SPATIOTEMPORAL VARIATION AND CLIMATE CHANGE IMPACT ON RADIAL GROWTH OF CHIR PINE (*PINUS ROXBURGHII)* IN A SUBTROPICAL PINE FOREST IN PAKISTAN

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Abstract. Climate and topography both have a paramount role in defining tree species distribution. Global warming had increased the risk of climatic influences on the sustainability of subtropical pine forests. The radial growth (R_g) allows to understand the long term variation in climate change-at different temporal and spatial scales. Here, we analyzed 144 R_g chronologies from 48 different sites in a subtropical pine forest in the Murree Hills of Pakistan. The results showed a strong non-linear relationship of annual precipitation (PPT) and annual mean air temperature (T_a) with R_g. The results further indicated that previous and present summer precipitation imposed a positive impact on the R_g ($p < 0.05$). The previous summer T_a showed a significant negative effect on R_g while positively correlated during current July. The growth response analysis indicated that R_g was often limited by variation in soil moisture associated with lower PPT and higher T_a. Moreover, the dependency of R_g on PPT and T_a varied along growing degree days (GDD >5°C), at different elevations. Our findings provide a remarkable evidence that the annual R_g of *P. roxburghii* species appeared to be progressively limited by the effect of climate warming and varied spatially.

Keywords: *air temperature, chronologies, growing degree days, Murree hills, precipitation*

Introduction

An amplification in global earth surface temperature from 1880 to 2012, was observed at 0.85°C and the period from 1983 to 2012 was supposed to be the warmest thirty years since last fourteen centuries in the Northern latitudes (IPCC, 2014). How these climatic variations will dramatically affect terrestrial ecosystems is far from understood (Ma et al., 2012). Among these terrestrial ecosystems the major subtropical pine forest is predominantly distributed across indo-pacific south-western Himalayan region (Sheikh, 1993). The structure and function of forests are subject to be change by climate warming which also enhances the risk of severity in biotic and abiotic feedbacks i.e., wild fires droughts and insect outbreaks (Allen et al., 2010; Kasischke and Stocks, 2012; Price et

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al., 2013). Consequently, it is important to know the response of pine species to increasing climate change for accurate prediction of potential variations in subtropical pine forests.

Previous studies revealed that tree ring analysis provides a high resolution proxy to reform past climatic variation change (Esper et al., 2002; Cook et al., 2004; D'Arrigo et al., 2008), which helps in comprehend the association between tree growth and climatic variables (Hughes et al., 2010; Speer, 2010). Climatic parameters and tree growth depicts a linear relationship calibrated by traditional statistical functions and it remains consistent through time period (Jones et al., 2009; Tolwinski-Ward et al., 2011). In contrast, various studies have shown the presence of nonlinear and unstable relationships among tree growth and meteorological variables due to climate warming (Visser et al., 2010; Zhang and Wilmking, 2010). In particular, it has been revealed that pine species has shown a nonlinear relationship with climate variability (Lloyd et al., 2013; Saeed et al., 2016). The white spruce growth pattern showed lessened sensitivity to temperature in high altitudes (Porter and Pisaric, 2011; Lloyd et al., 2013), pointing out the divergence concern (D'Arrigo et al., 2008). The influence of climatic variables on tree ring growth might tend to vary along altitudinal gradients in climate and growth relationship for temporal changes. Therefore, long term temporal scale radial growth analysis is required to evidently state how tree-rings responds to environmental variables.

Many hydrometeorological factors influence the tree growth among which the available soil water contents and air temperature are the key variables (Schweingruber, 1996). Therefore, ring series of long-lived trees have ability to record long-term multi-year variation in climatic circumstances (Olano et al., 2012). Tree species may respond to climatic fluctuations in more complex ways due to the nature of complex physiology (Drew et al., 2013; Zang et al., 2014). Furthermore, temporal instability between tree growth and climate mediates their response patterns due to changes in constraining factors (Briffa et al., 2002; Leburgeois et al., 2012).

Climate enforces dual adversity on subsistence and evolution of many trees and shrubs i.e., erratic, unpredictable rain and associated extreme summer droughts (Valladares et al., 2014). The effect of drought varied along altitudinal gradient (Altman et al., 2017). Dramatic shifting behavior in forest ecosystems may not be happened only by direct response to climatic variations but usually associated to disturbances caused by climate change (Ghazoul et al., 2015). As climatic conditions varied continuously, the occurrence, impact and severity of disturbances on forest ecosystems are tend to increase globally (Flannigan et al., 2009; Turner, 2010; Seidl et al., 2014) and significantly modify the forest growth, structure, function, and successional trajectories (McCullough et al., 1998). Climatic change resulting variation in precipitation and temperature patterns, however such variations does not exhibit uniform pattern over entire year. Consequently, these limiting factors have relative importance in modulating the response of tree ring formation to climate change, caused predictions more difficult.

Many researches have documented the species-specific response of growth parameters to climatic variations, although they are subjected to same environmental conditions (Fekedulegn et al., 2003; Maxime and Hendrik, 2011). During the growing season, the growth of Oak was influenced by precipitation rates and not by temperature (Bednarz and Ptak, 1990) and suffered during water deficit conditions, but could not under plentiful water availability (Pilcher and Gray, 1982). In contrast, during the 20th and 21st centuries the positive radial growth of Beech species was observed with increasing temperature (Maxime and Hendrik, 2011) that was observed to be closely associated to scarce soil water condition (Bouriaud et al., 2004). Another studies have reported the strong possibility of Sycamore to largely decline in England, being more sensitive to water shortage during dry periods (Lemoine et al., 2001; Tissier et al., 2004). The responses of pine species to climate variation has been investigated in several Mediterranean and subtropical forest ecosystems. However, climate growth relationship of *P. roxburghii* in subtropical forests of Pakistan is still poorly understood.

