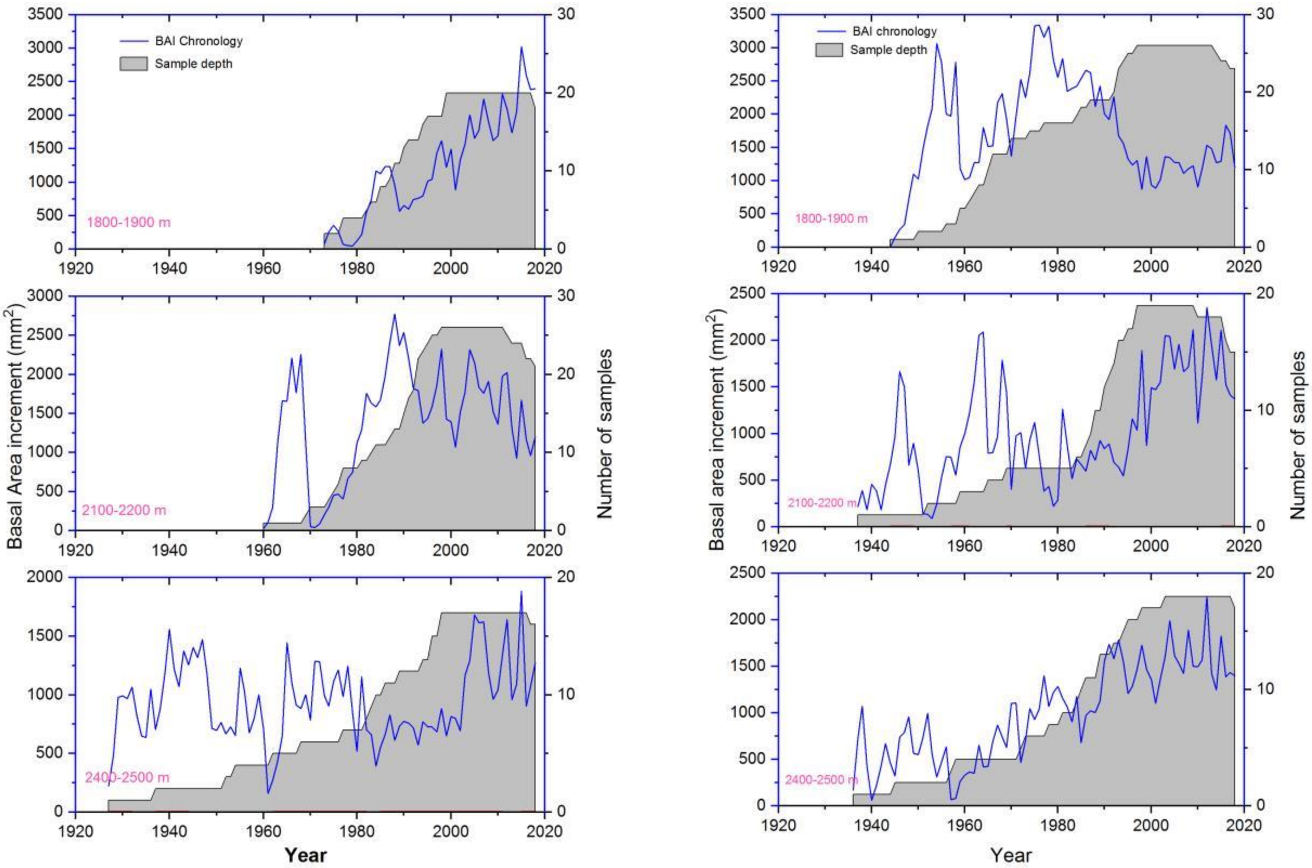


Figure 5. Correlation plot between tree-ring chronologies of *P. wallichiana* along the elevation gradient and climate variables (temperature, precipitation, and ScPDSI). The *X*-axis represents a lag-year month, current year month, and current year season. The climatic window includes one water year (previous October (PO) to current year September (Sep)). The bar height (*Y*-axis) represents the correlation coefficient, and line height indicates the 95% confidence interval of a Pearson correlation coefficient. The green star (*) in or above the bar indicates the significant correlation between right-width chronology and climate variable at 95% level. The left panel figures (**A**,**C**,**E**) are from the northeast aspect and the right panel figures (**B**,**D**,**F**) are from the northwest aspect in the study area at lower, middle, and higher elevation belts, respectively. Note: DJF means December, January, and February; MAM means March, April, and May; JJAS means June, July, August, and September.