In current study, to deeply insight on the species future persistence, we inspected the long-term continuing variation in the relationship stability between climate and growth of a subtropical Chir pine species (*P. roxburghii*). This model plant, considered as a representative species of subtropical pine zone and being significant to its functioning (Sheikh, 1993). It is uncertain that how long-term variation in climatic drivers would affect the tree growth of mature *P. roxburghii* over the previous century.

This study provides a fundamental prospective to forecast the species performance and sustainability, under the consequences of global warming. In particular, we sought to understand what kind of relationship between climate and growth is revealed by *P. roxburghii* at long-term scale and meanwhile the correlation is stable or not. We examined a complex network of tree radial ring-increment chronologies from 48 pine locations in the subtropical pine forest along different elevations in Murree Hills, Pakistan. We hypothesized that the impact of climatic factors on radial growth (R_g) of *P. roxburghii* might be varied along different elevations. The main objectives are: (1) to address the response of R_g to climatic variations by computing the domino effect of traditional linear and nonlinear functions; and (2) to explore the potential temporal variation in R_g along growing degree days (GDD), and different elevations.

Methods

Study area

The present study was conducted in Murree Hills of Pakistan (33° 47′ 15″ to 33° 54′ 47″ N and from 73° 16′ 54″ to 73° 29′ 18″ E) in September 2015 (*Fig. 1*). The study area is dominant representative part of Subtropical Chir pine forest zone (Conifer specialist group, 1996) about 33 km North-East of Islamabad, the country's capital place. The elevation range from 939 to 1873 m a. s. l. Mean monthly air temperature of the region varies gently, 35°C to 50°C in summer and 0 to 2°C in winter. Mean monthly relative humidity is 70 percent or above (Sheikh, 1993). While mean annual rainfall is around 1140 mm per year (Nizami et al., 2012). The main soil type is loamy with a variable composition of clay, sand, and silt. The sedimentary rocks are in comprises of sandstones, limestone, shales, and marls (Sheikh, 1993). The area is naturally dominated by stand of *Pinus roxburghii* (chir), managed under Punjab shelterwood silviculture system. The other related tree species are *Pinus wallichiana* (kail), *Pyrus pashia* (batangi), and *Quercus incana* (rhin). The understory vegetation contains grasses and shrubs i.e., *Dodonaea viscosa* (sanatha), *Carissa spinarum* (granda), *Myrsine africana* (khukhal), *Capparis decidua* (karir), *Adhatoda vasica* (Bahekar), *cannabis sativa* (Bang) and *Berberis lycium* species (sumblu).

Climate variables

Meteorological data was continuously collected from the meteorological station situated near the study site from 1995-2015. The climate variables used in this study includes, monthly and annual total precipitation, monthly and annual mean temperature, and growing degree days (GDD > 5°C). Continuous measurements of daily precipitation were monitored by tipping bucket rain gauges (TE525MM) and air temperature with HMP45C probes (HMP155A, Vaisala). The annual total precipitation was summed from the preceding September to the current August of each year. The climate of the region is subtropical, and is defined by hot, dry and long summer seasons while gentle mild, wet winters (CWB, 2006). In the study period, mean annual temperature varied considerably.

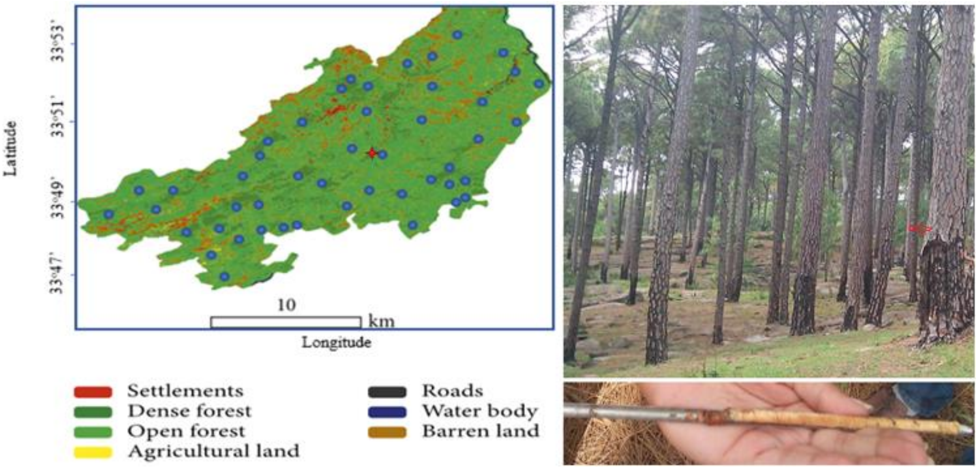

Figure 1. *Location of study sites (48 P. roxburghii stand), sampled tree and fresh tree ring core of pinus roxburghii in Murree Hills Pakistan. Sampled tree is indicated by red arrow*

Radial growth data

Trees were randomly sampled in the month of September during 2015 by following simple random sampling method. An average of three *Pinus roxburghii* trees were sampled from each site and 48 sites were sampled. The trees were cored with Pressler's increment borer (diameter 5 mm) at 1.3 m above the tree base. Each of increment cores was carefully wrapped and stored in polythene bags. In the laboratory, the cores were pasted to wooden boards, and polished after drying with successively finer grits of sandpaper (up to 600 grid) to create clearly visible tree ring sequences. All tree ring chronologies were visually cross-dated at 1st, then tree-rings of each core were counted under a dissecting microscope with 20x magnification and also by using a Velmex tree ring computing system having 0.001 mm resolution. COFECHA was used in the verification process of visual cross dating (Holmes, 1983). In addition, in order to date the trees centuries, half centuries, and decades were marked with lead pencil. Ring-widths were measured by hand using the computer program Measure J2X, a measuring table, and a microscope with 40x magnification. Rings were measured for their seasonal (dark and light bands separately) and annual growth. The standardized ring chronologies more often contains variation like natural or biological persistence. Residual chronologies were developed and less frequency persistence were removed using an autoregressive (AR) model. It considered as a bi weight dynamic approach to reduce the effect of outliers. In total, 48 Chir pine simple, residual and mean ring-width chronologies were prepared using R software (Bunn, 2008). The prepared chronologies were finalized by rechecking the ring series showing potential errors and corrected if dating miscalculation was happened (Holmes, 1986).

Climate-growth analysis

The relationship between climate and growth was evaluated by comparing tree ring chronologies to the climatic factors by using traditional nonlinear models and correlation analysis. Precipitation and air temperature of preceding to present growing season (May of previous year to August of current year) were tested. The significance of Pearson's correlation values was determined and the reliability of data was enhanced by bootstrapping method. The linear and nonlinear regression functions were fitted to represent the magnitude of variation in the correlation coefficients along growing degree days (GDD > 5°C) and different elevations. To analyze the growth response of *P. roxburghii* to climatic factors a multi linear mixed model was practiced, given below:

$$W_{ij} = \beta_0 + \beta_1 x_{ij} + \mu_{i1} + \mu_{i2} x_{ij} + \varepsilon_{ij} \tag{Eq.1}$$

where W_{ij} and x_{ij} denotes the tree ring chronologies and climatic factors for year i and site j; μ_{i1} and μ_{i2} are the intercept and slope values; $\beta 0$ and $\beta 1$ are the stable effects; ε_{ij} are site errors, μ_{i1}, μ_{i2} and εij are assumed to be independent. The parameters of linear mixed model were estimated (Bates et al., 2014) using the Matlab software (ver. R2017a, MathWorks Inc., USA).

Results

Variation in climatic factors

Seasonal variation in major climatic variables air temperature and precipitation were shown in *Fig. 2*. The long term (1995-2015) minimum, maximum, and mean air temperature from 1995-2015 were close to zero in winters and reached to seasonal maximum values during mid-summer period and peaked in June or July (*Fig. 2a*). The precipitation presented a clear seasonal trend generally varied with timing and amount (*Fig. 2b*). Winter and early springs were usually with little precipitation and the time period between July and August received most of the annual rainfall.

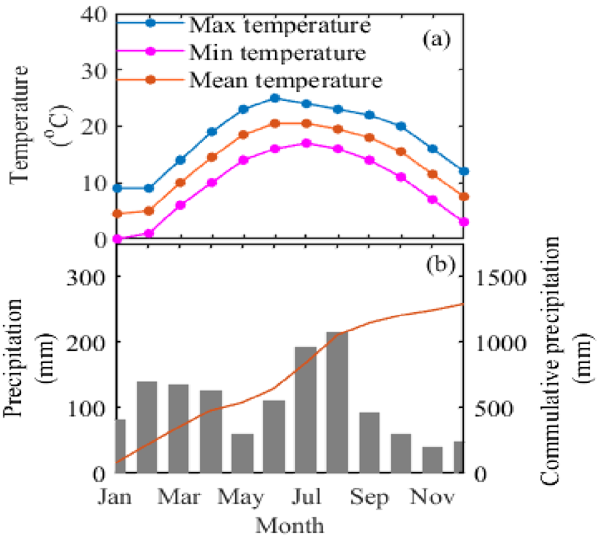

Figure 2. *Seasonal variation in (a) monthly mean minimum and maximum temperature (b) total monthly precipitation and cumulative precipitation during 1995-2015*

Long term variation in temperature and precipitation during the 20-year period were shown in *Fig. 3*. The annual maximum and minimum temperature ranged between 25.2-27.8°C and 12.8-14.7°C during 1995-2015. The variation in mean temperature was evident to be almost similar to the minimum temperature. The annual mean temperature was highest as 21.0°C, and lowest as 19.2°C, during 1999 and 1995, respectively (*Fig. 3b*). In addition, the slope pattern representing minimum and mean air temperature was steeper in comparison to the maximum temperature. The inter-annual mean values during 1995-2015 were 26.5 ± 0.57, 13.4 ± 0.39 and 20.90 ± 0.37°C for maximum, minimum and mean temperature respectively (*Fig. 3a,b*, *Table 1*). The variation was observed greater in minimum than maximum and mean temperatures with coefficient of variation 2.8, 2.01 and 1.85%, respectively. The inter-annual variation in annual total precipitation depicts an overall increasing trend whereas it varied markedly between 20 years (*Fig. 3b*). A great variation range between 590.8-1650 mm yr^{-1} was evident in the study area. The highest precipitation received in 2006 and lowest in 2000. Generally, the time period during 1999-2000 received lowest annual precipitation (*Fig. 3b*). The twenty-year inter-annual mean value of precipitation was 1190.7 ± 257.48 mm with 21% coefficient of variation (*Table 1*).