3.3. Basal Area Increment (BAI) Growth Trend

We calculated the BAI of the *P. wallichiana* trees of each elevation belt in both aspects of the mountain slope. In NEA, the mean BAI was recorded highest in the middle EB (1397.41 mm^2y^{-1}) followed by the lower EB (1211.21 mm^2y^{-1}) and the upper EB (943.24 mm^2y^{-1}), respectively. In NWA, the mean BAI was recorded highest in the lower EB (1730.22 mm^2y^{-1}) followed by the middle EB (1016.85 mm^2y^{-1}) and upper EB (999.98 mm^2y^{-1}), respectively. The overall long-term pattern of BAI is found similar in all elevation ranges (Figure 6). However, there is a slight decrease in BAI during recent years at the NWA's upper EB and the middle EB in NEA.



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

Figure 6. Basal area increment (BAI) chronologies (Blue line) of *P. wallichiana* with sample depth (shaded area) along the elevation gradient in the Makwanpur districts—lower elevation belt (1800–1900 masl), middle elevation belt (2100–2200 masl) and upper elevation belt (2400–2500 masl): (**a**) northeast aspect; (**b**) northwest aspect.

4. Discussion

4.1. Tree-Ring Growth Pattern

Conifers formed visible annual rings, so they are the primary source for dendrochronological study worldwide. In Nepal, several conifers' species are well-studied; however, research on Pinus species has been limited despite their potential to serve as proxies for climate [28,41], especially in the lower Himalayas. On average, chronologies of conifer species had been built from 30–35 sample cores collected from 20–25 trees [42,43]. The most extended chronology of *P. wallichiana* so far developed was 694 years (1303–1996) from the archeological wood [44], and from living trees it was a 405-year-old from Dolpa [25].

The forest presence in our study area is young and at the lower limit of *P. wallichiana* distribution, so the longest chronology we can develop is 92 years. Our chronology length decreases along the elevation gradient in both aspects, which might be due to the recent development of the forest or anthropogenic disturbances in the past. Lower-elevation sampling sites are close to human settlements, and bigger-sized trees might be cut down for timber wood production. Though the forest is young, the growth rings' presence on cores is clear and has a sharp boundary. Other studies from the Himalayan region [25,43,44] also observed clear annual rings in pine species. Even though this study was carried out at a lower distribution limit of *P. wallichiana*, tree-ring chronology statistics are comparable to similar studies from the Himalayan region [10,25,43,44]. The overall EPS value is more than the theoretical threshold of 0.85 [37]. Interseries correlation ranges from 0.32 to 0.29, and mean sensitivity also ranges from 0.277 to 0.466, indicating that this species has high potential for dendroclimatic study in this area. The overall growth of *P. wallichiana* was recorded the highest in the middle elevation belt, but the growth is somehow similar in all belts.