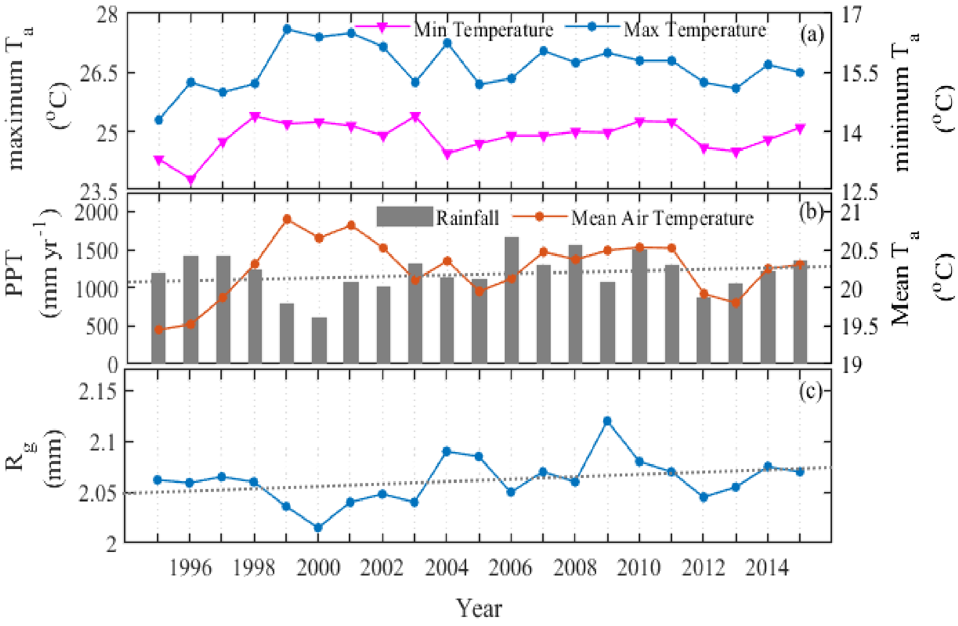

Figure 3. *Temporal variation in (a) maximum and minimum air temperature (b) precipitation and mean air temperature (c) tree radial growth (R_g) of P. roxburghii from 1995-2015. The dotted lines in b and c represents degree of slope*

Table 1. *Inter-annual variability in maximum, minimum, mean air temperature and total Precipitation over 1995-2015*

Variables	**Temperature**			**Precipitation**
	Max	**Min**	**Mean**	**Mean**
20 years average	26.5	13.4	20.90	1190.7
Standard deviation	0.57	0.39	0.37	257.48
Coefficient of variation (%)	2.8	2.01	1.85	21

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Statistical parameters of R_g

The constructed chronologies based on 48 *P. roxburghii* radial growth ring-series (each point was average of three replicates at one site) followed a time span length ranged between 33-91 years (*Table 2*). The two oldest trees had 104 rings. The maximum tree radial growth (R_g) was observed in 2004, 2009, and 2014 (2.065, 2.12, and 2.07 mm, respectively) while the smallest or depressed radial growth was 2.01 mm in 2000 and 2.04 mm in 2012 (*Fig. 3c*). The inter-annual mean R_g was 2.06 mm (±0.022) with 1.06% coefficient of variation during 1995–2015, which constitute both early and late wood formation (*Fig. 3c*). The annual sensitivity (slope) of the R_g was 0.19. Moreover, the years showing no ring formation (missing ring) or fused rings were few since last 20 years and there were no absent rings in last 10 years. Contrary an insignificant rise of 0.05 mm in ring widths was observed.

Table 2. *Relative information of the site variables and standard chronologies of P. roxburghii. Elev. and std. stands for elevation and standard deviation, respectively*

Site	**Elev.**	**Radial growth**	**Std.**	**Age**	**Site**	**Elev.**	**Radial growth**	**Std.**	**Age**
No.	**(m)**	**(mm)**	**(mm)**	**(Yr.)**	**No.**	**(m)**	**(mm)**	**(mm)**	**(Yr.)**
T1	1840	2.5	0.406	80	T 25	1380	2.8	0.32	73
T 2	1800	2	0.65	60	T 26	1360	2.6	0.286	78
T 3	1750	2.25	0.536	75	T 27	1340	3	0.392	66
T 4	1790	2.5	0.71	36	T 28	1320	2.7	0.554	64
T 5	1780	2.25	0.174	47	T 29	1300	2.7	0.144	56
T 6	1700	2.5	0.39	60	T 30	1280	2.25	0.315	53
T 7	1720	2.25	0.51	44	T 31	1260	2	0.25	61
T 8	1720	2.5	0.393	72	T 32	1240	2.75	0.55	65
T 9	1600	2.75	0.401	69	T 33	1220	2.75	0.174	58
T 10	1620	2	0.54	58	T 34	1200	2.25	0.35	47
T 11	1550	2.75	0.311	91	T 35	1180	2	0.25	48
T 12	1640	2.75	0.363	77	T 36	1160	2.3	0.047	59
T 13	1610	2.5	0.585	66	T 37	1140	2.9	0.233	59
T 14	1500	2.75	0.439	66	T 38	1130	2.6	0.266	55
T 15	1400	2.75	0.257	72	T 39	1120	2.75	0.161	74
T 16	1560	2	0.392	54	T 40	1100	2.3	0.4	75
T 17	1480	2.3	0.554	64	T 41	1090	2.4	0.021	55
T 18	1520	2.7	0.693	50	T 42	1080	2.7	0.286	62
T 19	1500	2.5	0.8	61	T 43	1070	2.5	0.392	67
T 20	1480	2.9	0.576	78	T 44	1050	2.3	0.554	71
T 21	1460	2.4	0.45	41	T 45	1030	2.5	0.144	74
T 22	1440	3.1	0.619	55	T 46	1020	1.9	0.315	82
T 23	1420	3.3	0.35	63	T 47	1000	2.55	0.25	69
T 24	1400	2.4	0.508	65	T 48	980	2.2	0.052	56