4.2. Climate–Growth Response

The relationships between the Himalayan conifers' radial growths are not always uniform along the elevation gradient [10,45–47]. Variations in aspect, slope, and elevation of the sites may influence the growth [48]. Gaire et al. [25] concluded that moisture availability during the early growing season and the entire growing season is the primary limiting factor of pine growth in the Trans-Himalayan region in Nepal. Strong precipitation signals at the higher altitude support that the precipitation decreases with increasing altitude [49]. In our study, in NEA, correlation analysis between the radial growth of *P. wallichiana* and climatic variables showed monthly and seasonal responses. The growth of *P. wallichiana* at the lower elevation range is weakly correlated to climatic factors compared to other elevation belts. In the middle elevation range, growth had a positive response to the precipitation of the April and winter season. In the same elevation belt, tree growth shows positive responses with the scPDSI of April and monsoon but a negative relationship with the temperature of December, April, August, and the winter season. In the upper elevation, tree growth is negatively correlated with the temperature of October but positively correlated with the precipitation of April and winter season and positively correlated with scPDSI in April. Our result is somehow similar to the study of Gaire et al. [25], which shows that there were negative responses to temperature and positive responses to precipitation and scPDSI. This indicates that moisture is the predominant limiting factor for the radial growth of *P. wallichiana* in this region, supported by the growth responses of the middle elevation range of the NEA. At the lower elevation range in NWA, pine tree growth showed a positive correlation with the precipitation of July, scPDSI of the months of November, December, January, and February and the winter and pre-monsoon seasons, while showing a negative correlation with the temperature of January and July. This indicates that soil moisture in the winter season and pre-monsoon season play a vital role in the growth of *P. wallichiana* [25]. In the middle elevation belt, tree growth showed a positive correlation with the precipitation of December, March, and the winter season and negatively correlated with the temperature of October and March, while positively correlating with scPDSI in March, April, and the pre-monsoon season. In the upper elevation belt, the tree growth showed a significant positive correlation with scPDSI of April. This result supports the finding of Liang et al. [49]. However, it is difficult to understand why tree growth at the lower altitude did not show a significant positive or negative correlation with temperature and precipitation. Some differences in the response along elevation and aspects indicated the influence of microtopography and associated microclimate, in addition to broader climatic trend or pattern in the study region. This also indicated differential sensitivity and vulnerability of pine forests in the lower Himalayas to climate change. Rai et al. [46] also found that trees growing at the 3335 masl elevation in Manang, central Himalayas, did not show any drought signal, whereas tree presence both above and below that elevation responded well. Temperature is the limiting factor for tree growth at higher elevations [50,51]. Increasing temperature and decreasing precipitation, as well as competition between nearby vegetation may accelerate moisture stress for tree growth [52–54]. Rising temperatures and drying of the suitable site increase tree motility in the Himalayas [49,55]. Many researchers agree that spring (March, April, and May) precipitation is a driving factor of tree growth in the Himalayas and adjacent areas [56–58].

4.3. Basal Area Increment (BAI) Growth Trend

BAI generally follows the sigmoid curve [10,57], and we calculated to estimate the trends in tree growth along an elevation gradient in both the study aspects (NWA and SWA). The overall pattern in the BAI of *P. wallichiana* indicates the growing stage of the forest. However, the decrease in the BAI in the two elevation belts (upper in NWA and middle in SWA) indicates the importance of site factors or site-level climatic factors (microclimate) for the growth of the pine species. Previous studies from the Himalayas also found a continuous increasing or increasing–decreasing trend in the BAI of different species [10,57,59,60]. Inconsistencies in BAI growth trends along elevation and aspect gradients in our sites and elsewhere from the Himalayas suggest that factors such as disturbances and competition in the stand are masking the effect of climate on growth [60] or that microtopography and microclimate also influence the tree growth and their climatic sensitivity. The implications of the site and aspect-specific response and site-specific BAI trends of the pine tree indicate their differential vulnerability to climate change. Climate change may affect the same species growing in different elevations in different ways. Therefore, forest conservation policies and programs should consider the broader-to-local-scale climate response of tree species or forests to protect them from the adverse impacts of climate change.

5. Conclusions

We developed ring-width chronologies of *P. wallichiana* along the elevation gradient of NEA and NWA of central Nepal's lower Himalayas. The relationship between climate data and tree-ring width shows that the radial growth of *P. wallichiana* was mainly controlled by the moisture stress from winter to spring. The tree growth climate analysis exhibited a slightly different relationship along the elevation belts in both aspects. Trees in the NEA in the higher elevation belt are more sensitive to the climatic signals; however, trees of the lower elevation belts are more sensitive in the NWA. Some differences in climatic response and BAI chronologies along elevation and aspects indicate spatially differential vulnerability of the pine forests to climate change. Findings from this study form the foundation to understand the impact of climate change on the forest ecosystems in the lower limit of the distributional range in the Himalayas. Further studies incorporating multiproxy tree-ring parameters covering the entire elevation transect of the species distribution in the Himalayas are of paramount importance to understand the sensitivity and vulnerability of forest species to the adverse impacts of climate change in the entire Himalayas.

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Data Availability Statement: The data that support the findings of this study are available from the first author, [D.G.], upon reasonable request.

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