Long-term climate–growth relationship

Fig. 3c revealed that inter annual variation in R_g clearly followed the variation pattern in precipitation and temperature, as clear rise in R_g was observed in 2004, 2005 and 2009 followed by moderate precipitation amount. Whereas significant depressions in R_g during 2000, 2001 and 2012 were clearly related with low precipitation and high temperature. In contrast, the three largest precipitation years did not exhibit any significant rise in ring widths (*Fig. 3b,c*). In fact, the ring widths formation was lower than average, with year of extreme precipitation (such as 2006 and 2010). Subsequently our findings highlighted a baseline effect, below which the R_g tend to be increased until attaining the baseline point. The R_g showed no discernable trend above from baseline effect with further precipitation. Though, it appears that low R_g (~2.01 mm) coincided with precipitation range between 690-900 mm. The larger R_g (2.1 mm and over) was supported by moderate precipitation levels of 950-1100 mm while large precipitation 1200 mm or above have adverse effects on annual growth (*Fig. 3b,c*). The results therefore point out that moderate precipitation causing larger R_g, compared to smaller and larger precipitation events resulting in reduced growth. The results are further supported by regression analysis in *Figure 4a*.

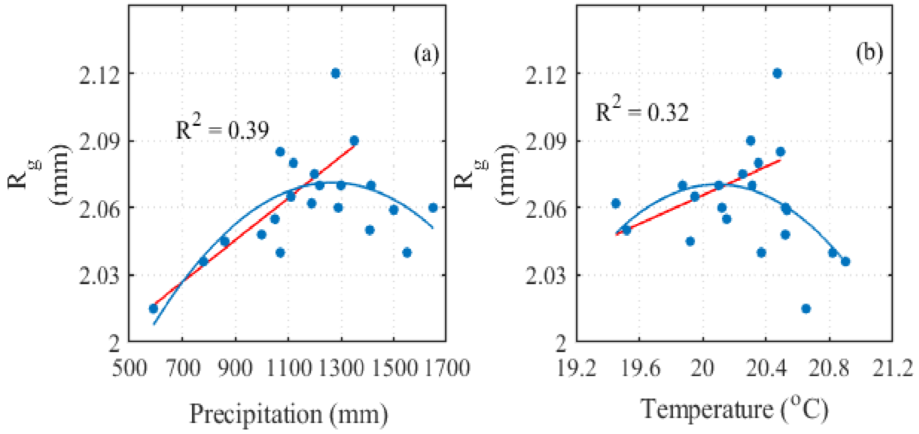

Figure 4. *Relationships between radial growth and major climatic drivers (a) precipitation and (b) temperature. Solid red lines are linear and blue lines are quadratic fitting between radial growth increement and the relevant variables. Each data point represents is annual mean from 1995-2015*

The tree R_g less influenced by mean annual temperature than precipitation (*Fig. 4a,b, Table 3*; based on Eq.1). R_g increased with increasing precipitation and temperature, then leveled off and gradually decreased showing 0.32 and 0.39 coefficient of determination respectively. Mean monthly precipitation and temperature also controls the R_g (*Fig. 5a-d*). Correlation coefficient values revealed that previous year precipitation from June-August was especially important for tree R_g (*$p < 0.01$, Fig. 5a*) and the association progressively weakened (*$p = 0.05$*) and turned into negative from October-December. The R_g often negatively correlated ($p < 0.05$) with preceding summer temperature of May and August ($R^2 = -0.36$ and -0.68, respectively) and positively correlated with October and January ($R^2 = 0.45$ *Fig. 5b*). In contrast, precipitation and temperature of current July showed strong positive control on R_g ($P < 0.05$; *Fig. 5c and d, Table 3*).

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Table 3. *Estimations of the response of radial ring-width of P. roxburghii to the total monthly precipitation, and mean monthly air temperature from May-Dec of preceding year and from Jan-Aug of current year by linear mixed models (Eq.1). One and two asterisk indicate p < 0.05, and p < 0.01, respectively. SE is the standard error*

Variables	**Precipitation**				**Temperature**			
	Month	**Estimation**	**SE value**	***t* stats**	**Month**	**Estimation**	**SE value**	***t* stats**
Previous year	May	0.06*	0.026	3.19	May	-0.17*	0.024	-2.15
	June	0.13	0.025	1.362	June	-0.85	0.021	-1.05
	July	0.22**	0.026	4.53	July	-0.31*	0.021	-2.42
	August	0.37*	0.024	8.0	August	-0.22*	0.023	-5.78
	September	0.056*	0.024	3.64	September	-0.29*	0.023	-2.81
	October	-0.038*	0.025	-2.24	October	0.48*	0.023	3.55
	November	0.018	0.024	0.743	November	0.26	0.023	1.73
	December	-0.001	0.026	-0.049	December	0.51*	0.023	2.65
Current year	January	0.043	0.027	0.62	January	0.10*	0.020	2.3
	February	0.089	0.024	0.93	February	-0.07	0.020	-0.31
	March	-0.057	0.022	-0.61	March	-0.19*	0.021	-1.5
	April	-0.087	0.022	-0.85	April	0.28**	0.021	2.74
	May	0.16	0.025*	4.80	May	0.32	0.021	0.87
	June	0.247	0.022*	6.72	June	-0.097*	0.022	-1.54
	July	0.43	0.024**	1.79	July	0.27*	0.023	2.95
	August	0.068	0.023	2.77	August	0.085	0.021	2.63

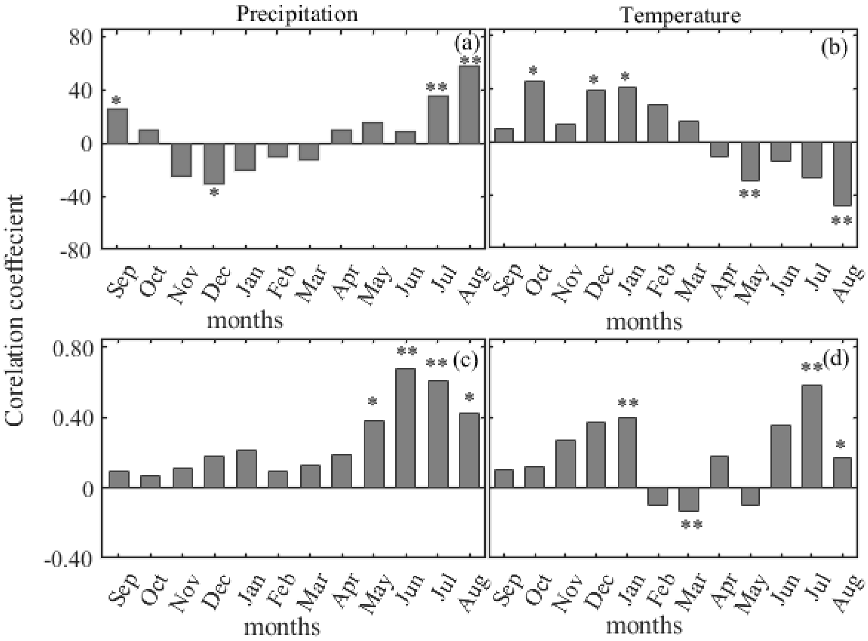

Figure 5. *Bootstrap correlations coefficients calculated among radial growth of P. roxburghii and major climatic factors i.e., monthly total precipitation of (a) preceding year from May-Jan; (c) current year from Jan-Sep, and monthly mean temperature of (b) preceding year from May-Jan; (d) current year from Jan-Sep in 1995–2015. One and two asterisks (*, **) denotes significance level at 95 and 99 % confidence (p < 0.05, p < 0.01) respectively*

Variation in climate-growth relationship along growing degree days (GDD > 5ºC) and different elevations

The coefficient of determination between R_g at 48 sites and total monthly precipitation of current summer decreased with increasing elevation (*Fig. 6a, p* < 0.05). In relation to elevation, *P. roxburghii* showed a robust dependency of R_g to mean summer temperature. The significant positive relationships between R_g and summer temperature was observed for higher elevations (> 1300 m), while below ~1300 m the relationships became negative (*Fig. 6b*). The correlations of previous and current summer precipitation with radial growth showed similar increasing trend but slightly differed in magnitude at high GDDs (*Fig. 6c*, *p* = 0.018, 0.025, respectively). In comparison, with increasing GDD, the influence of current and preceding summer temperatures on trees radial growth progressively declined and became negative above ~900 GDD (*Fig. 6d, p* = 0.041, 0.039, respectively).

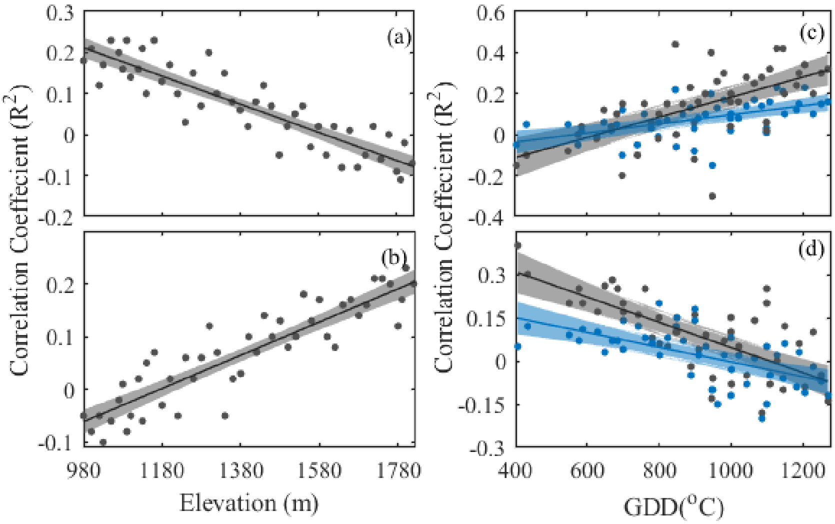

Figure 6. *Variability in correlation coefficients of radial growth with (a) total monthly precipitation and (b) mean monthly temperature of current summer along increasing elevation; (c) total monthly precipitation and (d) mean monthly temperature of preceding (blue) and current summer (grey); with growing degree days (GDD > 5◦C). The colored range shows 95% confidence level*

The response curves in *Fig. 7* showed radial growth responses to variation in temperature and soil moisture. Results indicated that radial growth affected by temperature were progressively increased and peaked its maximum in summer (July) and followed by zero effect in cold winter. Based on temperature and available soil water effected response curves, the R_g in 28 sites were mainly controlled by available soil water contents associated with precipitation (e.g., SN. 3-6 in *Fig. 7*), 9 sites were limited by temperature (e.g., SN. 7, in *Fig. 7*), and 11 sites were not affected by both variables (e.g., SN. 1, 2, 8, in *Fig. 7*). Therefore, 48 R_g trends could be grouped into 3 categories i.e., trend I (was related to soil water controlled), trend II (temperature controlled), and trend III (not controlled by both). The radial growth and three patterns were all significant (*P* < 0.05). The response curves showed the growth of *P. roxburghii* was observed to be frequently controlled by soil moisture that is directly related to precipitation and fewer by temperature, though varied among different sites.

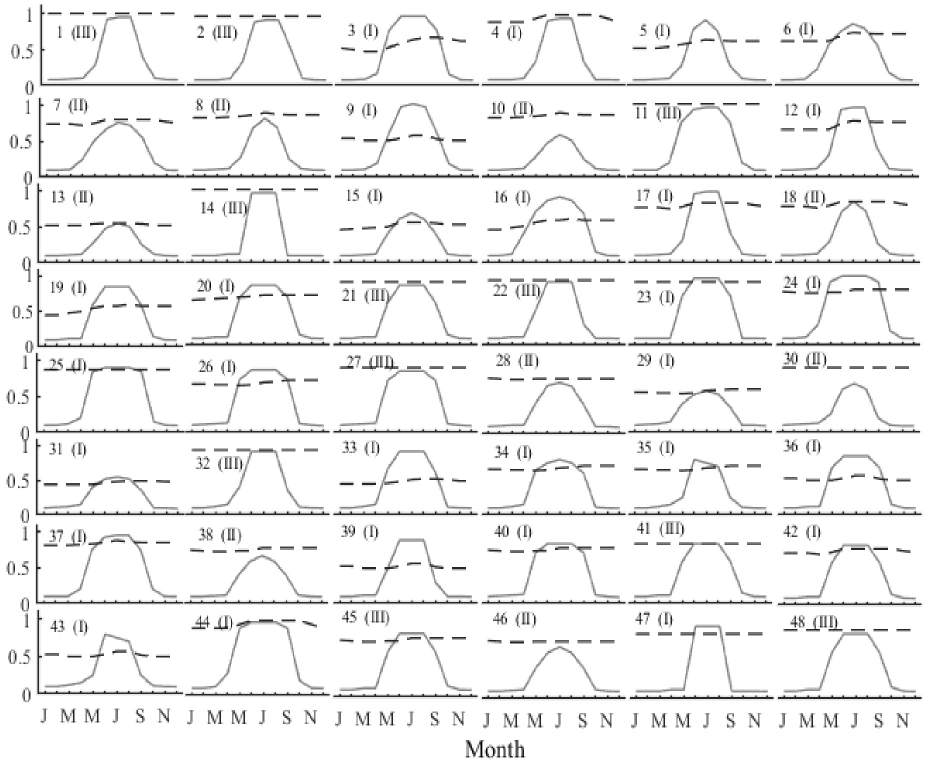

Figure 7. *Seasonal variation showing by growth response curves of temperature (the solid) and moisture level (dashed lines). The label I represents moisture controlled, II temperature controlled and III does not controlled by any of two variables. Each response graph shows the growth pattern at each site (n=48)*

Discussions

Temporal variation in R_g and its controlling mechanisms

In comparison to global average temperature, the rise was observed by 0.74°C at local levels during 1906-2005 (IPCC, 2007). This study indicated that the mean maximum and minimum temperature increases with 0.60 and 1.27°C, respectively, over long temporal scale (1995-2015). The results showed high variation in precipitation ranging between 590.8-1650 mmy^{-1} with significant rise of 21% in study area (*Fig. 3b*). The findings are in lined with previous results concluded by Grunewald et al. (2009) and Liu et al. (2010).

Previous research documented that several factors affect the tree radial growth characteristics, most of them are tree age and site specific related to management operations, however air temperature, precipitation and solar radiations were marked as broader climatic drivers (Yeh and Wensel, 2000). Our results showed that moderate precipitation range could produce larger ring growth and lower precipitation resulting smaller R_g (*Fig. 3c*). These findings are in line with previous researches which suggests that the years producing narrow rings were mainly due to low precipitation levels (Bouriaud et al., 2004; Morecroft et al., 2008). Previous researches have demonstrated the similar effects of precipitation and temperature on radial growth and ring width characteristics. It has been found that the annual radial growth (diameter increment) was more often influenced by the effect of growing season precipitation and temperature and also months preceding that season in *Pinus sylvestris*, *Abies alba*, *Picea abies*, *Picea sitchensis, Pseudotsuga menziesii* (Feliksik and Wilczynski, 2009). According to Khan et al. (2013) radial growth of *Cedrus deodara* was found being a function of precipitation and temperature in Chitral-Hindukush, Pakistan.

Precipitation limits the growth rate of trees in many ecosystems more than temperature (Cherubini et al., 2003). However, the winter cold was key limiting factor mainly for tree species habitat in mountainous environment (Leburgeois et al., 2012; Martin-Benito et al., 2013) and for evergreen species (Granda et al., 2013). The regression results specified that the summer temperature of preceding year exerted high negative effect on R_g of *P. roxburghii,* whereas the temperature of preceding autumn and winter (Oct-Jan) had positive influence on the R_g ($p < 0.05$, *Fig. 5b*). In summer season, when temperature increases to its maximum, the rate of evapotranspiration becomes high, which results in soil water shortages (Huang et al., 2010), thus become less responsive to temperature. The previous year temperature control was in lined to carryover effect explained by Fritts (2001) and Rammig et al. (2015) that, the deficient nutrient stored during preceding year marked a substantial influence on following year growth. Equally, high temperature in preceding year had inhibit the photosynthesis that impose a decline in growth formation of tree in the subsequent year owing to the inadequate carbohydrates storage. On the other hand, high autumn and winter temperatures favors the growth rate of following year (*Fig. 5d*) by increasing the size and subsistence of buds and thus, the acclimation ability of plant (Weber et al., 2007). Another reason might include, after dormant winter period, a warm end could gently accelerate the cambial reactivation and helps in earlier leaf out, which eventually prolong the period of wood formation (Sanz-Pérez et al., 2009; Viera et al., 2014).

The previous year precipitation showed positive and significant impacts on the R_g (*Fig. 5a*). Preceding year precipitation is also important to boost radial growth formation in many species (Di Filippo et al., 2010). Soil water recharge during autumn and winter precipitation, when growth of *P. roxburghii* remain dormant, appears to be a vital element effecting tree growth rate in the subsequent growth season. This phenomenon found to be an indispensable reserve for commencement of cambial activity and early wood production (Granda et al., 2013; Martin-Benito et al., 2013). During current growing period, tree R_g was more usual positive relationship with May and June precipitation (*Fig. 5c*) and revealed a negative correlation with temperature (*Fig. 5d*). Sufficient precipitation could positively effect on radial growth through making an improvement in xylem cell production and lessen the water stress in an area (Deslauriers et al., 2016). Consequently, this phenomenon favors the positive response of radial growth to precipitation in both preceding and present growing season.

Inclusively, these findings suggest that precipitation and temperature of previous and current growing seasons are the primary controlling factors for growth rate of Chir pine. Prior to the commencement of cold in winter, the species might complete photosynthesis process to stock energy thus execute a positive influence on the tree R_g similar to various evergreen conifers (Miyazawa and Kikuzawa, 2005). Consequently, the temperature of previous year October-December was positively correlated with R_g (*Table 3, Fig. 5b*). Previous studies showed the strong effect of previous summer climate variables on radial growth (Teets et al., 2018).

Spatial variation in the climate growth relationship with GDDs

Results specified that the R_g in *P. roxburghii* was more probably to down regulated by warmer summer temperature which suggests a higher dependency of tree R_g to summer temperature in context of elevation gradient (*Fig. 6b*). Over the past decades, the significant increasing trend in global temperature (IPCC, 2007) and 0.56-0.78°C in various forests of Pakistan was reported by Bukhari and Bajwa (2011). We also found that, warmer summers boosted the radial growth above ~1300 m but reduced it below this elevation (*Fig. 6b*). A winter with warmer end might prevent the soft tissues of tree i.e., roots and buds damage by freezing stress, in higher altitudes (Miller-Rushing and Primack, 2008). Correlation analyses specified the variation in climate–growth relationships with increasing elevation (Huo et al., 2017). The relationship between R_g and precipitation weakened with increasing elevation (*Fig. 6a*), due to the snow effect at higher elevation. A rise in precipitation can quickly reduce the environmental stress and stimulate the radial growth during water-deficit conditions at lower elevation and turn the relationship positive (Deslauriers et al., 2016). As a consequence, trees in the southern sites often grew in a dry and hot atmospheric conditions, so radial growth positively respond and being more sensitive to the increase of precipitation. Subsequently, the R_g was limited by temperature owing to increasing GDD and decreasing precipitation (*Fig. 6c,d*). Similar findings have been observed for silver fir species decreasing at the southern edge, likely as a consequence of the cumulative influence of severe drought (Linares and Camarero, 2010). Moreover, white spruce in Western Canada has also been reported by similar variation (Chen et al., 2017).

The results specified the monthly variation in the response of radial growth to climatic variables i.e., temperature and soil moisture at fortyeight sites (*Fig. 7*). The response curves can detect the signals of temperature influencing or moisture limiting effect on radial growth of *P. roxburghii* in the subtropical pine forest. For instance, the radial growth was limited by soil moisture in 28 sites and few sites were limited by temperature. The eleven sites were similarly effected by temperature and moisture (*Fig. 7*). The non-significant effect in eleven sits suggested that the R_g was neither restricted by precipitation nor by temperature, meanwhile could be influenced by some other site-specific factors (Gewehr et al., 2014). In addition, other site-specific factors such as micro environmental circumstances and species competition (Huang et al., 2013) may be crucial for tree growth determining at these pine sites.

Conclusion

Annual temperature and precipitation were the dominant limiting factor for the R_g of *P. roxburghii.* Summer precipitation (June-August) of previous and current year was most important for tree R_g. The previous summer temperature imposed negative impact on R_g while positive in current July. The R_g was more often limited by soil moisture associated with lower precipitation and high temperature. The control of precipitation was seen to be more significant at lower elevation (<1300 m). However, R_g showed clear dependency on summer temperature when elevation ranged above 1300 m. The approaches employed in this study for unstable temporal responses and nonlinear dependency of *P. roxburghii* to climate drivers, are related to manage and predict the effects of a substantially varied landscape. It also has the potential to forecast future resource outcomes from these forested ecosystems and vulnerability of other forests by using a combination of process-based and global circulation models. In addition, tree sensitivity to site specific climatic variables might useful to expect climate change to decrease stand growth. Due to continuous increase in global climate change, it is suggested that continuous large scale measurements are required to address the temperature and moisture induced variation in climate-growth analysis for sustainable forest management.

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